PTO/SB/05 (08-08)
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UTILITY PATENT APPLICATION TRANSMITTAL

(Only for new nonprovisional applications under 37 CFR 1.53(b))

Attorney Docket No.	MIT-0001-U01-C01-C10
First Inventor	John D. Joannopoulos
Title	WIRELESS ENERGY TRANSFER TO A MO
Express Mail Label No.	N/A

APPLICATION ELEMENTS

See MPEP chapter 600 concerning utility patent application contents.

1. ☐ **Fee Transmittal Form** (e.g., PTO/SB/17)
2. ☐ **Applicant claims small entity status.** See 37 CFR 1.27.
3. ☑ **Specification** [*Total Pages* 20]
   Both the claims and abstract must start on a new page
   (For information on the preferred arrangement, see MPEP 608.01(a))
4. ☑ **Drawing(s)** (*35 U.S.C. 113*) [*Total Sheets* 6]
5. **Oath or Declaration** [*Total Sheets* 2]
   a. ☐ Newly executed (original or copy)
   b. ☑ A copy from a prior application (37 CFR 1.63(d))
   (for continuation/divisional with Box 18 completed)
   i. ☐ DELETION OF INVENTOR(S)
   Signed statement attached deleting inventor(s) name in the prior application, see 37 CFR 1.63(d)(2) and 1.33(b).
6. ☑ **Application Data Sheet.** See 37 CFR 1.76
7. ☐ **CD-ROM or CD-R** in duplicate, large table or Computer Program *(Appendix)*
   ☐ Landscape Table on CD
8. **Nucleotide and/or Amino Acid Sequence Submission**
   (if applicable, items a. – c. are required)
   a. ☐ Computer Readable Form (CRF)
   b. Specification Sequence Listing on:
      i. ☐ CD-ROM or CD-R (2 copies); or
      ii. ☐ Paper
   c. ☐ Statements verifying identity of above copies

ADDRESS TO:

Commissioner for Patents
P.O. Box 1450
Alexandria VA 22313-1450

ACCOMPANYING APPLICATION PARTS

9. ☐ **Assignment Papers** (cover sheet & document(s))
   Name of Assignee _____
10. ☐ **37 CFR 3.73(b) Statement** *(when there is an assignee)* ☐ **Power of Attorney**
11. ☐ **English Translation Document** *(if applicable)*
12. ☐ **Information Disclosure Statement** (PTO/SB/08 or PTO-1449)
    ☐ Copies of citations attached
13. ☐ **Preliminary Amendment**
14. ☐ **Return Receipt Postcard** (MPEP 503)
    (Should be specifically itemized)
15. ☐ **Certified Copy of Priority Document(s)**
    (if foreign priority is claimed)
16. ☐ **Nonpublication Request** under 35 U.S.C. 122(b)(2)(B)(i). Applicant must attach form PTO/SB/35 or equivalent.
17. ☐ Other: _____

18. If a CONTINUING APPLICATION, *check appropriate box, and supply the requisite information below and in the first sentence of the specification following the title, or in an Application Data Sheet under 37 CFR 1.76:*

☑ Continuation ☐ Divisional ☐ Continuation-in-part (CIP) of prior application No.: 12/553,957

Prior application information: *Examiner* Not Yet Assigned *Art Unit:* 2817

19. CORRESPONDENCE ADDRESS

☑ The address associated with Customer Number: 87084 ***OR*** ☐ Correspondence address below

Name					
Address					
City		State		Zip Code	
Country		Telephone		Email	

Signature	/John A. Monocello,III/	Date	December 30, 2009
Name (Print/Type)	John A. Monocello, III	Registration No. (Attorney/Agent)	51,022

This collection of information is required by 37 CFR 1.53(b). The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 12 minutes to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

Privacy Act Statement

The **Privacy Act of 1974 (P.L. 93-579)** requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (*i.e.*, GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

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Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it contains a valid OMB control number.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-0001-U01-C01-C10
	Application Number	
Title of Invention	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS	

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.

Secrecy Order 37 CFR 5.2

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Applicant Information:

Applicant 1 Remove

Applicant Authority	◉ Inventor	○ Legal Representative under 35 U.S.C. 117	○ Party of Interest under 35 U.S.C. 118

Prefix	Given Name	Middle Name	Family Name	Suffix
	John	D.	Joannopoulos	

Residence Information (Select One) ◉ US Residency ○ Non US Residency ○ Active US Military Service

City	Belmont	State/Province	MA	Country of Residence [i]	US

Citizenship under 37 CFR 1.41(b) [i]	US

Mailing Address of Applicant:

Address 1	64 Douglas Road
Address 2	

City	Belmont	State/Province	MA
Postal Code	02478	Country [i]	US

Applicant 2 Remove

Applicant Authority	◉ Inventor	○ Legal Representative under 35 U.S.C. 117	○ Party of Interest under 35 U.S.C. 118

Prefix	Given Name	Middle Name	Family Name	Suffix
	Aristeidis		Karalis	

Residence Information (Select One) ◉ US Residency ○ Non US Residency ○ Active US Military Service

City	Boston	State/Province	MA	Country of Residence [i]	US

Citizenship under 37 CFR 1.41(b) [i]	GR

Mailing Address of Applicant:

Address 1	151 Tremont Street
Address 2	Apt. 21F

City	Boston	State/Province	MA
Postal Code	02111	Country [i]	US

Applicant 3 Remove

Applicant Authority	◉ Inventor	○ Legal Representative under 35 U.S.C. 117	○ Party of Interest under 35 U.S.C. 118

Prefix	Given Name	Middle Name	Family Name	Suffix
	Marin		Soljacic	

Residence Information (Select One) ◉ US Residency ○ Non US Residency ○ Active US Military Service

City	Belmont	State/Province	MA	Country of Residence [i]	US

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	Application Number	
Title of Invention	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS	

Citizenship under 37 CFR 1.41(b) [i]	HR		
Mailing Address of Applicant:			
Address 1	44 Westlund Road		
Address 2			
City	Belmont	**State/Province**	MA
Postal Code	02478	**Country**[i]	US

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below.
For further information see 37 CFR 1.33(a).

☐ **An Address is being provided for the correspondence Information of this application.**

Customer Number	87084		
Email Address		Add Email	Remove Email

Application Information:

Title of the Invention	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS		
Attorney Docket Number	MIT-0001-U01-C01-C10	**Small Entity Status Claimed**	☐
Application Type	Nonprovisional		
Subject Matter	Utility		
Suggested Class (if any)		**Sub Class (if any)**	
Suggested Technology Center (if any)			
Total Number of Drawing Sheets (if any)	6	**Suggested Figure for Publication (if any)**	

Publication Information:

☐ Request Early Publication (Fee required at time of Request 37 CFR 1.219)

☐ **Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32). Enter either Customer Number or complete the Representative Name section below. If both sections are completed the Customer Number will be used for the Representative Information during processing.

Please Select One:	◉ Customer Number	○ US Patent Practitioner	○ Limited Recognition (37 CFR 11.9)

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U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
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Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-0001-U01-C01-C10
	Application Number	
Title of Invention	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS	

Customer Number	87084

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, or 365(c) or indicate National Stage entry from a PCT application. Providing this information in the application data sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78(a)(2) or CFR 1.78(a)(4), and need not otherwise be made part of the specification.

Prior Application Status	Pending		Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
	Continuation of	12/553957	2009-09-03
Prior Application Status	Pending		Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
12/553957	Continuation of	11/481077	2006-07-05
Prior Application Status	Expired		Remove
Application Number	Continuity Type	Prior Application Number	Filing Date (YYYY-MM-DD)
11/481077	non provisional of	60/698442	2005-07-12

Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the **Add** button. Add

Foreign Priority Information:

This section allows for the applicant to claim benefit of foreign priority and to identify any prior foreign application for which priority is not claimed. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55(a).

Remove

Application Number	Country i	Parent Filing Date (YYYY-MM-DD)	Priority Claimed
			◉ Yes ○ No

Additional Foreign Priority Data may be generated within this form by selecting the **Add** button. Add

Assignee Information:

Providing this information in the application data sheet does not substitute for compliance with any requirement of part 3 of Title 37 of the CFR to have an assignment recorded in the Office.

Assignee 1 Remove

If the Assignee is an Organization check here. ☐

Prefix	**Given Name**	Middle Name	**Family Name**	Suffix

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	Application Number	
Title of Invention	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS	

Mailing Address Information:			
Address 1			
Address 2			
City		**State/Province**	
Country [i]		Postal Code	
Phone Number		Fax Number	
Email Address			
Additional Assignee Data may be generated within this form by selecting the **Add** button.		Add	

Signature:

A signature of the applicant or representative is required in accordance with 37 CFR 1.33 and 10.18. Please see 37 CFR 1.4(d) for the form of the signature.					
Signature	/John A. Monocello, III/			Date (YYYY-MM-DD)	2009-12-30
First Name	John	Last Name	Monocello, III	Registration Number	51022

This collection of information is required by 37 CFR 1.76. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 23 minutes to complete, including gathering, preparing, and submitting the completed application data sheet form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.**

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3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.

4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).

5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.

6. A record in this system of records may be disclosed, as a routine use, to another federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).

7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.

8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspections or an issued patent.

9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

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Exhibit 1024
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Electronic Patent Application Fee Transmittal

Application Number:	
Filing Date:	
Title of Invention:	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS
First Named Inventor/Applicant Name:	John D. Joannopoulos
Filer:	John A. Monocello/Jennifer Sammartin
Attorney Docket Number:	MIT-0001-U01-C01-C10

Filed as Large Entity

Utility under 35 USC 111(a) Filing Fees

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
Utility application filing	1011	1	330	330
Utility Search Fee	1111	1	540	540
Utility Examination Fee	1311	1	220	220
Pages:				
Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				
Miscellaneous:				
			Total in USD ($)	**1090**

Electronic Acknowledgement Receipt

EFS ID:	6727039
Application Number:	12649635
International Application Number:	
Confirmation Number:	5891
Title of Invention:	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS
First Named Inventor/Applicant Name:	John D. Joannopoulos
Customer Number:	87084
Filer:	John A. Monocello/Jennifer Sammartin
Filer Authorized By:	John A. Monocello
Attorney Docket Number:	MIT-0001-U01-C01-C10
Receipt Date:	30-DEC-2009
Filing Date:	
Time Stamp:	13:16:50
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	yes
Payment Type	Deposit Account
Payment was successfully received in RAM	$1090
RAM confirmation Number	7715
Deposit Account	505087
Authorized User	

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)

1		MIT_0001_U01_C01_C10_Specification.pdf	219503 80ffd7ff3a2e52059f95b4405952ca11e43c4aff6b	yes	20
	Multipart Description/PDF files in .zip description				
	Document Description		**Start**	**End**	
	Specification		1	17	
	Claims		18	19	
	Abstract		20	20	
Warnings:					
Information:					
2	Drawings-only black and white line drawings	MIT_0001_U01_C01_C10_Drawings.pdf	598809 31f0833c097ab3554658804f0607e7e1e4b60bbdc1	no	6
Warnings:					
Information:					
3	Oath or Declaration filed	MIT_0001_U01_C01_C10_Declaration.pdf	75992 4f321f94c94bd5ed11e88891c688d0ae8308d1427	no	2
Warnings:					
Information:					
4	Transmittal of New Application	MIT_0001_U01_C01_C10_Utility_Transmittal_Form.pdf	274268 f0b7d979b6211d8ec2f8a6e0b1e22335c106bc77	no	2
Warnings:					
Information:					
5	Application Data Sheet	MIT_0001_U01_C01_C10_ADS.pdf	1358098 8db08d8d11b55977da7e4539832c9e5d05ee1b41	no	5
Warnings:					
Information:					
6	Fee Worksheet (PTO-875)	fee-info.pdf	33075 b50c58aa0a52867a0089b09c4167378bc0800061	no	2
Warnings:					
Information:					
		Total Files Size (in bytes):	2559745		

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of co-pending United States Patent Application entitled WIRELESS NON-RADIATIVE ENERGY TRANSFER filed on September 3, 2009 having serial number 12/553,957 ('957 Application), the entirety of which is incorporated herein by reference. The '957 Application is a continuation of co-pending United States Patent Application entitled WIRELESS NON-RADIATIVE ENERGY TRANSFER filed on July 5, 2006 and having serial number 11/481,077 ('077 Application), the entirety of which is incorporated herein by reference. The '077 Application claims the benefit of provisional application serial number 60/698,442 filed July 12, 2005 ('442 Application), the entirety of which is incorporated herein by reference.

STATEMENT REGARDING GOVERNMENT FUNDING

[0002] This invention was made, in whole or in part by grant DMR-0213282 from the National Science Foundation. Accordingly, the Government may have certain rights in the invention.

BACKGROUND OF THE INVENTION

[0003] The invention relates to the field of oscillatory resonant electromagnetic modes, and in particular to oscillatory resonant electromagnetic modes, with localized slowly evanescent field patterns, for wireless non-radiative energy transfer.

[0004] In the early days of electromagnetism, before the electrical-wire grid was deployed, serious interest and effort was devoted towards the development of schemes to transport energy over long distances wirelessly, without any carrier medium. These efforts appear to have met with little, if any, success. Radiative modes of omni-directional antennas, which work very well for information transfer, are not suitable for

InductEV, Inc.
Exhibit 1024
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such energy transfer, because a vast majority of energy is wasted into free space. Directed radiation modes, using lasers or highly-directional antennas, can be efficiently used for energy transfer, even for long distances (transfer distance $L_{TRANS} \gg L_{DEV}$, where L_{DEV} is the characteristic size of the device), but require existence of an uninterruptible line-of-sight and a complicated tracking system in the case of mobile objects.

[0005] Rapid development of autonomous electronics of recent years (e.g. laptops, cell-phones, house-hold robots, that all typically rely on chemical energy storage) justifies revisiting investigation of this issue. Today, the existing electrical-wire grid carries energy *almost* everywhere; even a medium-range wireless non-radiative energy transfer would be quite useful. One scheme currently used for some important applications relies on induction, but it is restricted to very close-range ($L_{TRANS} \ll L_{DEV}$) energy transfers.

SUMMARY OF THE INVENTION

[0006] According to one aspect of the invention, there is provided an electromagnetic energy transfer device. The electromagnetic energy transfer device includes a first resonator structure receiving energy from an external power supply. The first resonator structure has a first Q-factor. A second resonator structure is positioned distal from the first resonator structure, and supplies useful working power to an external load. The second resonator structure has a second Q-factor. The distance between the two resonators can be larger than the characteristic size of each resonator. Non-radiative energy transfer between the first resonator structure and the second resonator structure is mediated through coupling of their resonant-field evanescent tails.

[0007] According to another aspect of the invention, there is provided a method of transferring electromagnetic energy. The method includes providing a first resonator structure receiving energy from an external power supply. The first resonator structure has a first Q-factor. Also, the method includes a second resonator structure being positioned distal from the first resonator structure, and supplying useful working power to an external load. The second resonator structure has a second Q-factor. The distance between the two resonators can be larger than the characteristic size of each resonator. Furthermore, the method includes transferring non-radiative energy between

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the first resonator structure and the second resonator structure through coupling of their resonant-field evanescent tails.

[0008] In another aspect, a method of transferring energy is disclosed including the steps of providing a first resonator structure receiving energy from an external power supply, said first resonator structure having a first resonant frequency ω_1, and a first Q-factor Q_1, and characteristic size L_1. Providing a second resonator structure being positioned distal from said first resonator structure, at closest distance D, said second resonator structure having a second resonant frequency ω_2, and a second Q-factor Q_2, and characteristic size L_2, where the two said frequencies ω_1 and ω_2 are close to within the narrower of the two resonance widths Γ_1, and Γ_2, and transferring energy non-radiatively between said first resonator structure and said second resonator structure, said energy transfer being mediated through coupling of their resonant-field evanescent tails, and the rate of energy transfer between said first resonator and said second resonator being denoted by κ, where non-radiative means D is smaller than each of the resonant wavelengths λ_1 and λ_2, where c is the propagation speed of radiation in the surrounding medium.

[0009] Embodiments of the method may include any of the following features. In some embodiments, said resonators have $Q_1>100$ and $Q_2>100$, $Q_1>200$ and $Q_2>200$, $Q_1>500$ and $Q_2>500$, or even $Q_1>1000$ and $Q_2>1000$. In some such embodiments, $\kappa/\mathrm{sqrt}(\Gamma_1*\Gamma_2)$ may be greater than 0.2, greater than 0.5, greater than 1, greater than 2, or even grater than 5. In some such embodiments D/L_2 may be greater than 1, greater than 2, greater than 3, greater than 5.

[0010] In another aspect, an energy transfer device is disclosed which includes: a first resonator structure receiving energy from an external power supply, said first resonator structure having a first resonant frequency ω_1, and a first Q-factor Q_1, and characteristic size L_1, and a second resonator structure being positioned distal from said first resonator structure, at closest distance D, said second resonator structure having a second resonant frequency ω_2, and a second Q-factor Q_2, and characteristic size L_2.

[0011] The two said frequencies ω_1 and ω_2 are close to within the narrower of the two resonance widths Γ_1, and Γ_2. The non-radiative energy transfer between said first resonator structure and said second resonator structure is mediated through coupling of

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their resonant-field evanescent tails, and the rate of energy transfer between said first resonator and said second resonator is denoted by κ. The non-radiative means D is smaller than each of the resonant wavelengths λ_1 and λ_2, where c is the propagation speed of radiation in the surrounding medium.

[0012] Embodiments of the device may include any of the following features. In some embodiments, said resonators have $Q_1>100$ and $Q_2>100$, $Q_1>200$ and $Q_2>200$, $Q_1>500$ and $Q_2>500$, or even $Q_1>1000$ and $Q_2>1000$. In some such embodiments, $\kappa/\mathrm{sqrt}(\Gamma_1*\Gamma_2)$ may be greater than 0.2, greater than 0.5, greater than 1, greater than 2, or even grater than 5. In some such embodiments D/L_2 may be greater than 1, greater than 2, greater than 3, or even greater than 5.

[0013] In some embodiments, the resonant field in the device is electromagnetic.

[0014] In some embodiments, the first resonator structure includes a dielectric sphere, where the characteristic size L1 is the radius of the sphere.

[0015] In some embodiments, the first resonator structure includes a metallic sphere, where the characteristic size L1 is the radius of the sphere.

[0016] In some embodiments, the first resonator structure includes a metallodielectric sphere, where the characteristic size L1 is the radius of the sphere.

[0017] In some embodiments, the first resonator structure includes a plasmonic sphere, where the characteristic size L1 is the radius of the sphere.

[0018] In some embodiments, the first resonator structure includes a polaritonic sphere, where the characteristic size L1 is the radius of the sphere.

[0019] In some embodiments, the first resonator structure includes a capacitively-loaded conducting-wire loop, where the characteristic size L1 is the radius of the loop.

[0020] In some embodiments, the second resonator structure includes a dielectric sphere, where the characteristic size L2 is the radius of the sphere.

[0021] In some embodiments, the second resonator structure includes a metallic sphere where the characteristic size L2 is the radius of the sphere.

[0022] In some embodiments, the second resonator structure includes a metallodielectric sphere where the characteristic size L2 is the radius of the sphere.

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[0023] In some embodiments, the second resonator structure includes a plasmonic sphere where the characteristic size L2 is the radius of the sphere.

[0024] In some embodiments, the second resonator structure includes a polaritonic sphere where the characteristic size L2 is the radius of the sphere.

[0025] In some embodiments, the second resonator structure includes a capacitively-loaded conducting-wire loop where the characteristic size L2 is the radius of the loop.

[0026] In some embodiments, the resonant field in the device is acoustic.

[0027] It is to be understood that embodiments of the above described methods and devices may include any of the above listed features, alone or in combination.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] FIG. 1 is a schematic diagram illustrating an exemplary embodiment of the invention;

[0029] FIG. 2A is a numerical FDTD result for a high-index disk cavity of radius r along with the electric field; FIG. 2B a numerical FDTD result for a medium-distance coupling between two resonant disk cavities: initially, all the energy is in one cavity (left panel); after some time both cavities are equally excited (right panel).

[0030] FIG. 3 is schematic diagram demonstrating two capacitively-loaded conducting-wire loops;

[0031] FIGs. 4A-4B are numerical FDTD results for reduction in radiation-Q of the resonant disk cavity due to scattering from extraneous objects;

[0032] FIG. 5 is a numerical FDTD result for medium-distance coupling between two resonant disk cavities in the presence of extraneous objects; and

[0033] FIGs. 6A-6B are graphs demonstrating efficiencies of converting the supplied power into useful work (ηw), radiation and ohmic loss at the device (ηd), and the source(ηs), and dissipation inside a human (ηh), as a function of the coupling-to-loss ratio $\kappa/\Gamma d$; in panel (a) Γw is chosen so as to minimize the energy stored in the device, while in panel (b) Γw is chosen so as to maximize the efficiency ηw for each $\kappa/\Gamma d$.

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DETAILED DESCRIPTION OF THE INVENTION

[0034] In contrast to the currently existing schemes, the invention provides the feasibility of using long-lived oscillatory resonant electromagnetic modes, with localized slowly evanescent field patterns, for wireless non-radiative energy transfer. The basis of this technique is that two same-frequency resonant objects tend to couple, while interacting weakly with other off-resonant environmental objects. The purpose of the invention is to quantify this mechanism using specific examples, namely quantitatively address the following questions: up to which distances can such a scheme be efficient and how sensitive is it to external perturbations. Detailed theoretical and numerical analysis show that a mid-range ($L_{TRANS} \approx few * L_{DEV}$) wireless energy-exchange can actually be achieved, while suffering only modest transfer and dissipation of energy into other off-resonant objects.

[0035] The omnidirectional but stationary (non-lossy) nature of the near field makes this mechanism suitable for mobile wireless receivers. It could therefore have a variety of possible applications including for example, placing a source connected to the wired electricity network on the ceiling of a factory room, while devices, such as robots, vehicles, computers, or similar, are roaming freely within the room. Other possible applications include electric-engine buses, RFIDs, and perhaps even nano-robots.

[0036] The range and rate of the inventive wireless energy-transfer scheme are the first subjects of examination, without considering yet energy drainage from the system for use into work. An appropriate analytical framework for modeling the exchange of energy between resonant objects is a weak-coupling approach called "coupled-mode theory". FIG. 1 is a schematic diagram illustrating a general description of the invention. The invention uses a source and device to perform energy transferring. Both the source 1 and device 2 are resonator structures, and are separated a distance D from each other. In this arrangement, the electromagnetic field of the system of source 1 and device 2 is approximated by $\mathbf{F}(\mathbf{r},t) \approx a_1(t)\mathbf{F}_1(\mathbf{r}) + a_2(t)\mathbf{F}_2(\mathbf{r})$, where $\mathbf{F}_{1,2}(\mathbf{r}) = [\mathbf{E}_{1,2}(\mathbf{r}) \; \mathbf{H}_{1,2}(\mathbf{r})]$ are the eigenmodes of source 1 and device 2 alone, and then the field amplitudes $a_1(t)$ and $a_2(t)$ can be shown to satisfy the "coupled-mode theory":

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$$\frac{da_1}{dt} = -i\left(\omega_1 - i\Gamma_1\right)a_1 + i\kappa_{11}a_1 + i\kappa_{12}a_2$$
$$\frac{da_2}{dt} = -i\left(\omega_2 - i\Gamma_2\right)a_2 + i\kappa_{22}a_2 + i\kappa_{21}a_1 \quad , \qquad (1)$$

where $\omega_{1,2}$ are the individual eigen-frequencies, $\Gamma_{1,2}$ are the resonance widths due to the objects' intrinsic (absorption, radiation etc.) losses, $\kappa_{12,21}$ are the coupling coefficients, and $\kappa_{11,22}$ model the shift in the *complex* frequency of each object due to the presence of the other.

[0037] The approach of Eq. 1 has been shown, on numerous occasions, to provide an excellent description of resonant phenomena for objects of similar complex eigen-frequencies (namely $|\omega_1-\omega_2| \ll |\kappa_{12,21}|$ and $\Gamma_1 \approx \Gamma_2$), whose resonances are reasonably well defined (namely $\Gamma_{1,2} \& \mathrm{Im}\{\kappa_{11,22}\} \ll |\kappa_{12,21}|$) and in the weak coupling limit (namely $|\kappa_{12,21}| \ll \omega_{1,2}$). Coincidentally, these requirements also enable optimal operation for energy transfer. Also, Eq. (1) show that the energy exchange can be nearly perfect at exact resonance ($\omega_1=\omega_2$ and $\Gamma_1=\Gamma_2$), and that the losses are minimal when the "coupling-time" is much shorter than all "loss-times". Therefore, the invention requires resonant modes of high $Q=\omega/(2\Gamma)$ for low intrinsic-loss rates $\Gamma_{1,2}$, and with evanescent tails significantly longer than the characteristic sizes L_1 and L_2 of the two objects for strong coupling rate $|\kappa_{12,21}|$ over large distances D, where D is the closest distance between the two objects. This is a regime of operation that has *not* been studied extensively, since one usually prefers short tails, to minimize interference with nearby devices.

[0038] Objects of nearly infinite extent, such as dielectric waveguides, can support guided modes whose evanescent tails are decaying exponentially in the direction away from the object, slowly if tuned close to cutoff, and can have nearly infinite Q. To implement the inventive energy-transfer scheme, such geometries might be suitable for certain applications, but usually finite objects, namely ones that are topologically surrounded everywhere by air, are more appropriate.

[0039] Unfortunately, objects of finite extent cannot support electromagnetic states that are exponentially decaying in *all* directions in air, since in free space: $\vec{k}^2 = \omega^2/c^2$. Because of this, one can show that they cannot support states of infinite Q. However, very long-lived (so-called "high-Q") states can be found, whose tails display

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the needed exponential-like decay away from the resonant object over long enough distances before they turn oscillatory (radiative). The limiting surface, where this change in the field behavior happens, is called the "radiation caustic", and, for the wireless energy-transfer scheme to be based on the near field rather than the far/radiation field, the distance between the coupled objects must be such that one lies within the radiation caustic of the other.

[0040] The invention is very general and *any* type of resonant structure satisfying the above requirements can be used for its implementation. As examples and for definiteness, one can choose to work with two well-known, but quite different electromagnetic resonant systems: dielectric disks and capacitively-loaded conducting-wire loops. Even without optimization, and despite their simplicity, both will be shown to exhibit fairly good performance. Their difference lies mostly in the frequency range of applicability due to practical considerations, for example, in the optical regime dielectrics prevail, since conductive materials are highly lossy.

[0041] Consider a 2D dielectric disk cavity of radius r and permittivity ε surrounded by air that supports high-Q whispering-gallery modes, as shown in FIG. 2A. Such a cavity is studied using both analytical modeling, such as separation of variables in cylindrical coordinates and application of boundary conditions, and detailed numerical finite-difference-time-domain (FDTD) simulations with a resolution of *30pts/r*. Note that the physics of the 3D case should not be significantly different, while the analytical complexity and numerical requirements would be immensely increased. The results of the two methods for the complex eigen-frequencies and the field patterns of the so-called "leaky" eigenmodes are in an excellent agreement with each other for a variety of geometries and parameters of interest.

[0042] The radial modal decay length, which determines the coupling strength $\kappa \equiv |\kappa_{21}| = |\kappa_{12}|$, is on the order of the wavelength, therefore, for near-field coupling to take place between cavities whose distance is much larger than their size, one needs subwavelength-sized resonant objects ($r \ll \lambda$). High-radiation-Q and long-tailed subwavelength resonances can be achieved, when the dielectric permittivity ε is as large as practically possible and the azimuthal field variations (of principal number m) are slow (namely m is small).

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[0043] One such TE-polarized dielectric-cavity mode, which has the favorable characteristics $Q_{rad}=1992$ and $\lambda/r=20$ using $\varepsilon=147.7$ and $m=2$, is shown in FIG. 2A, and will be the "test" cavity 18 for all subsequent calculations for this class of resonant objects. Another example of a suitable cavity has $Q_{rad}=9100$ and $\lambda/r=10$ using $\varepsilon=65.61$ and $m=3$. These values of ε might at first seem unrealistically large. However, not only are there in the microwave regime (appropriate for meter-range coupling applications) many materials that have both reasonably high enough dielectric constants and low losses, for example, Titania: $\varepsilon \approx 96$, $Im\{\varepsilon\}/\varepsilon \approx 10^{-3}$; Barium tetratitanate: $\varepsilon \approx 37$, $Im\{\varepsilon\}/\varepsilon \approx 10^{-4}$; Lithium tantalite: $\varepsilon \approx 40$, $Im\{\varepsilon\}/\varepsilon \approx 10^{-4}$; etc.), but also ε could instead signify the effective index of other known subwavelength ($\lambda/r \gg 1$) surface-wave systems, such as surface-plasmon modes on surfaces of metal-like (negative-ε) materials or metallodielectric photonic crystals.

[0044] With regards to material absorption, typical loss tangents in the microwave (e.g. those listed for the materials above) suggest that $Q_{abs} \sim \varepsilon/Im\{\varepsilon\} \sim 10000$. Combining the effects of radiation and absorption, the above analysis implies that for a properly designed resonant device-object d a value of $Q_d \sim 2000$ should be achievable. Note though, that the resonant source s will in practice often be immobile, and the restrictions on its allowed geometry and size will typically be much less stringent than the restrictions on the design of the device; therefore, it is reasonable to assume that the radiative losses can be designed to be negligible allowing for $Q_s \sim 10000$, limited only by absorption.

[0045] To calculate now the achievable rate of energy transfer, one can place two of the cavities 20, 22 at distance D between their centers, as shown in FIG. 2B. The normal modes of the combined system are then an even and an odd superposition of the initial modes and their frequencies are split by the coupling coefficient κ, which we want to calculate. Analytically, coupled-mode theory gives for dielectric objects $\kappa_{12}=\omega_2/2\cdot\int d^3\mathbf{r}\mathbf{E}_1^*(\mathbf{r})\mathbf{E}_2(\mathbf{r})\varepsilon_1(\mathbf{r})\Big/\int d^3\mathbf{r}\left|\mathbf{E}_1(\mathbf{r})\right|^2\varepsilon(\mathbf{r})$, where $\varepsilon_{1,2}(\mathbf{r})$ denote the dielectric functions of only object 1 alone or 2 alone excluding the background dielectric (free space) and $\varepsilon(\mathbf{r})$ the dielectric function of the entire space with both objects present. Numerically, one can find κ using FDTD simulations either by exciting one of the

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cavities and calculating the energy-transfer time to the other or by determining the split normal-mode frequencies. For the "test" disk cavity the radius r_C of the radiation caustic is $r_C \approx 11r$, and for non-radiative coupling $D < r_C$, therefore here one can choose $D/r=10, 7, 5, 3$. Then, for the mode of FIG. 3, which is odd with respect to the line that connects the two cavities, the analytical predictions are $\omega/2\kappa=1602, 771, 298, 48$, while the numerical predictions are $\omega/2\kappa=1717, 770, 298, 47$ respectively, so the two methods agree well. The radiation fields of the two initial cavity modes interfere constructively or destructively depending on their relative phases and amplitudes, leading to increased or decreased net radiation loss respectively, therefore for any cavity distance the even and odd normal modes have Qs that are one larger and one smaller than the initial single-cavity $Q=1992$ (a phenomenon not captured by coupled-mode theory), but in a way that the average Γ is always approximately $\Gamma \approx \omega/2Q$. Therefore, the corresponding coupling-to-loss ratios are $\kappa/\Gamma=1.16, 2.59, 6.68, 42.49$, and although they do not fall in the ideal operating regime $\kappa/\Gamma \gg 1$, the achieved values are still large enough to be useful for applications.

[0046] Consider a loop 10 or 12 of N coils of radius r of conducting wire with circular cross-section of radius a surrounded by air, as shown in FIG. 3. This wire has inductance $L = \mu_o N^2 r\left[\ln\left(8r/a\right)-2\right]$, where μ_o is the magnetic permeability of free space, so connecting it to a capacitance C will make the loop resonant at frequency $\omega = 1/\sqrt{LC}$. The nature of the resonance lies in the periodic exchange of energy from the electric field inside the capacitor due to the voltage across it to the magnetic field in free space due to the current in the wire. Losses in this resonant system consist of ohmic loss inside the wire and radiative loss into free space.

[0047] For non-radiative coupling one should use the near-field region, whose extent is set roughly by the wavelength λ, therefore the preferable operating regime is that where the loop is small ($r \ll \lambda$). In this limit, the resistances associated with the two loss channels are respectively $R_{ohm} = \sqrt{\mu_o \rho \omega/2} \cdot Nr/a$ and $R_{rad} = \pi/6 \cdot \eta_o N^2 \left(\omega r/c\right)^4$, where ρ is the resistivity of the wire material and $\eta_o \approx 120\pi\ \Omega$ is the impedance of free space. The quality factor of such a resonance is then $Q = \omega L/\left(R_{ohm}+R_{rad}\right)$ and is

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highest for some frequency determined by the system parameters: at lower frequencies it is dominated by ohmic loss and at higher frequencies by radiation.

[0048] To get a rough estimate in the microwave, one can use one coil ($N=1$) of copper ($\rho=1.69\cdot10^{-8}\Omega m$) wire and then for $r=1cm$ and $a=1mm$, appropriate for example for a cell phone, the quality factor peaks to $Q=1225$ at $f=380MHz$, for $r=30cm$ and $a=2mm$ for a laptop or a household robot $Q=1103$ at $f=17MHz$, while for $r=1m$ and $a=4mm$ (that could be a source loop on a room ceiling) $Q=1315$ at $f=5MHz$. So in general, expected quality factors are $Q\approx1000\text{-}1500$ at $\lambda/r\approx50\text{-}80$, namely suitable for near-field coupling.

[0049] The rate for energy transfer between two loops 10 and 12 at distance D between their centers, as shown in FIG. 3, is given by $\kappa_{12}=\omega M/2\sqrt{L_1L_2}$, where M is the mutual inductance of the two loops 10 and 12. In the limit $r\ll D\ll\lambda$ one can use the quasi-static result $M=\pi/4\cdot\mu_o N_1N_2\left(r_1r_2\right)^2/D^3$, which means that $\omega/2\kappa\sim\left(D/\sqrt{r_1r_2}\right)^3$. For example, by choosing again $D/r=10,\ 8,\ 6$ one can get for two loops of $r=1cm$, same as used before, that $\omega/2\kappa=3033,\ 1553,\ 655$ respectively, for the $r=30cm$ that $\omega/2\kappa=7131,\ 3651,\ 1540$, and for the $r=1m$ that $\omega/2\kappa=6481,\ 3318,\ 1400$. The corresponding coupling-to-loss ratios peak at the frequency where peaks the single-loop Q and are $\kappa/\Gamma=0.4,\ 0.79,\ 1.97$ and $0.15,\ 0.3,\ 0.72$ and $0.2,\ 0.4,\ 0.94$ for the three loop-kinds and distances. An example of dissimilar loops is that of a $r=1m$ (source on the ceiling) loop and a $r=30cm$ (household robot on the floor) loop at a distance $D=3m$ (room height) apart, for which $\kappa/\sqrt{\Gamma_1\Gamma_2}=0.88$ peaks at $f=6.4MHz$, in between the peaks of the individual Q's. Again, these values are not in the optimal regime $\kappa/\Gamma\gg1$, but will be shown to be sufficient.

[0050] It is important to appreciate the difference between this inductive scheme and the already used close-range inductive schemes for energy transfer in that those schemes are *non-resonant*. Using coupled-mode theory it is easy to show that, keeping the geometry and the energy stored at the source fixed, the presently proposed resonant-coupling inductive mechanism allows for Q approximately 1000 times more power delivered for work at the device than the traditional non-resonant mechanism, and this is why mid-range energy transfer is now possible. Capacitively-loaded conductive loops are actually being widely used as resonant antennas (for example in cell phones),

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but those operate in the far-field regime with $r/\lambda \sim 1$, and the radiation Q's are intentionally designed to be small to make the antenna efficient, so they are not appropriate for energy transfer.

[0051] Clearly, the success of the inventive resonance-based wireless energy-transfer scheme depends strongly on the robustness of the objects' resonances. Therefore, their sensitivity to the near presence of random non-resonant extraneous objects is another aspect of the proposed scheme that requires analysis. The interaction of an extraneous object with a resonant object can be obtained by a modification of the coupled-mode-theory model in Eq. (1), since the extraneous object either does not have a well-defined resonance or is far-off-resonance, the energy exchange between the resonant and extraneous objects is minimal, so the term κ_{12} in Eq. (1) can be dropped. The appropriate analytical model for the field amplitude in the resonant object $a_1(t)$ becomes:

$$\frac{da_1}{dt} = -i\left(\omega_1 - i\Gamma_1\right)a_1 + i\kappa_{11}a_1 \qquad (2)$$

[0052] Namely, the effect of the extraneous object is just a perturbation on the resonance of the resonant object and it is twofold: First, it shifts its resonant frequency through the real part of κ_{11} thus detuning it from other resonant objects. This is a problem that can be fixed rather easily by applying a feedback mechanism to every device that corrects its frequency, such as through small changes in geometry, and matches it to that of the source. Second, it forces the resonant object to lose modal energy due to scattering into radiation from the extraneous object through the induced polarization or currents in it, and due to material absorption in the extraneous object through the imaginary part of κ_{11}. This reduction in Q can be a detrimental effect to the functionality of the energy-transfer scheme, because it cannot be remedied, so its magnitude must be quantified.

[0053] In the first example of resonant objects that have been considered, the class of dielectric disks, small, low-index, low-material-loss or far-away stray objects will induce small scattering and absorption. To examine realistic cases that are more dangerous for reduction in Q, one can therefore place the "test" dielectric disk cavity 40 close to: a) another off-resonance object 42, such as a human being, of large $Re\{\varepsilon\}=49$ and $Im\{\varepsilon\}=16$ and of same size but different shape, as shown in FIG. 4A; and b) a

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roughened surface 46, such as a wall, of large extent but of small $Re\{\varepsilon\}=2.5$ and $Im\{\varepsilon\}=0.05$, as shown in FIG. 4B.

[0054] Analytically, for objects that interact with a small perturbation the reduced value of radiation-Q due to scattering could be estimated using the polarization $\int d^3\boldsymbol{r}\left|\boldsymbol{P}_{X1}(\boldsymbol{r})\right|^2 \propto \int d^3\boldsymbol{r}\left|\boldsymbol{E}_1(\boldsymbol{r})\cdot \mathrm{Re}\{\varepsilon_X(\boldsymbol{r})\}\right|^2$ induced by the resonant cavity 1 inside the extraneous object X=42 or roughened surface X=46. Since in the examined cases either the refractive index or the size of the extraneous objects is large, these first-order perturbation-theory results would not be accurate enough, thus one can only rely on numerical FDTD simulations. The absorption-Q inside these objects can be estimated through $\mathrm{Im}\{\kappa_{11}\}=\omega_1/2\cdot\int d^3\boldsymbol{r}\left|\boldsymbol{E}_1(\boldsymbol{r})\right|^2 \mathrm{Im}\{\varepsilon_X(\boldsymbol{r})\}\Big/\int d^3\boldsymbol{r}\left|\boldsymbol{E}_1(\boldsymbol{r})\right|^2 \varepsilon(\boldsymbol{r})$.

[0055] Using these methods, for distances $D/r=10, 7, 5, 3$ between the cavity and extraneous-object centers one can find that $Q_{rad}=1992$ is respectively reduced to $Q_{rad}=1988, 1258, 702, 226$, and that the absorption rate inside the object is $Q_{abs}=312530, 86980, 21864, 1662$, namely the resonance of the cavity is not detrimentally disturbed from high-index and/or high-loss extraneous objects, unless the (possibly mobile) object comes *very* close to the cavity. For distances $D/r=10, 7, 5, 3, 0$ of the cavity to the roughened surface we find respectively $Q_{rad}=2101, 2257, 1760, 1110, 572$, and $Q_{abs}>4000$, namely the influence on the initial resonant mode is acceptably low, even in the extreme case when the cavity is embedded on the surface. Note that a close proximity of metallic objects could also significantly scatter the resonant field, but one can assume for simplicity that such objects are not present.

[0056] Imagine now a combined system where a resonant source-object s is used to wirelessly transfer energy to a resonant device-object d but there is an off-resonance extraneous-object e present. One can see that the strength of all extrinsic loss mechanisms from e is determined by $|\mathbf{E}_s(\mathbf{r}_e)|^2$, by the square of the *small* amplitude of the tails of the resonant source, evaluated at the position $\mathbf{r}_e$ of the extraneous object. In contrast, the coefficient of resonant coupling of energy from the source to the device is determined by the *same-order* tail amplitude $|\mathbf{E}_s(\mathbf{r}_d)|$, evaluated at the position $\mathbf{r}_d$ of the device, but this time it is not squared! Therefore, for equal distances of the source to the device and to the extraneous object, the coupling time for energy exchange with the

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device is much shorter than the time needed for the losses inside the extraneous object to accumulate, especially if the amplitude of the resonant field has an exponential-like decay away from the source. One could actually optimize the performance by designing the system so that the desired coupling is achieved with smaller tails at the source and longer at the device, so that interference to the source from the other objects is minimal.

[0057] The above concepts can be verified in the case of dielectric disk cavities by a simulation that combines FIGs. 2A-2B and 4A-4B, namely that of two (source-device) "test" cavities 50 placed *10r* apart, in the presence of a same-size extraneous object 52 of $\varepsilon=49$ between them, and at a distance *5r* from a large roughened surface 56 of $\varepsilon=2.5$, as shown in FIG. 5. Then, the original values of $Q=1992$, $\omega/2\kappa=1717$ (and thus $\kappa/\Gamma=1.16$) deteriorate to $Q=765$, $\omega/2\kappa=965$ (and thus $\kappa/\Gamma=0.79$). This change is acceptably small, considering the extent of the considered external perturbation, and, since the system design has not been optimized, the final value of coupling-to-loss ratio is promising that this scheme can be useful for energy transfer.

[0058] In the second example of resonant objects being considered, the conducting-wire loops, the influence of extraneous objects on the resonances is nearly absent. The reason for this is that, in the quasi-static regime of operation ($r\ll\lambda$) that is being considered, the near field in the air region surrounding the loop is predominantly magnetic, since the electric field is localized inside the capacitor. Therefore, extraneous objects that could interact with this field and act as a perturbation to the resonance are those having significant magnetic properties (magnetic permeability $Re\{\mu\}>1$ or magnetic loss $Im\{\mu\}>0$). Since almost all common materials are non-magnetic, they respond to magnetic fields in the same way as free space, and thus will not disturb the resonance of a conducting-wire loop. The only perturbation that is expected to affect these resonances is a close proximity of large metallic structures.

[0059] An extremely important implication of the above fact relates to safety considerations for human beings. Humans are also non-magnetic and can sustain strong magnetic fields without undergoing any risk. This is clearly an advantage of this class of resonant systems for many real-world applications. On the other hand, dielectric systems of high (effective) index have the advantages that their efficiencies seem to be higher,

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judging from the larger achieved values of κ/Γ, and that they are also applicable to much smaller length-scales, as mentioned before.

[0060] Consider now again the combined system of resonant source s and device d in the presence of a human h and a wall, and now let us study the efficiency of this resonance-based energy-transfer scheme, when energy is being drained from the device for use into operational work. One can use the parameters found before: for dielectric disks, absorption-dominated loss at the source $Q_s \sim 10^4$, radiation-dominated loss at the device $Q_d \sim 10^3$ (which includes scattering from the human and the wall), absorption of the source- and device-energy at the human $Q_{s\text{-}h}$, $Q_{d\text{-}h} \sim 10^4\text{-}10^5$ depending on his/her not-very-close distance from the objects, and negligible absorption loss in the wall; for conducting-wire loops, $Q_s \sim Q_d \sim 10^3$, and perturbations from the human and the wall are negligible. With corresponding loss-rates $\Gamma=\omega/2Q$, distance-dependent coupling κ, and the rate at which working power is extracted Γ_w, the coupled-mode-theory equation for the device field-amplitude is

$$\frac{da_d}{dt} = -i\left(\omega - i\Gamma_d\right)a_d + i\kappa a_s - \Gamma_{d-h}a_d - \Gamma_w a_d \,. \tag{3}$$

[0061] Different temporal schemes can be used to extract power from the device and their efficiencies exhibit different dependence on the combined system parameters. Here, one can assume steady state, such that the field amplitude inside the source is maintained constant, namely $a_s(t)=A_s e^{-i\omega t}$, so then the field amplitude inside the device is $a_d(t)=A_d e^{-i\omega t}$ with $A_d=i\kappa/(\Gamma_d+\Gamma_{d\text{-}h}+\Gamma_w)A_s$. Therefore, the power lost at the source is $P_s=2\Gamma_s|A_s|^2$, at the device it is $P_d=2\Gamma_d|A_d|^2$, the power absorbed at the human is $P_h=2\Gamma_{s\text{-}h}|A_s|^2+2\Gamma_{d\text{-}h}|A_d|^2$, and the useful extracted power is $P_w=2\Gamma_w|A_d|^2$. From energy conservation, the total power entering the system is $P_{total}= P_s+P_d+P_h+P_w$. Denote the total loss-rates $\Gamma_s^{tot}=\Gamma_s+\Gamma_{s-h}$ and $\Gamma_d^{tot}=\Gamma_d+\Gamma_{d-h}$. Depending on the targeted application, the work-drainage rate should be chosen either $\Gamma_w=\Gamma_d^{tot}$ to minimize the required energy stored in the resonant objects or $\Gamma_w=\Gamma_d^{tot}\sqrt{1+\kappa^2/\Gamma_s^{tot}\Gamma_d^{tot}} > \Gamma_d^{tot}$ such that the ratio of useful-to-lost powers, namely the efficiency $\eta_w=P_w/P_{total}$, is maximized for some value of κ. The efficiencies η for the two different choices are shown in FIGs. 6A

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and 6B respectively, as a function of the κ/Γ_d figure-of-merit which in turn depends on the source-device distance.

[0062] FIGs. 6A-6B show that for the system of dielectric disks and the choice of optimized efficiency, the efficiency can be large, e.g., at least 40%. The dissipation of energy inside the human is small enough, less than 5%, for values $\kappa/\Gamma_d>1$ and $Q_h>10^5$, namely for medium-range source-device distances ($D_d/r<10$) and most human-source/device distances ($D_h/r>8$). For example, for $D_d/r=10$ and $D_h/r=8$, if $10W$ must be delivered to the load, then, from FIG. 6B, $\sim 0.4W$ will be dissipated inside the human, $\sim 4W$ will be absorbed inside the source, and $\sim 2.6W$ will be radiated to free space. For the system of conducting-wire loops, the achieved efficiency is smaller, ~20% for $\kappa/\Gamma_d\approx 1$, but the significant advantage is that there is no dissipation of energy inside the human, as explained earlier.

[0063] Even better performance should be achievable through optimization of the resonant object designs. Also, by exploiting the earlier mentioned interference effects between the radiation fields of the coupled objects, such as continuous-wave operation at the frequency of the normal mode that has the larger radiation-Q, one could further improve the overall system functionality. Thus the inventive wireless energy-transfer scheme is promising for many modern applications. Although all considerations have been for a static geometry, all the results can be applied directly for the dynamic geometries of mobile objects, since the energy-transfer time $\kappa^{-1}\sim 1\mu s$, which is much shorter than any timescale associated with motions of macroscopic objects.

[0064] The invention provides a resonance-based scheme for mid-range wireless non-radiative energy transfer. Analyses of very simple implementation geometries provide encouraging performance characteristics for the potential applicability of the proposed mechanism. For example, in the macroscopic world, this scheme could be used to deliver power to robots and/or computers in a factory room, or electric buses on a highway (source-cavity would in this case be a "pipe" running above the highway). In the microscopic world, where much smaller wavelengths would be used and smaller powers are needed, one could use it to implement optical inter-connects for CMOS electronics or else to transfer energy to autonomous nano-objects, without worrying much about the relative alignment between the sources and the devices; energy-

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transfer distance could be even longer compared to the objects' size, since $Im\{\varepsilon(\omega)\}$ of dielectric materials can be much lower at the required optical frequencies than it is at microwave frequencies.

[0065] As a venue of future scientific research, different material systems should be investigated for enhanced performance or different range of applicability. For example, it might be possible to significantly improve performance by exploring plasmonic systems. These systems can often have spatial variations of fields on their surface that are much shorter than the free-space wavelength, and it is precisely this feature that enables the required decoupling of the scales: the resonant object can be significantly smaller than the exponential-like tails of its field. Furthermore, one should also investigate using acoustic resonances for applications in which source and device are connected via a common condensed-matter object.

[0066] Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

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CLAIMS

What is claimed is:

1. A system, comprising:

a first resonator with a quality factor, Q1, greater than 100, coupled to an energy source, generating an oscillating near field region; and

a second resonator, with a quality factor, Q2, greater than 100, optionally coupled to an energy drain, and moving freely within the near field region of the first resonator,

wherein the first resonator and the second resonator are coupled to transfer electromagnetic energy from said first resonator to said second resonator as the second resonator moves freely within the near field region.

2. The system of claim 1, wherein near field of the near field region is a magnetic field.

3. The system of claim 1, wherein near field of the near field region is an electromagnetic field.

4. The system of claim 1, wherein near field of the near field region is acoustic.

5. A method, comprising:

providing a first resonator with a quality factor, Q1, greater than 100, coupled to an energy source, generating an oscillating near field region; and

providing a second resonator, with a quality factor, Q2, greater than 100, optionally coupled to an energy drain, and moving freely within the near field region of the first resonator,

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wherein the first resonator and the second resonator are coupled to transfer electromagnetic energy from said first resonator to said second resonator as the second resonator moves freely within the near field region.

6. The method of claim 5, wherein near field of the near field region is a magnetic field.

7. The method of claim 5, wherein near field of the near field region is an electromagnetic field.

8. The system of claim 5, wherein near field of the near field region is acoustic.

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ABSTRACT

[0067] Described herein are embodiments of a first resonator with a quality factor, Q1, greater than 100, coupled to an energy source, generating an oscillating near field region, and a second resonator, with a quality factor, Q2, greater than 100, optionally coupled to an energy drain, and moving freely within the near field region of the first resonator. The first resonator and the second resonator may be coupled to transfer electromagnetic energy from said first resonator to said second resonator as the second resonator moves freely within the near field region.

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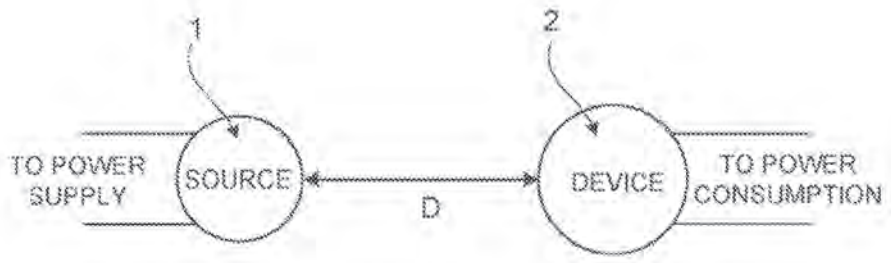


FIG. 1

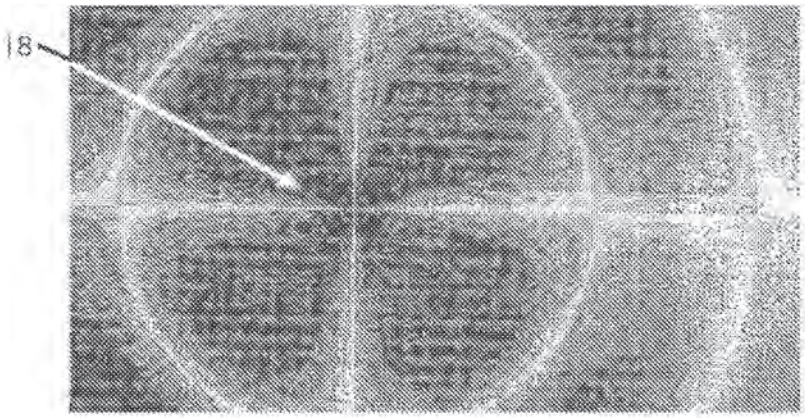


FIG. 2A

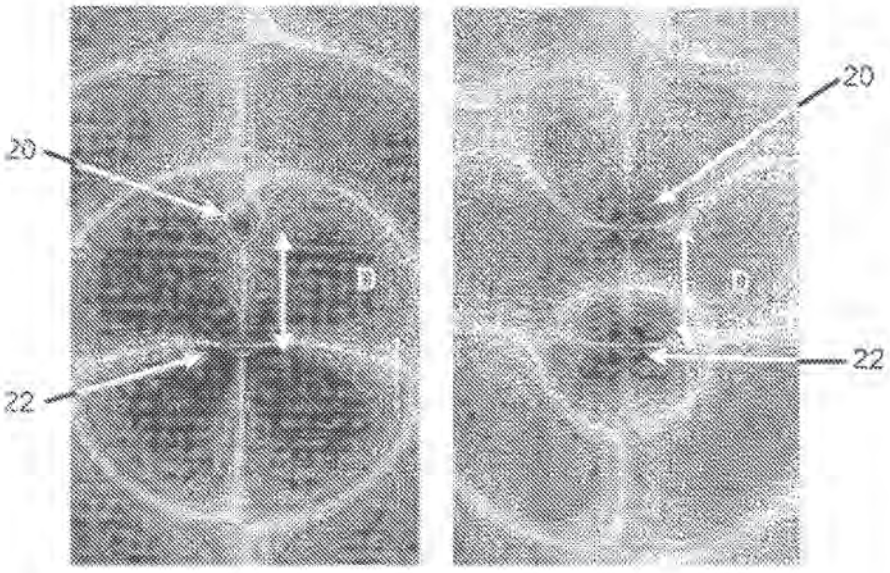


FIG. 2B

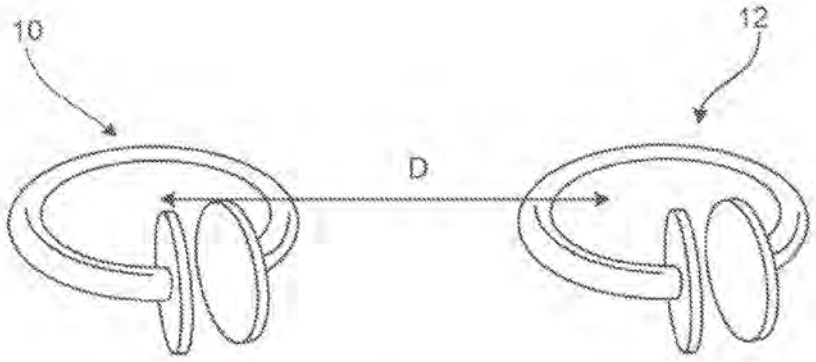


FIG. 3

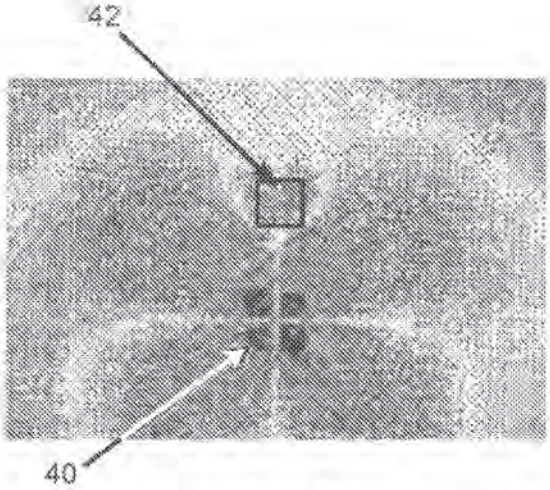


FIG. 4A

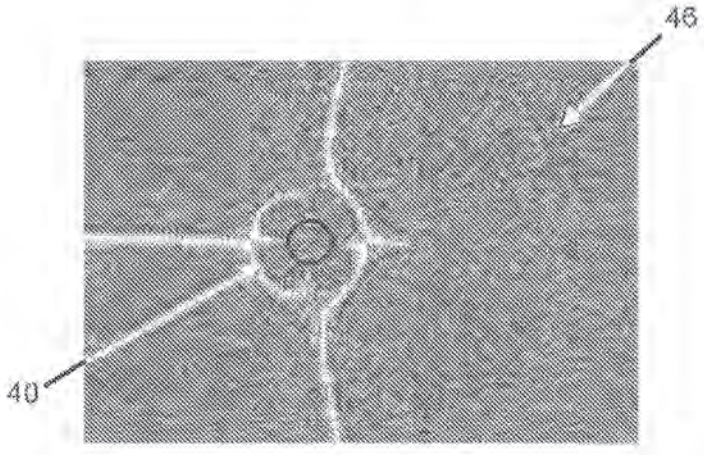


FIG. 4B

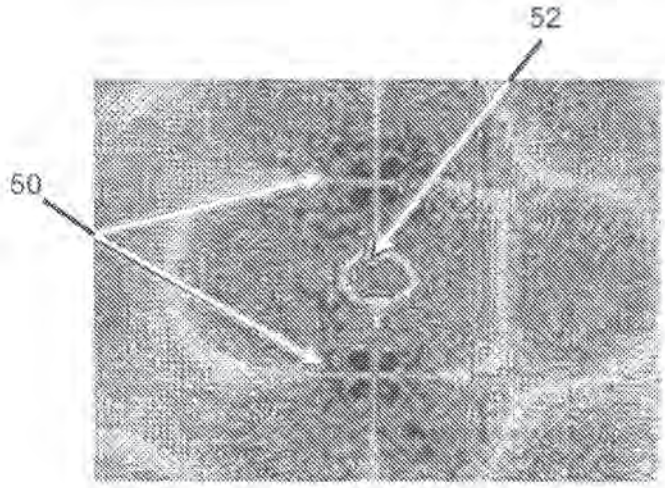


FIG. 5

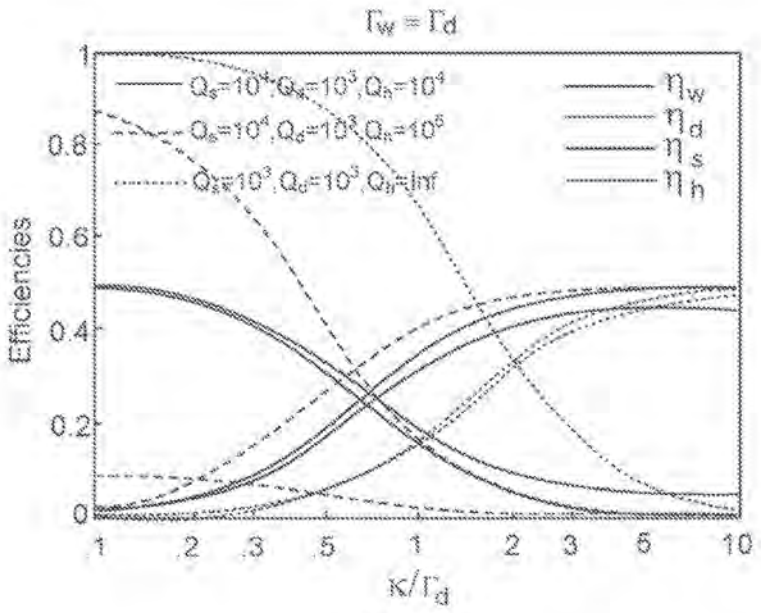

$\Gamma_w = \Gamma_d$
$Q_s=10^4, Q_d=10^3, Q_h=10^4$
$Q_s=10^4, Q_d=10^3, Q_h=10^6$
$Q_s=10^3, Q_d=10^3, Q_h=\inf$
η_w
η_d
η_s
η_h
Efficiencies
κ/Γ_d

FIG. 6A

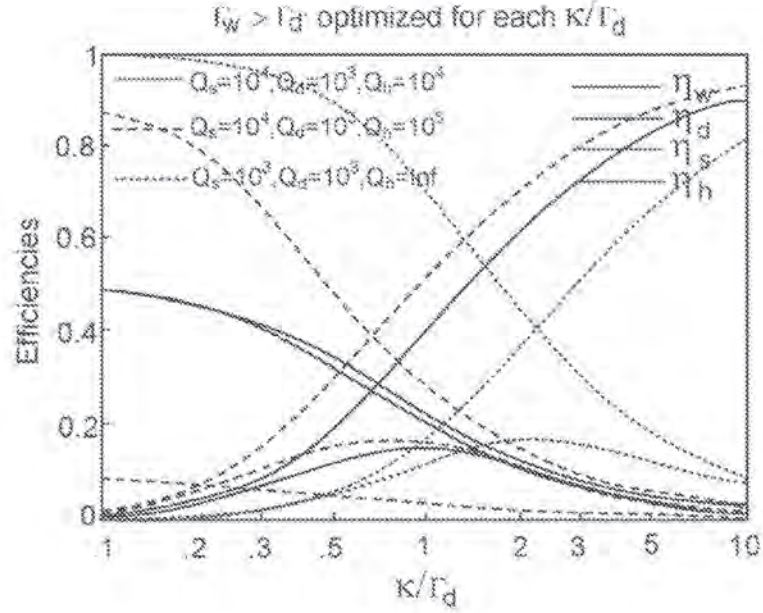

$\Gamma_w > \Gamma_d$ optimized for each κ/Γ_d
$Q_s=10^4, Q_d=10^3, Q_h=10^4$
$Q_s=10^4, Q_d=10^3, Q_h=10^6$
$Q_s=10^3, Q_d=10^3, Q_h=\inf$
η_w
η_d
η_s
η_h
Efficiencies
κ/Γ_d

FIG. 6B

OIPE IAP17
OCT 10 2006
PATENT & TRADEMARK OFFICE

MIT11757

DECLARATION AND POWER OF ATTORNEY

We, the below named inventors, hereby declare that:

Our residences, post office addresses, and citizenships are as stated below next to our respective names.

We believe we are the original, first, and joint inventors of the subject matter which is claimed and for which a patent is sought on the invention entitled WIRELESS NON-RADIATIVE ENERGY TRANSFER, the specification of which was filed with the United States Patent and Trademark Office on July 5, 2006, as Serial No. 11/481,077. This application claims priority under 35 U.S.C §119 (e) from United States provisional Patent Application Serial No. 60/698,442 filed on July 12, 2005.

We hereby state that we have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment specifically referred to above.

We acknowledge the duty to disclose information which is material to patentability in accordance with Title 37, Code of Federal Regulations, Section 1.56.

We hereby declare that all statements are made hereby of our own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

And we hereby appoint:

Maurice E. Gauthier	- Reg. No. 20,798
Matthew E. Connors	- Reg. No. 33,298
William E. Hilton	- Reg. No. 35,192
Arlene J. Powers	- Reg. No. 35,985
Peter S. Stecher	- Reg. No. 47,259

all of the firm of Gauthier & Connors, our attorneys with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith.

We request that all correspondence be directed to:

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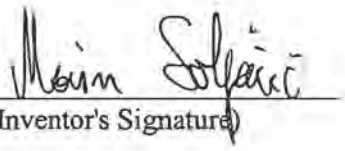
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PATENT APPLICATION FEE DETERMINATION RECORD

Substitute for Form PTO-875

Application or Docket Number: **12/649,635**

APPLICATION AS FILED – PART I

FOR	(Column 1) NUMBER FILED	(Column 2) NUMBER EXTRA	SMALL ENTITY RATE ($)	SMALL ENTITY FEE ($)	OR	OTHER THAN SMALL ENTITY RATE ($)	OTHER THAN SMALL ENTITY FEE ($)
BASIC FEE (37 CFR 1.16(a), (b), or (c))	N/A	N/A	N/A			N/A	330
SEARCH FEE (37 CFR 1.16(k), (i), or (m))	N/A	N/A	N/A			N/A	540
EXAMINATION FEE (37 CFR 1.16(o), (p), or (q))	N/A	N/A	N/A			N/A	220
TOTAL CLAIMS (37 CFR 1.16(i))	8	*	X 25=		OR	X 50=	
INDEPENDENT CLAIMS (37 CFR 1.16(h))	2	*	X 100=			X 200=	
APPLICATION SIZE FEE (37 CFR 1.16(s))	If the specification and drawings exceed 100 sheets of paper, the application size fee due is $250 ($125 for small entity) for each additional 50 sheets or fraction thereof. See 35 U.S.C. 41(a)(1)(G) and 37 CFR						
MULTIPLE DEPENDENT CLAIM PRESENT (37 CFR 1.16(j))			N/A			N/A	
			TOTAL			TOTAL	1,090

* If the difference in column 1 is less than zero, enter "0" in column 2.

APPLICATION AS AMENDED – PART II

		(Column 1) CLAIMS REMAINING AFTER AMENDMENT		(Column 2) HIGHEST NUMBER PREVIOUSLY PAID FOR	(Column 3) PRESENT EXTRA	SMALL ENTITY RATE ($)	SMALL ENTITY ADDITIONAL FEE ($)	OR	OTHER THAN SMALL ENTITY RATE ($)	OTHER THAN SMALL ENTITY ADDITIONAL FEE ($)
AMENDMENT A	Total (37 CFR 1.16(i))	*	Minus	**	=	X =		OR	X =	
	Independent (37 CFR 1.16(h))	*	Minus	***	=	X =		OR	X =	
	Application Size Fee (37 CFR 1.16(s))									
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))					N/A		OR	N/A	
						TOTAL ADD'T FEE		OR	TOTAL ADD'T FEE	

		(Column 1) CLAIMS REMAINING AFTER AMENDMENT		(Column 2) HIGHEST NUMBER PREVIOUSLY PAID FOR	(Column 3) PRESENT EXTRA	RATE ($)	ADDITIONAL FEE ($)	OR	RATE ($)	ADDITIONAL FEE ($)
AMENDMENT B	Total (37 CFR 1.16(i))	*	Minus	**	=	X =		OR	X =	
	Independent (37 CFR 1.16(h))	*	Minus	***	=	X =		OR	X =	
	Application Size Fee (37 CFR 1.16(s))									
	FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM (37 CFR 1.16(j))					N/A		OR	N/A	
						TOTAL ADD'T FEE		OR	TOTAL ADD'T FEE	

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.
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APPLICATION NUMBER	FILING or 371(c) DATE	GRP ART UNIT	FIL FEE RECD	ATTY.DOCKET.NO	TOT CLAIMS	IND CLAIMS
12/649,635	12/30/2009	2817	1090	MIT-0001-U01-C01-C10	8	2

CONFIRMATION NO. 5891

87084
GTC Law Group LLP & Affiliates
P.O. Box 113237
Pittsburgh, PA 15241

FILING RECEIPT

OC000000039716225

Date Mailed: 01/19/2010

Receipt is acknowledged of this non-provisional patent application. The application will be taken up for examination in due course. Applicant will be notified as to the results of the examination. Any correspondence concerning the application must include the following identification information: the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please submit a written request for a Filing Receipt Correction. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections**

Applicant(s)

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Marin Soljacic, Belmont, MA;

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Arlene Powers--35985
Peter Stecher--47259

Domestic Priority data as claimed by applicant

This application is a CON of 12/553,957 09/03/2009
which is a CON of 11/481,077 07/05/2006
which claims benefit of 60/698,442 07/12/2005

Foreign Applications

If Required, Foreign Filing License Granted: 01/14/2010

The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 12/649,635**

Projected Publication Date: 04/29/2010

Non-Publication Request: No

Early Publication Request: No

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Title

WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS

Preliminary Class

333

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For information on preventing theft of your intellectual property (patents, trademarks and copyrights), you may wish to consult the U.S. Government website, http://www.stopfakes.gov. Part of a Department of Commerce initiative, this website includes self-help "toolkits" giving innovators guidance on how to protect intellectual property in specific countries such as China, Korea and Mexico. For questions regarding patent enforcement issues, applicants may call the U.S. Government hotline at 1-866-999-HALT (1-866-999-4158).

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REVOCATION AND NEW POWER OF ATTORNEY

Under 37 CFR §3.73(b), MASSACHUSETTS INSTITUTE OF TECHNOLOGY, a university located at 77 Massachusetts Avenue, Cambridge, MA 02142-1324, certifies that it is the assignee of 100% of the right, title and interest in the patent applications listed in Appendix 1. The chain of title from the inventor(s) to Massachusetts Institute of Technology for each U.S. patent application listed in Appendix 1 is also set forth in that Appendix 1, referencing documents recorded in the United States Patent and Trademark Office or documents attached hereto as Appendices.

The undersigned has reviewed all the documents in the chain of title of the patent applications identified in Appendix 1, and, to the best of undersigned's knowledge and belief, title is in the assignee identified above.

The undersigned, whose title is supplied below, is empowered to act on behalf of the assignee.

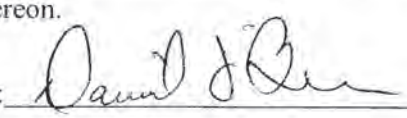
The undersigned, acting on behalf of the assignee, hereby revokes all powers of attorney previously granted in the application and appoints the attorney(s) and or agent(s) associated with the Customer Number provided below to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith with full powers of substitution and revocation, said appointment to be to the exclusion of the inventor(s) and his/their attorney(s) and or agent(s) in accordance with the provisions of 37 CFR. §3.71, et seq. of the Patent Office Rules of Practice.

PTO Customer Number: 26161

Directs all correspondence be addressed to that Customer Number.

PTO Customer Number: 26161

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patents issued thereon.

Signature: 

Typed name: Daniel O'Brien

Title: Intellectual Property Manager

Date: April 9, 2010

Assignee: Massachusetts Institute of Technology

MZW/czc

Fish & Richardson P.C.
225 Franklin Street
Boston, MA 02110-2804
Telephone: (617) 542-5070
Facsimile: (617) 542-8906

APPENDIX 1
LISTING APPLICATIONS FOR REVOCATION AND NEW POWER OF ATTORNEY AND SHOWING CHAIN OF TITLE TO MASSACHUSETTS INSTITUTE OF TECHNOLOGY (2 PAGES)

F&R Reference	MIT Reference	First Named Inventor/Applicant	Filed Serial No.	Date Issued Patent No.
01997-0359006	11757	John D. Joannopoulos	12/16/2009 12/639,958	

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359007	11757	John D. Joannopoulos	12/16/2009 12/639,961	

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359008	11757	John D. Joannopoulos	12/16/2009 12/639,962	

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359009	11757	John D. Joannopoulos	12/16/2009 12/639,963	

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359010	11757	John D. Joannopoulos	12/16/2009 12/639,966	

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359011	11757	John D. Joannopoulos	12/16/2009 12/639,967	

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359012	11757	John D. Joannopoulos	12/16/2009 12/639,972	

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359013	11757	John D. Joannopoulos	12/23/2009 12/646,442	

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359014	11757	John D. Joannopoulos	12/23/2009 12/646,524

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359015	11757	John D. Joannopoulos	12/30/2009 12/649,635

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359016	11757	John D. Joannopoulos	12/30/2009 12/649,777

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359017	11757	John D. Joannopoulos	12/30/2009 12/649,813

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359018	11757	John D. Joannopoulos	12/30/2009 12/649,852

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359019	11757	John D. Joannopoulos	12/30/2009 12/649,904

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

01997-0359020	11757	John D. Joannopoulos	12/30/2009 12/649,973

Assignment from Inventors to Assignee, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Executed by: John D. Joannopoulos on October 3, 2006; Aristeidis Karalis on September 27, 2006; and Marin Soljacic on September 27, 2006 (See Appendix 2)

APPENDIX 2

MIT11757

ASSIGNMENT

Know all men by these presents that:

WHEREAS we, John D. Joannopoulos
64 Douglas Road
Belmont, MA 02478

and Aristeidis Karalis
70 Pacific St., Apt. #907
Cambridge, MA 02139

and Marin Soljacic
67 Fairfax Street
Somerville, MA 02144

have made an invention for

WIRELESS NON-RADIATIVE ENERGY TRANSFER

described in the application filed in the United States Patent Office on July 5, 2006 as Serial No. 11/481,077. This application claims priority under 35 USC §119(e) from United States Provisional Patent Application Serial No. 60/698,442, filed July 12, 2005; and

WHEREAS Massachusetts Institute of Technology, a corporation duly organized and existing under the laws of Massachusetts and having a place of business at 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, for the benefit of itself, its successors and assigns, all inclusively hereinafter referred to as the Assignee, is desirous of acquiring the entire right, title and interest in and to the said invention, the said application, all inventions disclosed in said application and any and all Letters Patent of the United States and of all other countries which may be granted for the said invention or inventions, or any of them;

NOW, THEREFORE, for good and valuable consideration provided by said Assignee, the receipt whereof is hereby acknowledged, we do hereby sell, assign and transfer to the said Assignee the entire right, title and interest in and to the said invention, inventions and application, including all priority rights arising therefrom, all inventions disclosed in said application, and any and all Letters Patent of the United States, and of all other countries, together with the right to apply for such Letters Patent, which may be granted for the said invention, inventions or any of them,

TO HAVE, HOLD AND ENJOY the said invention, the said application, and the said Letters Patent, to said

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

InductEV, Inc.
Exhibit 1024
Page 050

its successors and assigns, to its and their own use and behoof to the full end of the term or terms for which the said Letters Patent may be granted, as fully and entirely as the same would have been held and enjoyed by us had this assignment and sale not been made.

AND we hereby authorize and request the Commissioner of Patents of the United States and the appropriate officers of all foreign patent offices to issue any and all Letters Patent which may be granted on the said application or applications above referred to, or for the said invention, or any of them, to the said Assignee in accordance with the terms of this instrument.

AND we hereby agree to execute and sign without further consideration any other legal document and any other assignments and any divisional, continuing, renewal, reissue or other application in and for all patents that may be appropriate and may be deemed necessary by the Assignee fully to secure to said Assignee its interests as aforesaid in and to the said invention or any part thereof and in and to the said patents or any of them.

AND we further covenant and agree that we will at any time upon request communicate to the said Assignee, its successors, assigns or other legal representatives, any facts known to us relating to the said invention and any patent that may be granted thereon, and will testify as to the same in any interference or litigation when requested to do so.

AND we hereby covenant for ourselves and our legal representatives that we have not hitherto assigned or granted any license to make, use or sell said invention, and that we will not henceforth purport to assign, license or execute any instrument to that effect in conflict with this assignment.

IN WITNESS WHEREOF, we have hereunto set our hands and seals on the dates below.

3 Oct 06	
Date	**JOHN D. JOANNOPOULOS**
Sep 27, 2006	
Date	**ARISTEIDIS KARALIS**
27th SEP 06	Marin Soljacic
Date	**MARIN SOLJACIC**

InductEV, Inc.
Exhibit 1024
Page 051

Electronic Acknowledgement Receipt

EFS ID:	7401264
Application Number:	12649635
International Application Number:	
Confirmation Number:	5891
Title of Invention:	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS
First Named Inventor/Applicant Name:	John D. Joannopoulos
Customer Number:	87084
Filer:	Marc M. Wefers/Cheryl Forrest
Filer Authorized By:	Marc M. Wefers
Attorney Docket Number:	MIT-0001-U01-C01-C10
Receipt Date:	13-APR-2010
Filing Date:	30-DEC-2009
Time Stamp:	09:54:31
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Power of Attorney	RevandNewPOA.pdf	242181	no	6

Warnings:	
Information:	

Total Files Size (in bytes):	242181

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111

If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371

If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office

If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
12/649,635	12/30/2009	John D. Joannopoulos	MIT-0001-U01-C01-C10

CONFIRMATION NO. 5891

POWER OF ATTORNEY NOTICE

87084
GTC Law Group LLP & Affiliates
P.O. Box 113237
Pittsburgh, PA 15241

OC000000041183151

Date Mailed: 04/22/2010

NOTICE REGARDING CHANGE OF POWER OF ATTORNEY

This is in response to the Power of Attorney filed 04/13/2010.

- The Power of Attorney to you in this application has been revoked by the assignee who has intervened as provided by 37 CFR 3.71. Future correspondence will be mailed to the new address of record(37 CFR 1.33).

/hgray/

Office of Data Management, Application Assistance Unit (571) 272-4000, or (571) 272-4200, or 1-888-786-0101

UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NUMBER	FILING OR 371(C) DATE	FIRST NAMED APPLICANT	ATTY. DOCKET NO./TITLE
12/649,635	12/30/2009	John D. Joannopoulos	MIT-0001-U01-C01-C10

CONFIRMATION NO. 5891

POA ACCEPTANCE LETTER

26161
FISH & RICHARDSON PC
P.O. BOX 1022
MINNEAPOLIS, MN 55440-1022

OC000000041183170

Date Mailed: 04/22/2010

NOTICE OF ACCEPTANCE OF POWER OF ATTORNEY

This is in response to the Power of Attorney filed 04/13/2010.

The Power of Attorney in this application is accepted. Correspondence in this application will be mailed to the above address as provided by 37 CFR 1.33.

/hgray/

Office of Data Management, Application Assistance Unit (571) 272-4000, or (571) 272-4200, or 1-888-786-0101

Substitute Form PTO-1449 (Modified) U.S. Department of Commerce Patent and Trademark Office	Attorney Docket No. 01997-0359015	Application No. 12/649,635
Information Disclosure Statement by Applicant (Use several sheets if necessary) (37 CFR §1.98(b))	Applicant John D. Joannopoulos et al.	
	Filing Date December 30, 2009	Group Art Unit

U.S. Patent Documents

Examiner Initial	Desig. ID	Document Number	Publication Date	Patentee	Class	Subclass	Filing Date If Appropriate
	1	787,412	4/18/1905	Tesla			
	2	1,119,732	12/1/1914	Tesla			
	3	2,133,494	10/18/1938	H.F. Waters			
	4	3,517,350	6/23/1970	Beaver			
	5	3,535,543	10/20/1970	Dailey			
	6	4,088,999	5/9/1978	Fletcher et al.			
	7	5,027,709	7/2/1991	Slagle			
	8	5,070,293	12/3/1991	Ishii et al.			
	9	5,216,402	6/1/1993	Carosa			
	10	5,341,083	8/23/1994	Klontz et al.			
	11	5,367,242	11/22/1994	Hulman			
	12	5,437,057	7/25/1995	Richley et al.			
	13	5,493,691	2/20/1996	Barrett			
	14	5,528,113	6/18/1996	Boys et al.			
	15	5,550,452	8/27/1996	Shirai et al.			
	16	5,898,579	4/27/1999	Boys et al.			
	17	5,999,308	12/7/1999	Nelson et al.			
	18	6,184,651	2/6/2001	Fernandez et al.			
	19	6,436,299	8/20/2002	Baarman et al.			
	20	6,450,946	9/17/2002	Forsell			
	21	6,452,465	9/17/2002	Brown et al.			
	22	6,515,878	2/4/2003	Meins et al.			
	23	6,597,076	7/22/2003	Scheible et al.			
	24	6,673,250	1/6/2004	Kuennen et al.			
	25	6,731,071	5/4/2004	Baarman			
	26	6,749,119	6/15/2004	Scheible et al.			
	27	6,798,716	9/28/2004	Charych			

Examiner Signature	Date Considered
EXAMINER: Initials citation considered. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.	

Substitute Disclosure Form (PTO-1449)

Substitute Form PTO-1449 (Modified) U.S. Department of Commerce Patent and Trademark Office	Attorney Docket No. 01997-0359015	Application No. 12/649,635
Information Disclosure Statement by Applicant (Use several sheets if necessary) (37 CFR §1.98(b))	Applicant John D. Joannopoulos et al.	
	Filing Date December 30, 2009	Group Art Unit

U.S. Patent Documents

Examiner Initial	Desig. ID	Document Number	Publication Date	Patentee	Class	Subclass	Filing Date If Appropriate
	28	6,806,649	10/19/2004	Mollema et al.			
	29	6,812,645	11/2/2004	Baarman			
	30	6,825,620	11/30/2004	Kuennen et al.			
	31	6,831,417	12/14/2004	Baarman			
	32	6,856,291	2/15/2005	Mickle et al.			
	33	6,844,702	1/18/2005	Giannopoulos et al.			
	34	6,906,495	6/14/2005	Cheng et al.			
	35	6,917,431	7/12/2005	Soljacic et al.			
	36	6,917,163	7/12/2005	Baarman			
	37	6,937,130	8/30/2005	Scheible et al.			
	38	6,960,968	11/1/2005	Odendaal et al.			
	39	6,975,198	12/13/2005	Baarman			
	40	7,042,196	5/9/2006	Ka-Lai et al.			
	41	7,069,064	6/27/2006	Govorgian et al.			
	42	7,116,200	10/3/2006	Baarman et al.			
	43	7,118,240	10/10/2006	Baarman et al.			
	44	7,126,450	10/24/2006	Baarman et al.			
	45	7,132,918	11/7/2006	Baarman et al.			
	46	7,180,248	2/20/2007	Kuennen et al.			
	47	7,212,414	5/1/2007	Baarman			
	48	7,239,110	7/3/2007	Cheng et al.			
	49	7,248,017	7/24/2007	Cheng et al.			
	50	7,375,492	5/20/2008	Calhoon et al.			
	51	7,375,493	5/20/2008	Calhoon et al.			
	52	7,378,817	5/27/2008	Calhoon et al.			
	53	7,382,636	6/3/2008	Baarman et al.			
	54	7,385,357	6/10/2008	Kuennen et al.			

Examiner Signature	Date Considered
EXAMINER: Initials citation considered. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.	

Substitute Disclosure Form (PTO-1449)

Substitute Form PTO-1449 (Modified) U.S. Department of Commerce Patent and Trademark Office	Attorney Docket No. 01997-0359015	Application No. 12/649,635
Information Disclosure Statement by Applicant (Use several sheets if necessary) (37 CFR §1.98(b))	Applicant John D. Joannopoulos et al.	
	Filing Date December 30, 2009	Group Art Unit

U.S. Patent Documents

Examiner Initial	Desig. ID	Document Number	Publication Date	Patentee	Class	Subclass	Filing Date If Appropriate
	55	7,462,951	12/9/2008	Baarman			
	56	7,466,213	12/16/2008	Lobl et al.			
	57	7,474,058	1/6/2009	Baarman			
	58	7,492,247	2/17/2009	Schmidt et al.			
	59	7,518,267	4/14/2009	Baarman			
	60	7,525,283	4/28/2009	Cheng et al.			
	61	7,615,936	11/10/2009	Baarman et al.			
	62	2002/0032471	3/14/2002	Loftin et al.			
	63	2002/0105343	8/8/2002	Scheible et al.			
	64	2002/0118004	8/29/2002	Scheible et al.			
	65	2003/0038641	2/27/2003	Scheible			
	66	2003/0062794	4/3/2003	Scheible et al.			
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	69	2003/0214255	11/20/2003	Baarman et al.			
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	79	2005/0007067	1/13/2005	Baarman et al.			
	80	2005/0085873	4/21/2005	Gord et al.			
	81	2005/0093475	5/5/2005	Kuennen et al.			

Examiner Signature	Date Considered
EXAMINER: Initials citation considered. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.	

Substitute Disclosure Form (PTO-1449)

Substitute Form PTO-1449 (Modified) U.S. Department of Commerce Patent and Trademark Office	Attorney Docket No. 01997-0359015	Application No. 12/649,635
Information Disclosure Statement by Applicant (Use several sheets if necessary) (37 CFR §1.98(b))	Applicant John D. Joannopoulos et al.	
	Filing Date December 30, 2009	Group Art Unit

U.S. Patent Documents

Examiner Initial	Desig. ID	Document Number	Publication Date	Patentee	Class	Subclass	Filing Date If Appropriate
	82	2005/0104064	5/19/2005	Hegarty et al.			
	83	2005/0116650	6/2/2005	Baarman			
	84	2005/0122058	6/9/2005	Baarman et al.			
	85	2005/0122059	6/9/2005	Baarman et al.			
	86	2005/0127849	6/16/2005	Baarman et al.			
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	88	2005/0127866	6/16/2005	Hamilton et al.			
	89	2005/0156560	7/21/2005	Shimaoka et al.			
	90	2006/0022636	2/2/2006	Xian et al.			
	91	2006/0061323	3/23/2006	Cheng et al.			
	92	2006/0132045	6/22/2006	Baarman			
	93	2006/0181242	8/17/2006	Freed et al.			
	94	2006/0185809	8/24/2006	Elfrink et al.			
	95	2006/0205381	9/14/2006	Beart et al.			
	96	2006/0270440	11/30/2006	Shearer et al.			
	97	2007/0064406	3/22/2007	Beart			
	98	2007/0171681	7/26/2007	Baarman			
	99	2007/0178945	8/2/2007	Cook et al.			
	100	2007/0222542	9/27/2007	Joannopoulos et al.			
	101	2007/0267918	11/22/2007	Gyland			
	102	2007/0276538	11/29/2007	Kjellsson et al.			
	103	2008/0014897	1/7/2008	Cook et al.			
	104	2008/0191638	8/14/2008	Kuennen et al.			
	105	2008/0197710	8/21/2008	Kreitz et al.			
	106	2008/0211320	9/4/2008	Cook et al.			
	107	2008/0278264	11/13/2008	Karalis et al.			
	108	2009/0010028	1/8/2009	Baarmen et al.			

Examiner Signature	Date Considered
EXAMINER: Initials citation considered. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.	

Substitute Disclosure Form (PTO-1449)

Substitute Form PTO-1449 (Modified)	U.S. Department of Commerce Patent and Trademark Office	Attorney Docket No. 01997-0359015	Application No. 12/649,635
Information Disclosure Statement by Applicant (Use several sheets if necessary) (37 CFR §1.98(b))		Applicant John D. Joannopoulos et al.	
		Filing Date December 30, 2009	Group Art Unit

U.S. Patent Documents

Examiner Initial	Desig. ID	Document Number	Publication Date	Patentee	Class	Subclass	Filing Date If Appropriate
	109	2009/0015075	1/15/2009	Cook et al.			
	110	2009/0033564	2/5/2009	Cook et al.			
	111	2009/0045772	2/19/2009	Cook et al.			
	112	2009/0051224	2/26/2009	Cook et al.			
	113	2009/0058189	3/5/2009	Cook et al.			
	114	2009/0072627	3/19/2009	Cook et al.			
	115	2009/0072628	3/19/2009	Cook et al.			
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Substitute Form PTO-1449 (Modified) U.S. Department of Commerce Patent and Trademark Office	Attorney Docket No. 01997-0359015	Application No. 12/649,635
Information Disclosure Statement by Applicant (Use several sheets if necessary) (37 CFR §1.98(b))	Applicant John D. Joannopoulos et al.	
	Filing Date December 30, 2009	Group Art Unit

U.S. Patent Documents

Examiner Initial	Desig. ID	Document Number	Publication Date	Patentee	Class	Subclass	Filing Date If Appropriate
	136						

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	156	WO 2004/073166	8/26/2004	WIPO				
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Substitute Disclosure Form (PTO-1449)

Electronic Acknowledgement Receipt

EFS ID:	7474024
Application Number:	12649635
International Application Number:	
Confirmation Number:	5891
Title of Invention:	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS
First Named Inventor/Applicant Name:	John D. Joannopoulos
Customer Number:	26161
Filer:	Marc M. Wefers/Cheryl Forrest
Filer Authorized By:	Marc M. Wefers
Attorney Docket Number:	01997-0359015
Receipt Date:	23-APR-2010
Filing Date:	30-DEC-2009
Time Stamp:	11:20:11
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1		359015IDS.pdf	1058732 26f8cdc0516f6c30fc37c10990727d7d11a9	yes	15

	Multipart Description/PDF files in .zip description		
	Document Description	**Start**	**End**
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	Information Disclosure Statement (IDS) Filed (SB/08)	4	15
Warnings:			
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New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant	: John D. Joannopoulos et al.	Art Unit	: Unknown
Serial No.	: 12/649,635	Examiner	: Unknown
Filed	: December 30, 2009	Conf. No.	: 5891
Title	: WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS		

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

INFORMATION DISCLOSURE STATEMENT

Please consider the references listed on the enclosed PTO-1449 form.

Under 35 USC §120, this application relies on the earlier filing date of application serial number 11/481,077, filed on July 5, 2006. All of the references listed on the enclosed PTO-1449 form were submitted to and/or cited by the Office in the prior application and, therefore, are not provided in this application.

The applicant invites the examiner to consider the position of the examiner and replies by the applicant that have been set forth in the prosecution of the following U.S. patent applications. These applications are related to the present application under Section 120 and/or contain at least some material that is similar to the material set forth in the specification of this application. The applicant assumes that the examiner has direct access to these files, but will be happy to provide copies to the examiner upon request.

Application No.	Filing Date	Status
11/481,077	July 5, 2006	Published
12/055,963	March 26, 2008	Published
12/415,650	March 31, 2009	Published
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Respectfully submitted,

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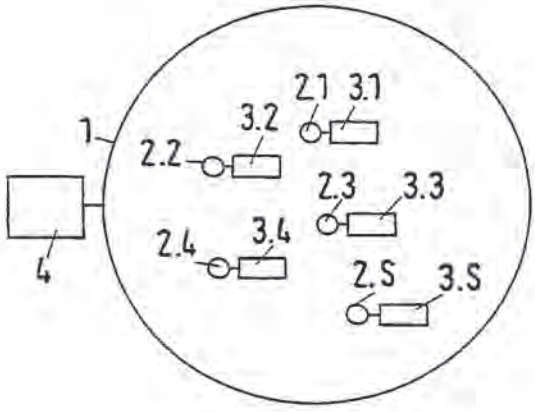
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[Fortsetzung auf der nächsten Seite]

(54) Title: METHOD AND ASSEMBLY FOR THE WIRELESS SUPPLY OF ELECTRIC ENERGY TO A NUMBER OF ACTUATORS, ACTUATOR AND PRIMARY WINDING THEREFOR AND SYSTEM FOR A MACHINE WITH A NUMBER OF ACTUATORS

(54) Bezeichnung: VERFAHREN UND ANORDNUNG ZUR DRAHTLOSEN VERSORGUNG EINER VIELZAHL AKTOREN MIT ELEKTRISCHER ENERGIE, AKTOR UND PRIMÄRWICKLUNG HIERZU SOWIE SYSTEM FÜR EINE EINE VIELZAHL VON AKTOREN AUFWEISENDE MASCHINE



(57) Abstract: The invention relates to a method for the wireless supply of electric energy to a number of actuators (3.1 to 3.s). In said method, a medium-frequency, magnetic field, emitted by at least one primary winding (1, 1.1 to 1.p) is transmitted to each respective actuator which has at least one secondary winding (2.1 to 2.s) and is then converted into electric energy. The invention also relates to an assembly for the wireless supply of electric energy to a number of actuators (3.1 to 3.s), using at least one primary winding (1, 1.1 to 1.p), fed by a medium-frequency oscillator (4), whereby each actuator (3.1 to 3.s) has at least one secondary winding (2.1 to 2.s) which is suitable for absorbing energy from a medium-frequency magnetic field. The invention further relates to an actuator and a primary winding for said assembly and a system for a machine which has a number of actuators.

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— *Mit internationalem Recherchenbericht.*

— *Vor Ablauf der für Änderungen der Ansprüche geltenden Frist; Veröffentlichung wird wiederholt, falls Änderungen eintreffen.*

Zur Erklärung der Zweibuchstaben-Codes, und der anderen Abkürzungen wird auf die Erklärungen ("Guidance Notes on Codes and Abbreviations") am Anfang jeder regulären Ausgabe der PCT-Gazette verwiesen.

(57) Zusammenfassung: Es wird ein Verfahren zur drahtlosen Versorgung einer Vielzahl Aktoren (3.1 bis 3.s) mit elektrischer Energie vorgeschlagen, wobei ein von mindestens einer Primärwicklung (1, 1.1 bis 1.p) abgestrahltes, mittelfrequentes magnetisches Feld zu jedem mindestens eine Sekundärwicklung (2.1 bis 2.s) aufweisenden Aktor übertragen und dort in elektrische Energie umgewandelt wird. Des weiteren wird eine Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren (3.1 bis 3.s) mit elektrischer Energie unter Einsatz mindestens einer von einem mittelfrequenten Oszillator (4) gespeisten Primärwicklung (1, 1.1 bis 1.p) vorgeschlagen, wobei jeder Aktor (3.1 bis 3.s) mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung (2.1 bis 2.s) aufweist. Ausserdem werden ein Aktor und eine Primärwicklung hierzu sowie ein System für eine eine Vielzahl von Aktoren aufweisende Maschine vorgeschlagen.

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Verfahren und Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie, Aktor und Primärwicklung hierzu sowie System für eine eine Vielzahl von Aktoren aufweisende Maschine

Beschreibung

Die Erfindung bezieht sich auf ein Verfahren und eine Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie, auf einen Aktor und eine Primärwicklung hierzu sowie auf ein System für eine eine Vielzahl von Aktoren aufweisende Maschine. Die Erfindung kann beispielsweise zur elektrischen Energieversorgung von mikromechanischen, piezoelektrischen, elektrochemischen, magnetostriktiven, elektrostriktiven, elektrostatischen oder elektromagnetischen Aktoren verwendet werden, wie sie in Aktoren-Systemen oder Maschinen, beispielsweise bei Steuer/Regelsystemen, in Fernsteuersystemen, in der Robotertechnik, bei Herstellungsautomaten bzw. Fertigungsautomaten, als Anzeigeelemente und in Schutz- und Sicherheitssystemen (beispielsweise bei Freiluft- oder Innenraum-Schaltanlagen) zum Einsatz gelangen.

Aus der DE 44 42 677 A1 sind ein Verfahren und eine Anordnung zum Versorgen eines elektrischen Verbrauchers mit einer elektrischen Versorgungsspannung oder einem elektrischen Versorgungsstrom bekannt, wobei Funkwellen eines Funksenders zu einem mit dem Verbraucher elektrisch verbundenen Funkempfänger übertragen werden und vom Funkempfänger in die elektrische Versorgungsspannung bzw. den elektrischen Versorgungsstrom umgewandelt werden. Die Funkwellen können aus dem elektromagnetischen Hochfrequenzbereich (Radiowellen) oder auch aus dem Mikrowellenbereich (Richtfunk) kommen.

Dabei ist es von Nachteil, daß aufgrund der hohen Frequenzen und dementsprechend kleinen Antennen einerseits und der durch EMV-Vorschriften und Regeln für Sicherheit und Gesundheitsschutz an Arbeitsplätzen mit Exposition durch elektrische,

magnetische oder elektromagnetische Felder beschränkten zulässigen Sendeleistung andererseits nur sehr unzureichend geringe Abstände zwischen Funksender und Funkempfänger erzielbar sind. Das gleiche trifft für die erzielbaren Leistungen zu, welche im Bereich weniger µW liegen, was meist unzureichend für Aktoren ist.

Der Erfindung liegt die Aufgabe zugrunde, ein kostengünstiges und zuverlässiges Verfahren zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie anzugeben.

Des weiteren ist eine kostengünstige und zuverlässige Anordnung zur Durchführung dieses Verfahrens anzugeben.

Ferner soll ein hierzu geeigneter Aktor vorgeschlagen werden.

Des weiteren soll eine hierzu geeignete Primärwicklung vorgeschlagen werden.

Außerdem soll ein System für eine eine Vielzahl von Aktoren aufweisende Maschine angegeben werden.

Diese Aufgabe wird bezüglich des Verfahrens erfindungsgemäß durch ein Verfahren zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie gelöst, wobei ein von mindestens einer Primärwicklung abgestrahltes, mittelfrequentes magnetisches Feld zu jedem mindestens eine Sekundärwicklung aufweisenden Aktor übertragen und dort in elektrische Energie umgewandelt wird.

Unter den in diesem Zusammenhang interessierenden mittelfrequenten Schwingungen wird der Bereich von etwa 15 kHz bis etwa 15 MHz verstanden.

Diese Aufgabe wird bezüglich der Vorrichtung erfindungsgemäß durch eine Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren mit elektrischer Energie unter Einsatz mindestens einer von einem mittelfrequenten Oszillator gespeisten Primärwicklung gelöst, wobei jeder Aktor mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung aufweist.

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Die Aufgabe wird bezüglich des Aktors durch einen Aktor mit mehreren zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeigneten, orthogonalen Sekundärwicklungen gelöst.

Die Aufgabe wird bezüglich der Primärwicklung durch eine Primärwicklung, bestehend aus mehreren separaten Wicklungsabschnitten gelöst, welche jeweils aus mehreren parallelen Leitern aufgebaut sind, wobei die einzelnen Wicklungsabschnitte über Verbindungselemente mechanisch und elektrisch miteinander verbunden sind und wobei bei einem Verbindungselement zwei Wicklungsabschnitte versetzt gegeneinander elektrisch miteinander verbunden sind, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

Die Aufgabe wird alternativ bezüglich der Primärwicklung durch eine Primärwicklung, bestehend aus einem flexiblen, aus mehreren parallelen Leitern aufgebauten Kabel und einem Verbindungselement gelöst, welches die beiden Kabelenden versetzt gegeneinander elektrisch und mechanisch miteinander verbindet, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

Die Aufgabe wird bezüglich des Systems durch ein System für eine eine Vielzahl von Aktoren aufweisende Maschine, insbesondere Fertigungsautomat, gelöst, wobei jeder Aktor mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung aufweist, wobei mindestens eine von einem mittelfrequenten Oszillator gespeiste Primärwicklung zur drahtlosen Versorgung der Aktoren mit elektrischer Energie vorgesehen ist und wobei jeder Aktor mit einer Empfangseinrichtung ausgestattet ist, welche Funksignale einer mit einem Prozeßrechner der Maschine verbundenen zentralen Sendeeinrichtung empfängt.

Die mit der Erfindung erzielbaren Vorteile bestehen insbesondere darin, daß im Vergleich zu konventionellen Lösungen mit Kabelanschluß zur elektrischen Energieversorgung der Aktoren der durch Planung, Material, Installation, Dokumentation und Wartung bedingte relativ hohe Kostenfaktor eines Kabelanschlusses entfällt. Es kön-

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nen keine Ausfälle aufgrund von Kabelbrüchen oder schlechten, beispielsweise korrodierten Kontakten auftreten.

Im Vergleich zur Verwendung von Batterien zur Energieversorgung von Aktoren entfällt der Wartungsaufwand und Kostenaufwand, der durch den erforderlichen Austausch von Batterien – zumal an schwer zugänglichen Stellen – bedingt ist.

Im angegebenen Mittelfrequenz-Bereich von etwa 15 kHz bis etwa 15 MHz sind die sich durch Skineffekte ergebenden Nachteile, beispielsweise die auftretenden Verluste, noch handhabbar. Die elektromagnetischen Wellen werden aufgrund der im Vergleich zu den auftretenden Wellenlängen zu kleinen und deshalb als Antennen unwirksamen Primärwicklungen nicht abgestrahlt, wodurch ein einfacher Aufbau der Anordnungen ermöglicht wird. Eine EMV-Messung von eventuell abgestrahlten Störungen muß nicht erfolgen. Günstig wirkt sich zudem aus, daß mittelfrequente Magnetfelder durch metallische Maschinen-Komponenten nur in geringem Ausmaß abgeschirmt werden, so daß vorteilhaft auch an unzugänglichen Stellen eines Aktoren-Systems bzw. einer Maschine ein zur Energieversorgung ausreichend starkes Magnetfeld auftritt.

Weitere Vorteile sind aus der nachstehenden Beschreibung ersichtlich.

Vorteilhafte Ausgestaltungen der Erfindung sind in den Unteransprüchen gekennzeichnet.

Die Erfindung wird nachstehend anhand der in der Zeichnung dargestellten Ausführungsbeispiele erläutert. Es zeigen:

Fig.1 ein Prinzipschaltbild der Anordnung zur drahtlosen elektrischen Versorgung von Aktoren,

Fig. 2 ein Schaltbild zur Erläuterung des verwendeten Transformatorprinzips,

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Fig.3 eine erste praktische Ausführungsform,

Fig.4 eine zweite praktische Ausführungsform,

Fig.5 eine dritte Ausführungsform mit orthogonalen Primärwicklungen,

Fig.6 eine vierte Ausführungsform mit unterschiedlich gestalteten Primärwicklungen,

Fig.7 eine fünfte Ausführungsform mit bandförmiger Primärwicklung,

Fig.8 ein Ersatzschaltbild mit primärseitigen und sekundärseitigen Weiterbildungen,

Fig.9 eine Primärwicklung gemäß sechster Ausführungsform,

Fig. 10 eine Detailansicht einer Ecke einer Primärwicklung gemäß sechster Ausführungsform,

Fig. 11 eine Detailansicht der Wicklungseinspeisung bei der sechsten Ausführungsform,

Fig. 12 eine Primärwicklung gemäß siebter Ausführungsform,

Fig. 13 eine Detailansicht der Wicklungseinspeisung bei der siebten Ausführungsform,

Fig. 14 eine Detailansicht einer Ecke einer Primärwicklung gemäß siebter Ausführungsform,

Fig. 15 eine Primärwicklung gemäß achter Ausführungsform.

In Fig. 1 ist ein Prinzipschaltbild der Anordnung zur drahtlosen elektrischen Versorgung von Aktoren dargestellt. Es ist eine kreisförmige, vorzugsweise aus mehreren

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Windungen aufgebaute Primärwicklung 1 zu erkennen, welche eine Vielzahl – gegebenenfalls bis zu einigen Hundert - von Sekundärwicklungen 2.1, 2.2, 2.3....2.s (s = beliebige ganze Zahl) umfaßt, wobei jede Sekundärwicklung 2.1 bzw. 2.2 bzw. 2.3....2.s mit einem Aktor 3.1 bzw. 3.2 bzw. 3.3....3.s verbunden ist. Die Primärwicklung 1 ist an einen Oszillator 4 (Mittelfrequenz-Oszillator) angeschlossen. Der Oszillator 4 speist die Primärwicklung 1 mit einer mittelfrequenten Schwingung im Bereich von etwa 15 kHz bis etwa 15 MHz. Diese Mittelfrequenz würde zur Abstrahlung von elektromagnetischen Feldern führen, deren Wellenlängen größer als 22 m bis 22 km sind und damit wesentlich größer als die Abmessungen der eingesetzten Primärwicklung – kleiner als 2 m - , so daß die Primärwicklung nicht als Antenne für derartige elektromagnetische Strahlung wirkt. Es liegt also eine rein magnetische Kopplung (und keine wirksame elektromagnetische Kopplung) zwischen der Primärwicklung und den Sekundärwicklungen im Sinne eines Mittelfrequenz-Transformators vor.

Als Aktoren werden beispielsweise mikromechanische, piezoelektrische, elektrochemische, magnetostriktive, elektrostriktive, elektrostatische oder elektromagnetische Aktoren eingesetzt.

In Fig. 2 ist ein Schaltbild zur Erläuterung des verwendeten Transformatorprinzips dargestellt. Es sind wiederum die Primärwicklung 1 mit einspeisendem Oszillator 4 und die Aktoren 3.1....3.s mit den angeschlossenen Sekundärwicklungen 2.1....2.s zu erkennen.

In Fig. 3 ist eine erste praktische Ausführungsform dargestellt. Es ist ein Aktoren-System 5 – insbesondere eine Maschine bzw. ein Industrieroboter bzw. Herstellungsautomat bzw. Fertigungsautomat - gezeigt, welches mit zahlreichen an unterschiedliche, zumindest teilweise bewegliche Systemkomponenten montierten Aktoren 3.1....3.s versehen ist. Die Aktoren 3.1...3.s dienen beispielsweise als Anzeigeelemente, als Steuer/Regelelemente und als Schutz/Sicherheitselemente. Das Aktoren-System 5 befindet sich zwischen zwei horizontal angeordneten Primärwicklungen 1.1 und 1.2. Diese beiden Primärwicklungen 1.1, 1.2 liegen elektrisch parallel am Oszillator 4 (Generator) oder werden alternativ von zwei separaten Oszillatoren gespeist. Zwischen beiden Primärwicklungen tritt ein relativ gleichmäßiges Magnetfeld auf. Von Wichtigkeit ist es dabei, daß sich die Aktoren stets im sich zwischen beiden

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Primärwicklungen 1.1, 1.2 ausbildenden magnetischen Feld befinden, so daß über ihre Sekundärwicklungen eine magnetische Ankopplung wirksam und demzufolge eine Energieeinspeisung möglich ist.

Jeder Aktor ist mit einer Empfangseinrichtung und Sendeeinrichtung ausgestattet, die Funksignale hinsichtlich der Befehle an die Aktoren zur Ausführung bestimmter Handlungen empfängt und Funksignale hinsichtlich aktueller Aktor-Informationen, wie die Rückmeldungen "gewünschte Handlung erfolgreich/nicht erfolgreich ausgeführt" abgibt. Die Funksignale zu allen Aktoren bzw. von allen Aktoren werden von einer zentralen Sende/Empfangseinrichtung 9 abgegeben bzw. empfangen und von einem Prozeßrechner 10 (speicherprogrammierbare Steuerung) vorgegeben bzw. an diesen weitergeleitet. Vorzugsweise befindet sich die Sende/Empfangseinrichtung in unmittelbarer Nähe des Aktoren-Systems 5, um eine optimale Funkverbindung mit den Aktoren zu gewährleisten, während der die Maschine steuernde Prozeßrechner 10 auch entfernt vom Aktoren-System 5 angeordnet sein kann. Wie leicht erkennbar ist, ergibt sich durch das vorgeschlagene System eine kabellose Konfiguration der Aktoren sowohl hinsichtlich ihrer elektrischen Energieversorgung als auch hinsichtlich der Informationsübertragung vom und zum Prozeßrechner 10.

In Fig. 4 ist eine zweite praktische Ausführungsform dargestellt. Bei dieser Ausführungsform ist lediglich eine einzige Primärwicklung 1 vorgesehen, welche das Aktoren-System 5 – insbesondere ein Industrieroboter bzw. Herstellungsautomat bzw. Fertigungsautomat - mit den zahlreichen, an ihm montierten Aktoren 3.1....3.s global umfaßt.

In Fig. 5 ist eine dritte Ausführungsform mit drei orthogonal zueinander angeordneten Primärwicklungen dargestellt. Es ist ein Aktoren-System 5 gezeigt, welches von einer ersten vertikalen Primärwicklung 1.1, einer hierzu orthogonalen zweiten vertikalen Primärwicklung 1.2 und einer horizontalen dritten Primärwicklung 1.2 umschlossen ist. Bei dieser Ausführungsform mit drei orthogonalen Primärwicklungen ergibt sich eine besonders gleichmäßige und nicht gerichtete Ausbildung des magnetischen Feldes. Alternativ bzw. ergänzend hierzu ist es auch möglich, jeden Aktor mit zwei oder drei orthogonalen Sekundärwicklungen auszurüsten.

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Des weiteren ist auch eine Ausführungsform realisierbar, bei der lediglich zwei orthogonale Primärwicklungen vorgesehen sind. Selbstverständlich sind auch Ausführungsformen realisierbar, welche mehrere Primärwicklungen 1.1 bis 1.p aufweisen, die nicht orthogonal angeordnet sind.

In Fig. 6 ist eine vierte Ausführungsform mit mehreren unterschiedlich gestalteten Primärwicklungen dargestellt. Es handelt sich um ein relativ ausgedehntes Aktoren-System 5, bei dem die einzelnen Aktoren 3.1....3.s nicht einigermaßen homogen über das System verteilt angeordnet sind, sondern lediglich an einigen bestimmten Bereichen des Systems gehäuft auftreten. Bei einer derartigen ausgedehnten Konfiguration ist aus Gründen der zu erzielenden magnetischen Feldstärke der Einsatz mehrerer, gezielt angeordneter Primärwicklungen vorteilhaft, welche jeweils mindestens eine Sekundärwicklung eines Aktors lokal beeinflussen.

Ein erster mit Aktoren bestückter Systembereich liegt dabei im Magnetfeld zwischen zwei horizontalen, rechteckförmigen, sich einander gegenüberliegenden Primärwicklungen 1.1, 1.2. Ein zweiter, hierzu benachbarter, mit Aktoren bestückter Systembereich liegt im Magnetfeld zwischen zwei horizontalen, kreisringförmigen oder ovalen, sich einander gegenüberliegender Primärwicklungen 1.3, 1.4. Ein dritter mit Aktoren bestückter Systembereich wird vom Magnetfeld einer Primärwicklung 1.5 beeinflußt, wobei diese Primärwicklung um den Mittelschenkel eines E-förmigen Ferritkernes angeordnet ist, wodurch sich teilweise eine Abschirmung des Magnetfeldes und sich teilweise eine Verstärkung im interessierenden, lokal begrenzten Bereich ergibt ("Spot-Wirkung"). Ein vierter mit Aktoren bestückter Systembereich liegt im Einflußbereich einer Primärwicklung 1.6. Die Magnetfelder der einzelnen Primärwicklungen 1.1 bis 1.6 in den einzelnen Systembereichen sind jeweils gestrichelt angedeutet.

In Fig. 7 ist eine fünfte Ausführungsform mit bandförmiger Primärwicklung dargestellt. Die bandförmige Primärwicklung 1 ist an ihrem einen Ende am Oszillator 4 angeschlossen, während das weitere Ende zusammengeschaltet ist. Auf diese Weise ergibt sich eine Doppelleitung mit zwei vom gleichen Strom mit entgegengesetzter Richtung durchflossenen Leitern, was das Magnetfeld zwischen beiden Leitern in gewünschter Weise verstärkt und das Magnetfeld im Bereich außerhalb der beiden Leiter abschwächt. Vorteilhaft wird die bandförmige Primärwicklung 1 an der Maschi-

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ne derart installiert, daß sich die einzelnen Aktoren 3.1 bis 3.n im Bereich zwischen beiden Leitern der Doppelleitung befinden.

Selbstverständlich kann dabei jede Leitung der Doppelleitung aus mehreren Einzelleitern bestehen, wobei die Einzelleiter beider Leitungen im Sinne einer Wicklung miteinander verbunden sind, so daß sich quasi eine Primärwicklung 1 wie unter Fig. 4 beschrieben ergibt, welche extrem flach ausgebildet ist.

In Fig. 8 ist ein Ersatzschaltbild mit primärseitigen und sekundärseitigen Weiterbildungen dargestellt. Wie zu erkennen ist, liegt die Primärwicklung 1 über einem Kompensationskondensator 6 am Oszillator 4, wodurch ein resonanter Betrieb des Oszillators erzielt wird. Lediglich beispielhaft ist die magnetische Kopplung zwischen Primärwicklung 1 und Sekundärwicklung 2.1 angedeutet. An die Sekundärwicklung 2.1 ist ein AC/DC-Steller 7 angeschlossen, der einen zur Energieversorgung des Aktors 3.1 dienenden Energiespeicher 8 speist.

In Erweiterung des in Fig. 8 dargestellten Schaltbildes ist es auch möglich, einen Kompensationskondensator in der Anschlußleitung zwischen Sekundärwicklung 2.1 und AC/DC-Steller 7 vorzusehen.

Wicklungen werden üblicherweise durch Wickeln eines Leiters in mehreren Windungen gewünschter Anzahl hergestellt. Bei großflächig auszubildenden Wicklungen kann dies Schwierigkeiten bereiten, beispielsweise bei nachträglicher Integration einer relativ großen Primärwicklung in einem Herstellungs- bzw. Fertigungsautomaten oder allgemein in einer Maschine. Unter "relativ groß" ist zu verstehen, daß die Primärwicklung etwa die Größe des Herstellungsautomaten selbst aufweist.

Nachstehend werden Primärwicklungen gemäß sechster, siebter und achter Ausführungsform angegeben, die ohne Schwierigkeiten auch nachträglich in einer Anlage oder Maschine integriert werden können.

Dabei kann die Primärwicklung aus mehreren separaten, jeweils aus mehreren parallelen Leitern aufgebauten Wicklungsabschnitten bestehen, wobei die einzelnen Wicklungsabschnitte über Verbindungselemente mechanisch und elektrisch mitein-

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ander verbunden sind und wobei bei einem Verbindungselement zwei Wicklungsabschnitte versetzt gegeneinander elektrisch miteinander verbunden sind, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

Alternativ hierzu kann die Primärwicklung aus einem flexiblen, aus mehreren parallelen Leitern aufgebauten Kabel und einem Verbindungselement bestehen, welches die beiden Kabelenden versetzt gegeneinander elektrisch und mechanisch miteinander verbindet, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

Die mit der sechsten, siebten und achten Ausführungsform erzielbaren Vorteile bestehen insbesondere darin, daß die Primärwicklung auftrennbar ist und deshalb ein nachträglicher Einbau der vorgeschlagenen Primärwicklung in einer Maschine in einfacher Art möglich ist. Die Primärwicklung wird erst in der Maschine selbst durch Verbinden der einzelnen Wicklungsabschnitte bzw. des flexiblen Kabels unter Einsatz des mindestens einen Verbindungselementes hergestellt, wobei eine exakte Anpassung an die Maschine durch die Anzahl und Lage der Verbindungselemente und durch flexible Ausgestaltung der Wicklungsabschnitte, bestehend vorzugsweise aus flexiblem Flachbandkabel, ermöglicht wird. Der Einsatz von Flachbandkabel hat den weiteren Vorteil, daß das von der Primärwicklung produzierte Magnetfeld axial relativ breit ausgebildet ist, was die magnetische Ankopplung an weitere Wicklungen verbessert.

In Fig. 9 ist eine Primärwicklung gemäß sechster Ausführungsform dargestellt. Diese sechste Ausführungsform ist insbesondere für eine vertikale Anordnung der Primärwicklung geeignet. Die rechteckförmige Primärwicklung weist vier separate Wicklungsabschnitte 1a´, 1b´, 1c´, 1d´ auf, die an den vier Ecken über Verbindungselemente 2a´, 2b´, 2c´, 2d´ elektrisch und mechanisch miteinander verbunden sind. Für die Wicklungsabschnitte 1a´ bis 1d´ wird vorzugsweise flexibles mehradriges Flachbandkabel mit mehreren parallelen Leitern eingesetzt.

In Fig. 10 ist eine Detailansicht einer Ecke einer Primärwicklung gemäß sechster Ausführungsform dargestellt. Das gezeigte Verbindungselement 2a´ weist sieben

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winkelförmig ausgebildete, in einer Reihe nebeneinander angeordnete und gegenseitig elektrisch isolierte Kontaktstellen mit jeweils zwei Anschlüssen für die beiden Wicklungsabschnitte 1a´, 1b´ auf. Die Abwinkelung der nebeneinander angeordneten Kontaktstellen erfolgt in zwei Ebenen. Zur elektrischen Kontaktierung weisen diese Kontaktstellen beispielsweise Öffnungen mit Kontaktzungen auf, in welche die elektrischen Leiter der Wicklungsabschnitte eingesteckt werden.

In Fig. 11 ist eine Detailansicht der Wicklungseinspeisung bei der sechsten Ausführungsform dargestellt. Wie zu erkennen ist, sind die beiden Wicklungsabschnitte 1a´, 1d´ versetzt gegeneinander in das Verbindungselement 2d´ eingesteckt. Die jeweils freien Enden des Wicklungsabschnittes 1a´ bzw. des Wicklungsabschnittes 1d´ bilden die Wicklungsenden und sind mit einer Verbindungsleitung 3´ bzw. 4´ kontaktiert, welche andererseits mit einem Generator bzw. Oszillator verbunden sind. Die Kontaktierung zwischen der Verbindungsleitung 4´ und dem Wicklungsabschnitt 1d´ erfolgt über das Verbindungselement 2d´. Die weitere elektrische Verbindung zwischen der Verbindungsleitung 3´ und dem Wicklungsabschnitt 1a´ erfolgt beispielsweise durch Verlöten.

Alternativ kann auch an der Wicklungseinspeisung ein Verbindungselement eingesetzt sein, das eine Kontaktstelle mehr aufweist, als dies der Anzahl der parallelen Leiter eines Wicklungsabschnittes entspricht. Dann können beide Kontaktierungen zwischen den Verbindungsleitungen 3´, 4´ und den Wicklungsabschnitten über das Verbindungselement selbst erfolgen.

Die weiteren Verbindungselemente 2b´, 2c´der Primärwicklung sind in der gemäß Fig. 10 dargestellten Art und Weise mit den Wicklungsabschnitten verbunden. Insgesamt ergibt sich eine Primärwicklung mit sieben Windungen.

In Fig. 12 ist eine Primärwicklung gemäß siebter Ausführungsform dargestellt. Diese siebte Ausführungsform ist insbesondere für eine horizontale Anordnung der Primärwicklung geeignet. Die rechteckförmige Primärwicklung weist vier separate Wicklungsabschnitte 5a´, 5b´, 5c´, 5d´ auf, die an den vier Ecken über Verbindungselemente 6a´, 6b´, 6c´, 6d´ elektrisch und mechanisch miteinander verbunden sind. Für

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die Wicklungsabschnitte 5a´ bis 5d´ wird vorzugsweise mehradriges Flachbandkabel eingesetzt.

In Fig. 13 ist eine Detailansicht der Wicklungseinspeisung bei der siebten Ausführungsform dargestellt. Zur elektrischen Kontaktierung weisen die Verbindungselemente wiederum Öffnungen mit Kontaktzungen auf, in welche die elektrischen Leiter der Wicklungsabschnitte eingeführt werden. Wie zu erkennen ist, sind die beiden Wicklungsabschnitte 5a´, 5d´ versetzt gegeneinander in das Verbindungselement 6d´ eingesteckt. Die jeweils freien Enden des Wicklungsabschnittes 5a´ bzw. des Wicklungsabschnittes 5d´ bilden die Wicklungsenden und sind mit einer Verbindungsleitung 8´ bzw. 7´ kontaktiert, welche andererseits mit einem Generator bzw. Oszillator verbunden sind. Da ein Verbindungselement 6d´ eingesetzt ist, welches ein Kontaktpaar mehr aufweist als dies der Anzahl der parallelen Leiter der Wicklungsabschnitte entspricht, erfolgt die Kontaktierung zwischen der Verbindungsleitung 7´ und dem Wicklungsabschnitt 5d´ sowie die Kontaktierung zwischen der Verbindungsleitung 8´ und dem Wicklungsabschnitt 5a´ über das Verbindungselement 6d´.

In Fig. 14 ist eine Detailansicht einer Ecke einer Primärwicklung gemäß siebter Ausführungsform dargestellt. Das gezeigte Verbindungselement 6a´ weist fünf winkelförmig ausgebildete, in einer Reihe nebeneinander angeordnete und gegenseitig elektrisch isolierte Kontaktstellen für die beiden Wicklungsabschnitte 5a´, 5b´ auf, wobei die Abwinkelungen der nebeneinander angeordneten Kontaktstellen in einer Ebene erfolgen. Die elektrische und mechanische Verbindung der weiteren Wicklungsabschnitte über die Verbindungselemente 6b´ und 6c´ erfolgt in gleicher Art und Weise.

Vorstehend ist ausgeführt, daß für die Wicklungsabschnitte 1a´ bis 1d´ und 5a´ bis 5d´ vorzugsweise mehradriges, flexibles Flachbandkabel eingesetzt wird. Alternativ hierzu ist es insbesondere zur Bildung einer sehr leistungsstarken Primärwicklung mit relativ hohem Stromdurchgang möglich, die Wicklungsabschnitte aus mehreren nebeneinander anzuordnenden, elektrisch gegeneinander zu isolierenden, starren Leiterstäben aufzubauen.

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Vorstehend werden rechteckförmige Konfigurationen der Primärwicklung beschrieben, welche den Einsatz von Verbindungselementen mit rechtwinklig abgebogenen Kontaktstellen erfordern. Abweichend hiervon können selbstverständlich auch andere Wicklungs-Konfigurationen (dreieckig, fünfeckig usw.) realisiert werden.

Im einfachsten Fall ist eine aus einem flexiblen Kabel 9', insbesondere Flachbandkabel und einem einzigen Verbindungselement 10' bestehende Primärwicklung herstellbar, wobei die beiden Enden des Kabels über das einzige Verbindungselement 10' versetzt gegeneinander elektrisch miteinander verbunden sind, wodurch sich freie, zum Anschluß von Verbindungsleitungen 11', 12' zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben. Eine derartige Primärwicklung ist in Fig. 15 gezeigt.

Patentansprüche

1. Verfahren zur drahtlosen Versorgung einer Vielzahl Aktoren (3.1 bis 3.s) mit elektrischer Energie, wobei ein von mindestens einer Primärwicklung (1, 1.1 bis 1.p) abgestrahltes, mittelfrequentes magnetisches Feld zu jedem mindestens eine Sekundärwicklung (2.1 bis 2.s) aufweisenden Aktor übertragen und dort in elektrische Energie umgewandelt wird.

2. Anordnung zur drahtlosen Versorgung einer Vielzahl Aktoren (3.1 bis 3.s) mit elektrischer Energie unter Einsatz mindestens einer von einem mittelfrequenten Oszillator (4) gespeisten Primärwicklung (1, 1.1 bis 1.p), wobei jeder Aktor (3.1 bis 3.s) mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung (2.1 bis 2.s) aufweist.

3. Anordnung nach Anspruch 2, gekennzeichnet durch eine einzige, die Sekundärwicklungen (2.1 bis 2.s) der Aktoren (3.1 bis 3.s) global umfassende Primärwicklung (1).

4. Anordnung nach Anspruch 2, gekennzeichnet durch mindestens zwei parallel nebeneinander angeordnete Primärwicklungen (1.1, 1.2), zwischen denen die Sekundärwicklungen (2.1 bis 2.s) der Aktoren (3.1 bis 3.s) angeordnet sind.

5. Anordnung nach Anspruch 2, gekennzeichnet durch zwei orthogonal zueinander angeordnete Primärwicklungen (1.1, 1.2).

6. Anordnung nach Anspruch 2, gekennzeichnet durch drei orthogonal zueinander angeordnete Primärwicklungen (1.1, 1.2, 1.3).

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7. Anordnung nach Anspruch 2, gekennzeichnet durch mindestens eine, mindestens eine Sekundärwicklung (2.1 bis 2.s) eines Aktors (3.1 bis 3.s) lokal beeinflussende Primärwicklung (1.1 bis 1.p).

8. Anordnung nach Anspruch 2, gekennzeichnet durch eine in Form einer Doppelleitung ausgeführte Primärwicklung (1), wobei die Sekundärwicklungen (2.1 bis 2.s) der Aktoren (3.1 bis 3.s) zwischen der Doppelleitung angeordnet sind.

9. Anordnung nach einem der Ansprüche 2 bis 8, dadurch gekennzeichnet, daß mindestens eine Primärwicklung mit einem Ferritkern versehen ist.

10. Anordnung nach einem der Ansprüche 2 bis 9, dadurch gekennzeichnet, daß die mindestens eine Primärwicklung mit einem Kompensationskondensator (6) beschaltet ist.

11. Aktor mit mehreren zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeigneten, orthogonalen Sekundärwicklungen (2.1 bis 2.s).

12. Aktor nach Anspruch 11, dadurch gekennzeichnet, daß die Sekundärwicklungen (2.1 bis 2.s) mit einem Kompensationskondensator (6) beschaltet sind.

13. Aktor nach Anspruch 11 oder 12, dadurch gekennzeichnet, daß die Sekundärwicklungen (2.1 bis 2.s) mit einem AC/DC-Steller beschaltet sind, welcher einen Energiespeicher (8) auflädt.

14. System für eine eine Vielzahl von Aktoren aufweisende Maschine, insbesondere Fertigungsautomat,

- wobei jeder Aktor (3.1 bis 3.s) mindestens eine zur Energieaufnahme aus einem mittelfrequenten Magnetfeld geeignete Sekundärwicklung (2.1 bis 2.s) aufweist,
- wobei mindestens eine von einem mittelfrequenten Oszillator (4) gespeiste Primärwicklung (1, 1.1 bis 1.p) zur drahtlosen Versorgung der Aktoren (3.1 bis 3.s) mit elektrischer Energie vorgesehen ist,

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- wobei jeder Aktor mit einer Empfangseinrichtung ausgestattet ist, welche Funksignale einer mit einem Prozeßrechner der Maschine verbundenen zentralen Sendeeinrichtung empfängt.

15. System nach Anspruch 14, dadurch gekennzeichnet, daß die Aktoren mit Sendeeinrichtungen versehen sind, welche interessierende Aktor-Informationen beinhaltende Funksignale an eine zentrale, mit dem Prozeßrechner verbundene Empfangseinrichtung abgeben, so daß ein bidirektionaler Informationsaustausch zwischen dem Prozeßrechner und den Aktoren möglich ist.

16. Primärwicklung, bestehend aus mehreren separaten Wicklungsabschnitten (1a´ bis 1d´, 5a´ bis 5d´), welche jeweils aus mehreren parallelen Leitern aufgebaut sind, wobei die einzelnen Wicklungsabschnitte über Verbindungselemente (2a´ bis 2d´, 6a´ bis 6d´) mechanisch und elektrisch miteinander verbunden sind und wobei bei einem Verbindungselement zwei Wicklungsabschnitte versetzt gegeneinander elektrisch miteinander verbunden sind, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen (3´, 4´, 7´, 8´) zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

17. Primärwicklung, bestehend aus einem flexiblen, aus mehreren parallelen Leitern aufgebauten Kabel (9´) und einem Verbindungselement (10´), welches die beiden Kabelenden versetzt gegeneinander elektrisch und mechanisch miteinander verbindet, wodurch sich zwei freie, zum Anschluß von Verbindungsleitungen (11´, 12´) zu einem Generator oder Oszillator geeignete Wicklungsenden ergeben.

18. Primärwicklung nach Anspruch 16 und/oder 17, dadurch gekennzeichnet, daß ein Verbindungselement (2a´ bis 2d´, 6a´ bis 6d´) aus mehreren in einer Reihe nebeneinander angeordneten, elektrisch gegeneinander isolierten Kontaktstellen mit jeweils zwei Anschlüssen besteht.

19. Primärwicklung nach Anspruch 18, dadurch gekennzeichnet, daß eine Abwinkelung der nebeneinander angeordneten Kontaktstellen in einer Ebene erfolgt.

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20. Primärwicklung nach Anspruch 18, dadurch gekennzeichnet, daß eine Abwinkelung der nebeneinander angeordneten Kontaktstellen in zwei Ebenen erfolgt.

21. Primärwicklung nach Anspruch 19 oder 20, dadurch gekennzeichnet, daß die Abwinkelungen rechtwinklig erfolgen.

22. Primärwicklung nach Anspruch 16, dadurch gekennzeichnet, daß die Anzahl der Kontaktstellen eines Verbindungselementes (2a´ bis 2c´, 6a´ bis 6c´) gleich der Anzahl der parallelen Leiter eines Wicklungsabschnittes ist, mit Ausnahme des Verbindungselementes (2d´, 6d´) für den Anschluß der gegeneinander zu versetzenden Wicklungsabschnitte (1a´ und 1d´, 5a´ und 5d´), welches eine Kontaktstelle mehr aufweist als dies der Anzahl der parallelen Leiter eines Wicklungsabschnittes entspricht.

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Fig.1

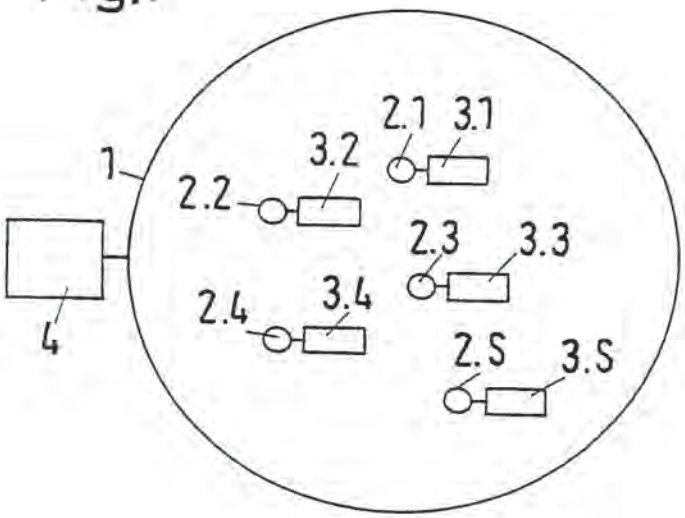


Fig.2

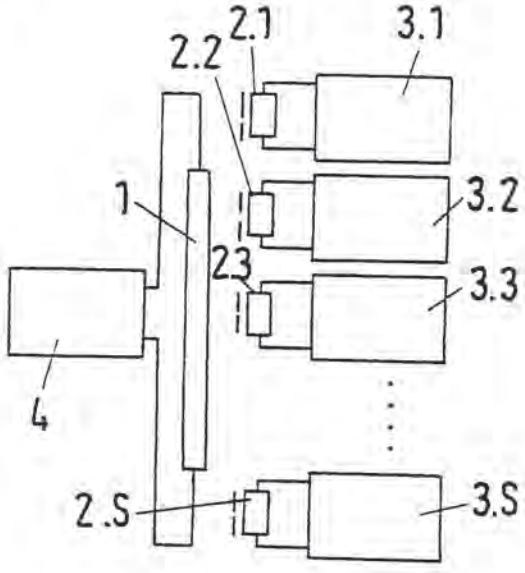


Fig.3

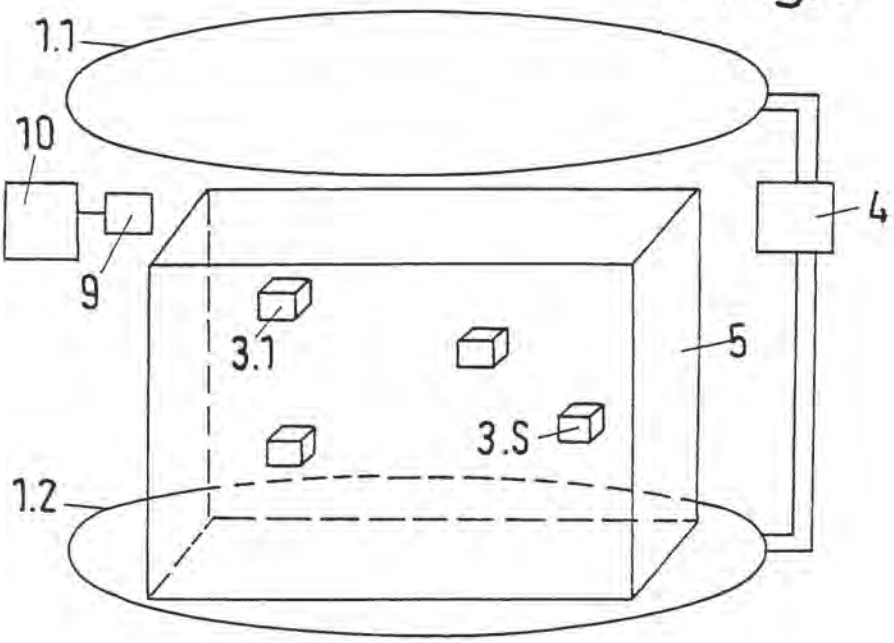
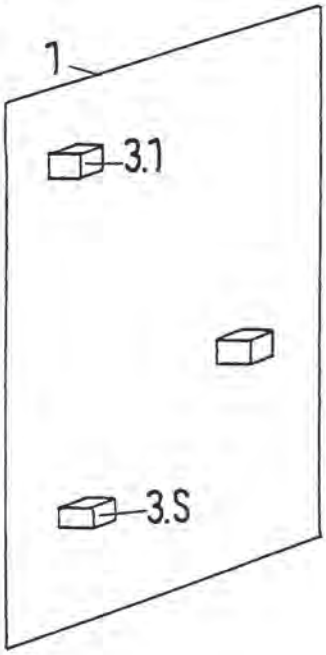


Fig.4



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Fig.5

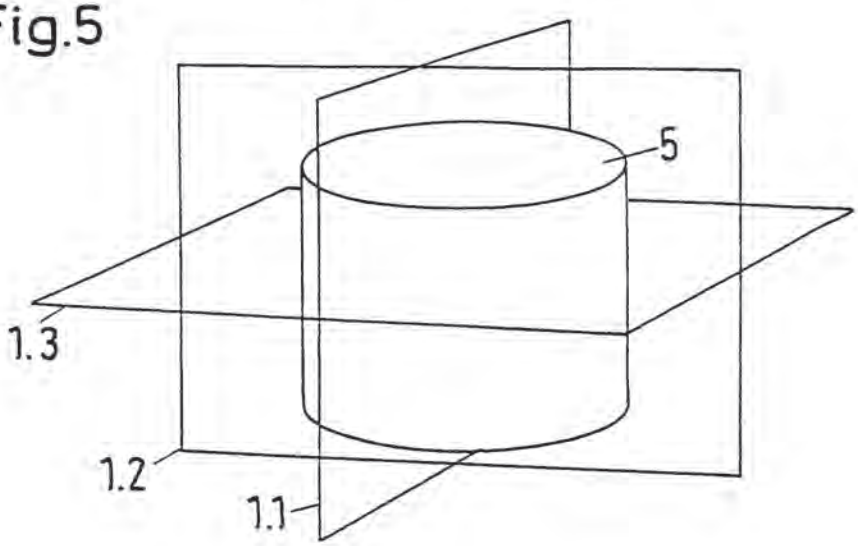


Fig. 6

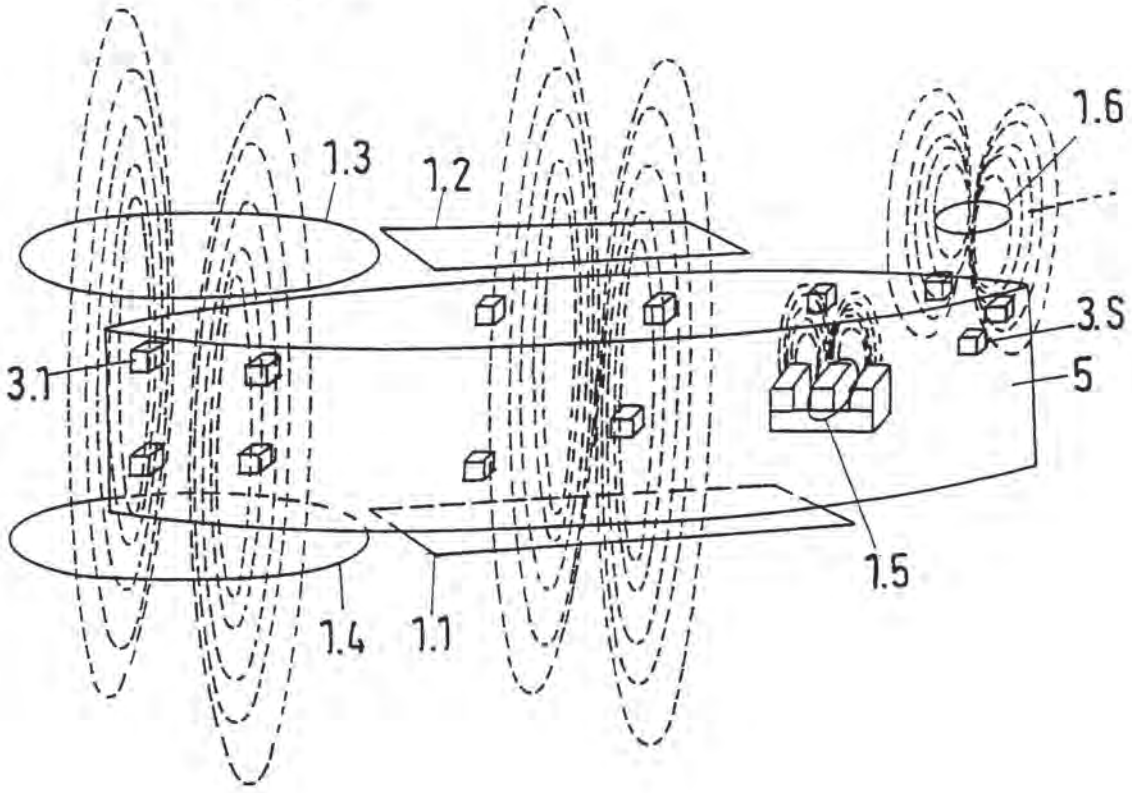


Fig.7

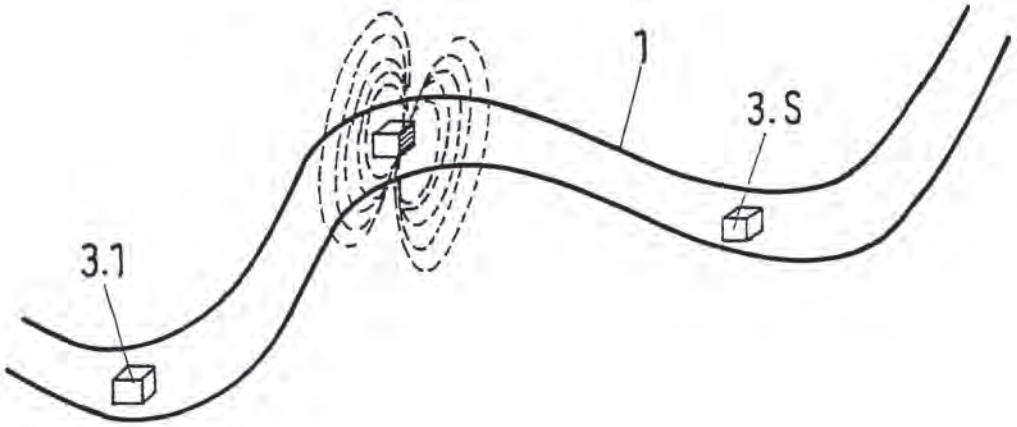


Fig. 8

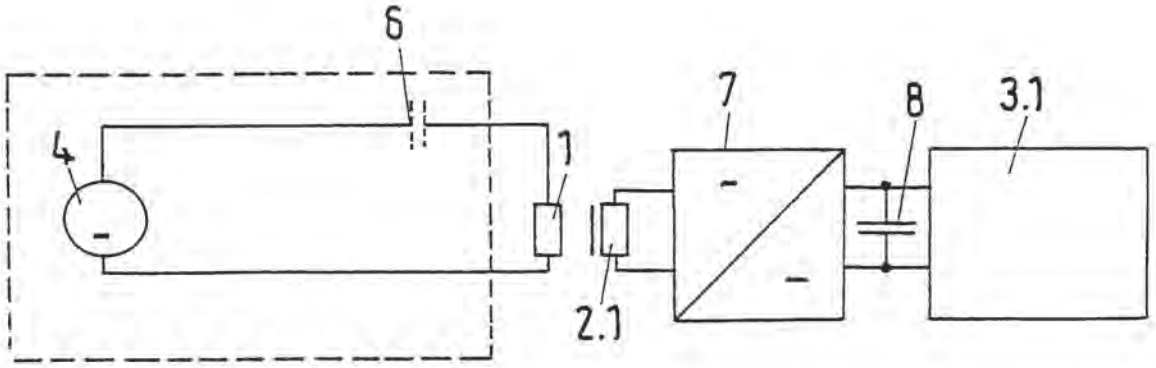


Fig.9

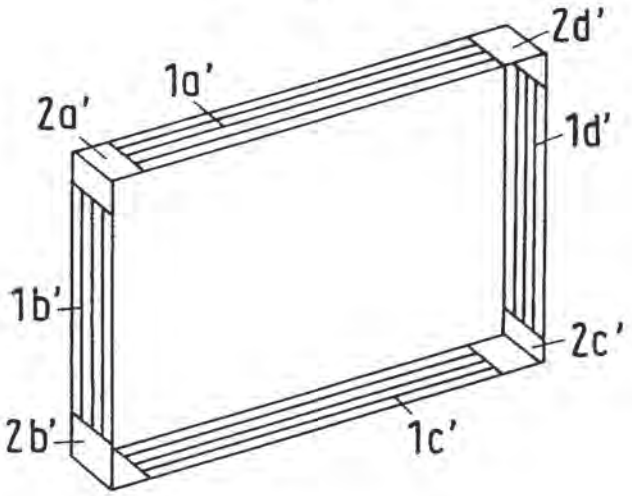


Fig.10

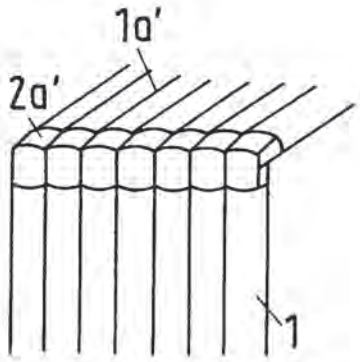
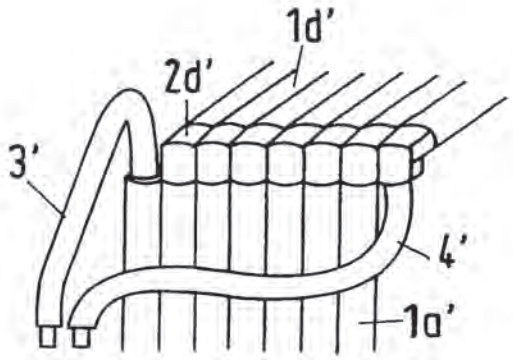


Fig.11



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Fig.12

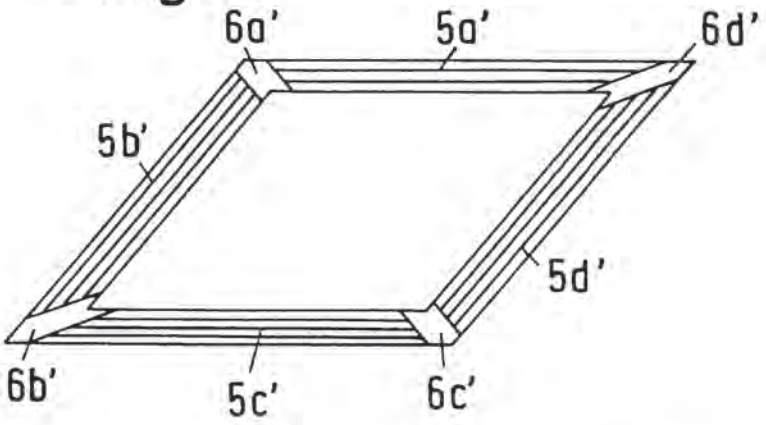


Fig.13

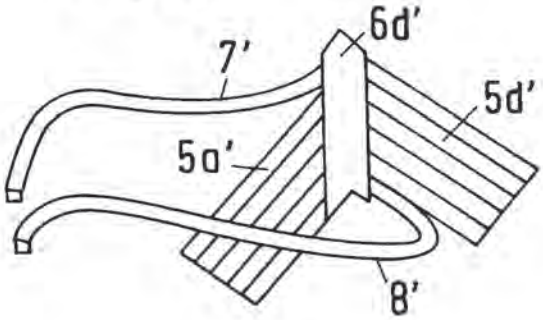


Fig.14

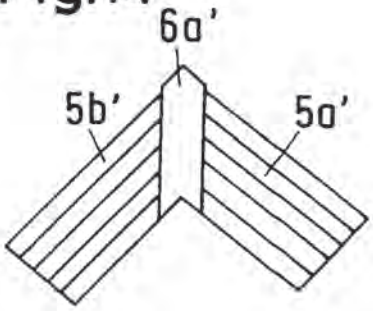
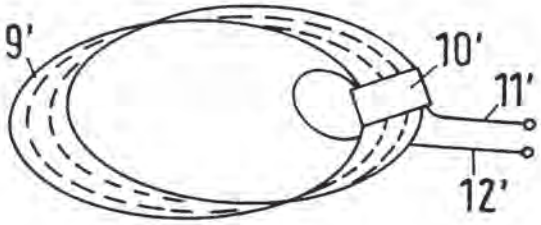


Fig.15



InductEV, Inc.
Exhibit 1024
Page 099

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/05138

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H02J5/00 G05B19/042

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H02J G05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 89 10030 A (MAGELLAN TECH PTY LTD ;UNISCAN LTD (AU)) 19 October 1989 (1989-10-19) page 9, line 7 - line 33; figures 1A,2,3 ---	1,11,12, 14,15
Y	DE 195 28 341 C (ILG GMBH) 10 October 1996 (1996-10-10) claim 3; figure 1 ---	1,11,12, 14,15
Y	DE 197 35 624 C (DAIMLER BENZ AG) 10 December 1998 (1998-12-10) page 2, paragraph 4; figure 1 --- -/--	1,11,12, 14,15

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
8 September 2000	01 12. 2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	MOYLE, J

Form PCT/ISA/210 (second sheet) (July 1992)

InductEV, Inc.
Exhibit 1024
Page 100

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/05138

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KAWAMURA A ET AL: "WIRELESS TRANSMISSION OF POWER AND INFORMATION THROUGH ONE HIGH FREQUENCY RESONANT AC LINK INVERTER FOR ROBOT MANIPULATOR APPLICATIONS" RECORD OF THE INDUSTRY APPLICATIONS CONFERENCE (IAS),US,NEW YORK, IEEE, vol. CONF. 30, 8 October 1995 (1995-10-08), pages 2367-2372, XP000547151 ISBN: 0-7803-3009-9 abstract ----	1-15

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

InductEV, Inc.
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Page 101

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP00/05138

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See supplemental sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-15

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

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Page 102

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP 00/05138

Additional Matter PCT/ISA/210

The International Searching Authority found that this application contains multiple inventions, as follows :

1. Claims Nos. 1-15
Transportation of inductive energy and data to machine tool actuators

2. Claims Nos. 16-22
Structural inductive transmission coil units

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Exhibit 1024
Page 103

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 00/05138

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 8910030 A	19-10-1989	AT 115792 T	15-12-1994
		AU 624377 B	11-06-1992
		AU 3429889 A	03-11-1989
		CA 1338675 A	22-10-1996
		CA 1340489 A	06-04-1999
		DE 68920038 D	26-01-1995
		DE 68920038 T	03-08-1995
		EP 0409880 A	30-01-1991
		EP 0609964 A	10-08-1994
		JP 3505148 T	07-11-1991
		US 5701121 A	23-12-1997
		ZA 8902468 A	27-12-1989
DE 19528341 C	10-10-1996	NONE	
DE 19735624 C	10-12-1998	AU 9159798 A	08-03-1999
		WO 9909634 A	25-02-1999
		EP 0968559 A	05-01-2000

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Page 104

INTERNATIONALER RECHERCHENBERICHT

Internationales Aktenzeichen
PCT/EP 00/05138

A. KLASSIFIZIERUNG DES ANMELDUNGSGEGENSTANDES
IPK 7 H02J5/00 G05B19/042

Nach der Internationalen Patentklassifikation (IPK) oder nach der nationalen Klassifikation und der IPK

B. RECHERCHIERTE GEBIETE

Recherchierter Mindestprüfstoff (Klassifikationssystem und Klassifikationssymbole)
IPK 7 H02J G05B

Recherchierte aber nicht zum Mindestprüfstoff gehörende Veröffentlichungen, soweit diese unter die recherchierten Gebiete fallen

Während der internationalen Recherche konsultierte elektronische Datenbank (Name der Datenbank und evtl. verwendete Suchbegriffe)
EPO-Internal

C. ALS WESENTLICH ANGESEHENE UNTERLAGEN

Kategorie°	Bezeichnung der Veröffentlichung, soweit erforderlich unter Angabe der in Betracht kommenden Teile	Betr. Anspruch Nr.
Y	WO 89 10030 A (MAGELLAN TECH PTY LTD ;UNISCAN LTD (AU)) 19. Oktober 1989 (1989-10-19) Seite 9, Zeile 7 - Zeile 33; Abbildungen 1A,2,3 ---	1,11,12, 14,15
Y	DE 195 28 341 C (ILG GMBH) 10. Oktober 1996 (1996-10-10) Anspruch 3; Abbildung 1 ---	1,11,12, 14,15
Y	DE 197 35 624 C (DAIMLER BENZ AG) 10. Dezember 1998 (1998-12-10) Seite 2, Absatz 4; Abbildung 1 --- -/--	1,11,12, 14,15

[X] Weitere Veröffentlichungen sind der Fortsetzung von Feld C zu entnehmen

[X] Siehe Anhang Patentfamilie

° Besondere Kategorien von angegebenen Veröffentlichungen :
"A" Veröffentlichung, die den allgemeinen Stand der Technik definiert, aber nicht als besonders bedeutsam anzusehen ist
"E" älteres Dokument, das jedoch erst am oder nach dem internationalen Anmeldedatum veröffentlicht worden ist
"L" Veröffentlichung, die geeignet ist, einen Prioritätsanspruch zweifelhaft erscheinen zu lassen, oder durch die das Veröffentlichungsdatum einer anderen im Recherchenbericht genannten Veröffentlichung belegt werden soll oder die aus einem anderen besonderen Grund angegeben ist (wie ausgeführt)
"O" Veröffentlichung, die sich auf eine mündliche Offenbarung, eine Benutzung, eine Ausstellung oder andere Maßnahmen bezieht
"P" Veröffentlichung, die vor dem internationalen Anmeldedatum, aber nach dem beanspruchten Prioritätsdatum veröffentlicht worden ist
"T" Spätere Veröffentlichung, die nach dem internationalen Anmeldedatum oder dem Prioritätsdatum veröffentlicht worden ist und mit der Anmeldung nicht kollidiert, sondern nur zum Verständnis des der Erfindung zugrundeliegenden Prinzips oder der ihr zugrundeliegenden Theorie angegeben ist
"X" Veröffentlichung von besonderer Bedeutung; die beanspruchte Erfindung kann allein aufgrund dieser Veröffentlichung nicht als neu oder auf erfinderischer Tätigkeit beruhend betrachtet werden
"Y" Veröffentlichung von besonderer Bedeutung; die beanspruchte Erfindung kann nicht als auf erfinderischer Tätigkeit beruhend betrachtet werden, wenn die Veröffentlichung mit einer oder mehreren anderen Veröffentlichungen dieser Kategorie in Verbindung gebracht wird und diese Verbindung für einen Fachmann naheliegend ist
"&" Veröffentlichung, die Mitglied derselben Patentfamilie ist

Datum des Abschlusses der internationalen Recherche	Absendedatum des internationalen Recherchenberichts
8. September 2000	01 12 2000

Name und Postanschrift der Internationalen Recherchenbehörde	Bevollmächtigter Bediensteter
Europäisches Patentamt, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	MOYLE, J

Formblatt PCT/ISA/210 (Blatt 2) (Juli 1992)

InductEV, Inc.
Exhibit 1024
Page 105

INTERNATIONALER RECHERCHENBERICHT

I. ıatlonales Aktenzeichen
PCT/EP 00/05138

C.(Fortsetzung) ALS WESENTLICH ANGESEHENE UNTERLAGEN

Kategorie°	Bezeichnung der Veröffentlichung, soweit erforderlich unter Angabe der in Betracht kommenden Teile	Betr. Anspruch Nr.
A	KAWAMURA A ET AL: "WIRELESS TRANSMISSION OF POWER AND INFORMATION THROUGH ONE HIGH FREQUENCY RESONANT AC LINK INVERTER FOR ROBOT MANIPULATOR APPLICATIONS" RECORD OF THE INDUSTRY APPLICATIONS CONFERENCE (IAS),US,NEW YORK, IEEE, Bd. CONF. 30, 8. Oktober 1995 (1995-10-08), Seiten 2367-2372, XP000547151 ISBN: 0-7803-3009-9 Zusammenfassung -----	1-15

Formblatt PCT/ISA/210 (Fortsetzung von Blatt 2) (Juli 1992)

InductEV, Inc.
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Page 106

INTERNATIONALER RECHERCHENBERICHT

Internationales Aktenzeichen
PCT/EP 00/05138

Feld I Bemerkungen zu den Ansprüchen, die sich als nicht recherchierbar erwiesen haben (Fortsetzung von Punkt 2 auf Blatt 1)

Gemäß Artikel 17(2)a) wurde aus folgenden Gründen für bestimmte Ansprüche kein Recherchenbericht erstellt:

1. ☐ Ansprüche Nr.
weil sie sich auf Gegenstände beziehen, zu deren Recherche die Behörde nicht verpflichtet ist, nämlich

2. ☐ Ansprüche Nr.
weil sie sich auf Teile der internationalen Anmeldung beziehen, die den vorgeschriebenen Anforderungen so wenig entsprechen, daß eine sinnvolle internationale Recherche nicht durchgeführt werden kann, nämlich

3. ☐ Ansprüche Nr.
weil es sich dabei um abhängige Ansprüche handelt, die nicht entsprechend Satz 2 und 3 der Regel 6.4 a) abgefaßt sind.

Feld II Bemerkungen bei mangelnder Einheitlichkeit der Erfindung (Fortsetzung von Punkt 3 auf Blatt 1)

Die internationale Recherchenbehörde hat festgestellt, daß diese internationale Anmeldung mehrere Erfindungen enthält:

siehe Zusatzblatt

1. ☐ Da der Anmelder alle erforderlichen zusätzlichen Recherchengebühren rechtzeitig entrichtet hat, erstreckt sich dieser internationale Recherchenbericht auf alle recherchierbaren Ansprüche.

2. ☐ Da für alle recherchierbaren Ansprüche die Recherche ohne einen Arbeitsaufwand durchgeführt werden konnte, der eine zusätzliche Recherchengebühr gerechtfertigt hätte, hat die Behörde nicht zur Zahlung einer solchen Gebühr aufgefordert.

3. ☐ Da der Anmelder nur einige der erforderlichen zusätzlichen Recherchengebühren rechtzeitig entrichtet hat, erstreckt sich dieser internationale Recherchenbericht nur auf die Ansprüche, für die Gebühren entrichtet worden sind, nämlich auf die Ansprüche Nr.

4. ☒ Der Anmelder hat die erforderlichen zusätzlichen Recherchengebühren nicht rechtzeitig entrichtet. Der internationale Recherchenbericht beschränkt sich daher auf die in den Ansprüchen zuerst erwähnte Erfindung; diese ist in folgenden Ansprüchen erfaßt:
1-15

Bemerkungen hinsichtlich eines Widerspruchs

☐ Die zusätzlichen Gebühren wurden vom Anmelder unter Widerspruch gezahlt.

☐ Die Zahlung zusätzlicher Recherchengebühren erfolgte ohne Widerspruch.

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Page 107

WEITERE ANGABEN **PCT/ISA/** 210

Die internationale Recherchenbehörde hat festgestellt, daß diese internationale Anmeldung mehrere (Gruppen von) Erfindungen enthält, nämlich:

1. Ansprüche: 1-15

   Induktive Energie- und Daten- Transport zu Werkzeugmaschinenaktoren

2. Ansprüche: 16-22

   Strukturelle Einzelheiten von induktiven Übertragungsspulen

INTERNATIONALER RECHERCHENBERICHT

Angaben zu Veröffentlichungen, die zur selben Patentfamilie gehören

	ationales Aktenzeichen
	PCT/EP 00/05138

Im Recherchenbericht angeführtes Patentdokument	Datum der Veröffentlichung	Mitglied(er) der Patentfamilie	Datum der Veröffentlichung
WO 8910030 A	19-10-1989	AT 115792 T	15-12-1994
		AU 624377 B	11-06-1992
		AU 3429889 A	03-11-1989
		CA 1338675 A	22-10-1996
		CA 1340489 A	06-04-1999
		DE 68920038 D	26-01-1995
		DE 68920038 T	03-08-1995
		EP 0409880 A	30-01-1991
		EP 0609964 A	10-08-1994
		JP 3505148 T	07-11-1991
		US 5701121 A	23-12-1997
		ZA 8902468 A	27-12-1989
DE 19528341 C	10-10-1996	KEINE	
DE 19735624 C	10-12-1998	AU 9159798 A	08-03-1999
		WO 9909634 A	25-02-1999
		EP 0968559 A	05-01-2000

InductEV, Inc.
Exhibit 1024
Page 109

Electronic Acknowledgement Receipt	
EFS ID:	7823792
Application Number:	12649635
International Application Number:	
Confirmation Number:	5891
Title of Invention:	WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS
First Named Inventor/Applicant Name:	John D. Joannopoulos
Customer Number:	26161
Filer:	Marc M. Wefers/Cheryl Forrest
Filer Authorized By:	Marc M. Wefers
Attorney Docket Number:	01997-0359015
Receipt Date:	16-JUN-2010
Filing Date:	30-DEC-2009
Time Stamp:	12:17:43
Application Type:	Utility under 35 USC 111(a)

Payment information:

Submitted with Payment	no

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1		359015.pdf	90661 [illegible]	yes	3

	Multipart Description/PDF files in .zip description				
	Document Description		Start	End	
	Transmittal Letter		1	2	
	Information Disclosure Statement (IDS) Filed (SB/08)		3	3	
Warnings:					
Information:					
2	Foreign Reference	Art1.pdf	1261502 672b8652a1c9e1de9d2adcb91ea4dc13f6b4e6d5	no	35
Warnings:					
Information:					
		Total Files Size (in bytes):	1352163		

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

New Applications Under 35 U.S.C. 111
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.

National Stage of an International Application under 35 U.S.C. 371
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.

New International Application Filed with the USPTO as a Receiving Office
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant	: John D. Joannopoulos et al.	Art Unit	: Unknown
Serial No.	: 12/649,635	Examiner	: Unknown
Filed	: December 30, 2009	Conf. No.	: 5891
Title	: WIRELESS ENERGY TRANSFER TO A MOVING DEVICE BETWEEN HIGH-Q RESONATORS		

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

INFORMATION DISCLOSURE STATEMENT

Please consider the references listed on the enclosed PTO-1449 form. Foreign patent documents and non-patent literature are enclosed; cited U.S. patents and patent application publications will be provided on request.

Applicant notes that reference Desig. ID No. 3 listed on the enclosed PTO-1449 form was previously cited in an Information Disclosure Statement filed on April 23, 2010. However, this reference was incorrectly listed on the PTO-1449 form submitted with the April 23, 2010 Information Disclosure Statement as "WO 00/79910", though the Publication Date, Country or Patent Office, Class and Subclass were listed correctly and the foreign reference submitted was in fact WO 00/77910. The correct WO 00/77910 document was submitted in the parent application, Serial No. 11/481,077, on November 24, 2009, however, we enclose an additional copy of WO 00/77910 for your convenience.

This statement is being filed within three months of the filing date of the application or before the receipt of a first Office Action on the merits. Apply any charges or credits to Deposit Account No. 06-1050, referencing 01997-0359015.

Respectfully submitted,

Date: 6/16/10

Marc M. Wefers
Reg. No. 56,842

Customer Number
Fish & Richardson P.C.
Telephone: (617) 542-5070
Facsimile: (877) 769-7945

22436958.doc

Substitute Form PTO-1449 (Modified) U.S. Department of Commerce Patent and Trademark Office	Attorney Docket No. 01997-0359015	Application No. 12/649,635
Information Disclosure Statement by Applicant (Use several sheets if necessary) (37 CFR §1.98(b))	Applicant John D. Joannopoulos et al.	
	Filing Date December 30, 2009	Group Art Unit

U.S. Patent Documents

Examiner Initial	Desig. ID	Document Number	Publication Date	Patentee	Class	Subclass	Filing Date If Appropriate
	1	5,118,997	6/2/1992	El-Hamamsy			
	2	5,986,895	11/16/1999	Stewart et al.			
	3	7,147,604	12/12/2006	Allen et al.			
	4	7,191,007	3/13/2007	Desai et al.			
	5	7,599,743	10/6/2009	Hassler, Jr. et al.			
	6	7,639,514	12/29/2009	Baarman			
	7	7,825,543	11/2/2010	Karalis et al.			
	8	7,843,288	11/30/2010	Lee et al.			
	9	2005/0288739	12/29/2005	Hassler, Jr. et al.			
	10	2005/0288740	12/29/2005	Hassler, Jr. et al.			
	11	2007/0182367	8/9/2007	Partovi			
	12	2008/0012569	1/17/2008	Hall et al.			
	13	2008/0030415	2/7/2008	Homan et al.			
	14	2008/0067874	3/20/2008	Tseng			
	15	2008/0265684	10/30/2008	Farkas			
	16	2009/0015075	1/15/2009	Cook et al.			
	17	2009/0067198	3/12/2009	Graham et al.			
	18	2009/0085408	4/2/2009	Bruhn			
	19	2009/0085706	4/2/2009	Baarman et al.			
	20	2009/0096413	4/16/2009	Patovi et al.			
	21	2009/0180679	4/30/2009	Porwal			
	22	2009/0108997	4/30/2009	Patterson et al.			
	23	2009/0146892	6/11/2009	Shimizu et al.			
	24	2009/0160261	6/25/2009	Elo			
	25	2009/0174263	9/9/2009	Baarman et al.			
	26	2009/0189458	7/30/2009	Kawasaki			
	27	2009/0230777	9/17/2009	Baarman et al.			

Examiner Signature	Date Considered
EXAMINER: Initials citation considered. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.	

Substitute Form PTO-1449 (Modified) U.S. Department of Commerce Patent and Trademark Office	Attorney Docket No. 01997-0359015	Application No. 12/649,635
Information Disclosure Statement by Applicant (Use several sheets if necessary) (37 CFR §1.98(b))	Applicant John D. Joannopoulos et al.	
	Filing Date December 30, 2009	Group Art Unit

U.S. Patent Documents

Examiner Initial	Desig. ID	Document Number	Publication Date	Patentee	Class	Subclass	Filing Date If Appropriate
	28	2009/0237194	9/24/2009	Waffenschmidt et al.			
	29	2009/0251008	10/8/2009	Sugaya			
	30	2009/0267558	10/29/2009	Jung			
	31	2009/0271047	10/29/2009	Wakamatsu			
	32	2009/0271048	10/29/2009	Wakamatsu			
	33	2009/0281678	11/12/2009	Wakamatsu			
	34	2009/0284082	11/19/2009	Mohammadian			
	35	2009/0284218	11/19/2009	Mohammadian et al.			
	36	2009/0284220	11/19/2009	Toncich et al.			
	37	2009/0284227	11/19/2009	Mohammadian et al.			
	38	2009/0284245	11/19/2009	Kirby et al.			
	39	2009/0284369	11/19/2001	Toncich et al.			
	40	2009/0286470	11/19/2009	Mohammadian et al.			
	41	2009/0286475	11/19/2009	Toncich et al.			
	42	2009/0286476	11/19/2009	Toncich et al.			
	43	2009/0289595	11/26/2009	Chen et al.			
	44	2010/0231163	9/19/2010	Mashinsky			
	45	2010/0289449	11/18/2010	Elo			
	46						

Foreign Patent Documents or Published Foreign Patent Applications

Examiner Initial	Desig. ID	Document Number	Publication Date	Country or Patent Office	Class	Subclass	Translation Yes	Translation No
	47	WO 2009/033043	3/12/2009	WIPO				
	48	WO 2009/070730	6/4/2009	WIPO				
	49	WO 2009/126963	10/15/2009	WIPO				
	50	WO 2009/149464	12/10/2009	WIPO				
	51	WO 2009/155000	12/23/2009	WIPO				

Examiner Signature	Date Considered
EXAMINER: Initials citation considered. Draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.	

Substitute Disclosure Form (PTO-1449)

Substitute Form PTO-1449 (Modified) U.S. Department of Commerce Patent and Trademark Office	Attorney Docket No. 01997-0359015	Application No. 12/649,635
Information Disclosure Statement by Applicant (Use several sheets if necessary) (37 CFR §1.98(b))	Applicant John D. Joannopoulos et al.	
	Filing Date December 30, 2009	Group Art Unit

Foreign Patent Documents or Published Foreign Patent Applications

Examiner Initial	Desig. ID	Document Number	Publication Date	Country or Patent Office	Class	Subclass	Translation Yes	Translation No
	52							
	53							

Other Documents (include Author, Title, Date, and Place of Publication)

Examiner Initial	Desig. ID	Document
	54	A. Mediano et al. "Design of class E amplifier with nonlinear and linear shunt capacitances for any duty cycle", IEEE Trans. Microwave Theor. Tech., volume 55, no. 3, pp. 484-492, (2007)
	55	H. Sekiya et al. "FM/PWM control scheme in class DE inverter", IEEE Trans. Circuits Syst. I, vol. 51, no. 7 (July 2004)
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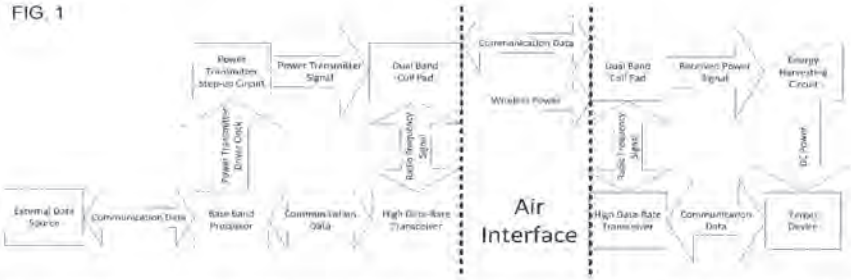
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FIG. 1



(57) Abstract: In one aspect, the present disclosure describes a planar near-field wireless power charging system that is capable of charging small portable devices. Embodiments can incorporate coils for generating time-varying magnetic fields into a pad. In an exemplary embodiment, the charging system incorporates a charging pad that can act as an electrically small coil antenna for the low frequencies and long wavelengths, used for charging, and long wavelengths, and which can also be used for communication purposes by treating it as an electrically large antenna at higher frequencies, and shorter wavelengths, used for communications. In an exemplary embodiment, the system uses multiple lower powered transmitters, where each transmitter feeds a separate coil. The separate coils can be stacked so that the magnetic fields are substantially coextensive. The simultaneous driving of the multiple coils by the multiple transmitters can achieve similar power delivery as a single high powered transmitter. Multiple stacked sets of coils can be integrated into a pad such that each stacked set of coils provides vertical magnetic fields over a section of the pad. Embodiments of the subject invention can be designed to couple energy to the receiver coil of the device via magnetic fields that have a substantial vertical component. An embodiment of the present disclosure describes a receiver coil attached to a portable electronic device with a mechanical connection that allows the receiver coil to be positioned such that the vertical fields do not need to pass through a substantial portion of the device to pass through the receiver coil during charging and can allow the receiver coil to be conveniently positioned adjacent the device when not changing.

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DESCRIPTION

PLANAR NEAR-FIELD WIRELESS POWER CHARGER AND HIGH-SPEED DATA COMMUNICATION PLATFORM

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 60/970,201, filed September 5, 2007, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

Portable electronic equipment, such as mobile phones, handheld computers, and personal data assistants, are normally powered by batteries. In many cases, rechargeable batteries are preferred because of environmental and economical concerns. The most common way to charge rechargeable batteries is to use a conventional charger, which normally includes an AC-DC power supply when the AC mains are used, or a DC-DC power supply when a car battery is used. Conventional chargers normally use an electric cable to connect the charger circuit to the battery located in the portable electronic equipment.

In large part due to the inconvenience of conventional chargers, wireless power solutions have been presented. Examples of wireless power solutions include electric toothbrushes and electric razors. Current wireless power solutions have limitations such as requiring a particular alignment of the device being charged to the charging unit, or other inconveniences such as the need for the device being charged to be within a certain distance of a certain section of the charging unit.

Thus, there remains a need for a system for wireless charging of portable electronic devices in an efficient manner.

BRIEF SUMMARY

In one aspect, the present disclosure describes a planar near-field wireless power charging system that is capable of charging small portable devices. Embodiments can incorporate coils for generating time-varying magnetic fields into a pad. In an exemplary

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embodiment, the charging system incorporates a charging pad that can act as an electrically small coil antenna for the low frequencies and long wavelengths, used for charging, and long wavelengths, and which can also be used for communication purposes by treating it as an electrically large antenna at higher frequencies, and shorter wavelengths, used for communications.

In an exemplary embodiment, the system uses multiple lower powered transmitters, where each transmitter feeds a separate coil. The separate coils can be stacked so that the magnetic fields are substantially coextensive. The simultaneous driving of the multiple coils by the multiple transmitters can achieve similar power delivery as a single high powered transmitter. Multiple stacked sets of coils can be integrated into a pad such that each stacked set of coils provides vertical magnetic fields over a section of the pad. Embodiments of the subject invention can be designed to couple energy to the receiver coil of the device via magnetic fields that have a substantial vertical component.

An embodiment of the present disclosure describes a receiver coil attached to a portable electronic device with a mechanical connection that allows the receiver coil to be positioned such that the vertical fields do not need to pass through a substantial portion of the device to pass through the receiver coil during charging and can allow the receiver coil to be conveniently positioned adjacent the device when not charging. In exemplary embodiments, the mechanical connection can be a flip or slide mechanism that allows the receiver coil to be positioned such that a vertical magnetic field does not need to pass through the portable device in order to pass through the receiver coil during charging, but allows the receiver coil to reside adjacent to the device when not charging in order to make the device with receiver coil easier to carry and store.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 shows one embodiment of a system architecture of a planar near-field wireless power charger and high-speed data communication platform.

Figure 2 shows an embodiment of a planar wireless power charger platform in accordance with the present disclosure.

Figure 3 shows a diagram of one embodiment of a multiple-transmitter power delivery system.

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Figure 4 shows a system block diagram of a multiple-transmitter power delivery system.

Figures 5A-5B show embodiments of a single transmitter coil for a wireless power system.

Figure 6 shows an existing technology using a horizontal field to charge the portable device.

Figure 7 shows a cell phone incorporating an embodiment of a power charging receiver in accordance with the present disclosure.

Figures 8A-8B show a power charging receiver attached to a cell phone using a flip mechanism.

Figure 9 shows a power charging receiver attached to a cell phone using the a slide mechanism.

DETAILED DISCLOSURE

In one aspect, the present disclosure describes a planar near-field wireless power charging system that is capable of charging small portable devices. Embodiments can incorporate coils for generating time-varying magnetic fields into a pad. Embodiments of the wireless power charging system can allow powering devices at close proximity. In an embodiment, a charging efficiency of greater than 75% can be achieved. In a further embodiment, a charging efficiency of greater than 85% can be achieved. Specific embodiments can allow charging to occur at a distance of, for example, up to about 5 inches above the pad. The ability to charge the device with up to a 5 inch separation between the device and the charging unit, or portion thereof, allows versatility as to where devices can be positioned during the charging process. In a specific embodiment, a receiver coil as small as 10% of the transmitting coil can be utilized. In an exemplary embodiment, the system is capable of charging multiple devices at the same time.

In an exemplary embodiment, the charging system incorporates a charging pad that can act as an electrically small coil antenna for the low frequencies and long wavelengths, used for charging, and long wavelengths, and which can also be used for communication purposes by treating it as an electrically large antenna at higher frequencies, and shorter wavelengths, used for communications. In a specific embodiment, a power signal for

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charging can have a frequency less than or equal to 1MHz. in a further embodiment, the data signal for communications can have a frequency in the ultra wide band (UWB) of 3.1GHz-10.6GHz and use a carrier-less signal with pulses, or a carrier based signal with a carrier frequency in the WiFi band, e.g., at 2.4GHz.

Figure 1 shows one embodiment of a system architecture of a planar near-field wireless power charger and high-speed data communication platform. The system architecture can include a power transmitter, power receiver and energy harvesting circuit, and transmitting coil pad. In an exemplary embodiment, the subject platform is designed for short range applications using near field coupling. This embodiment can achieve high data rates using a simple transceiver architecture. In various embodiments, the base station can: transmit a power signal; transmit a power signal and transmit a data signal; transmit a power signal, transmit a data signal, and receive a data signal; or transmit a power signal and receive a data signal. The base station can break the various transmit and/or receive functions into separate transmitters and receivers, or combine such functions into one or more transceivers. By using a single coil to transmit and receive costs and space can be saved. Likewise, the receiver can: receive a power signal; receive a power signal and transmit a data signal; receive a power signal, transmit a data signal, and receive a data signal; or receive a power signal and transmit a data signal. The transmit power, transmit data, receive power, and receive data functions can be performed sequentially or simultaneously.

The wireless transfer of power and data can allow a variety of configurations. An embodiment can use a first pad and a second pad, each having a base station, and a television having a receiver, with the TV on the first pad and a DVD player having a receiver on a second pad. Power is provided to the DVD player and data can be received by the second pad from the DVD player. The received data can then be transferred from the second pad to the first pad and then from the data transmitter in the first pad to the receiver in the TV. Other embodiments can use a pad and an audio device, such as and MP3 player, where power is supplied to the audio device and music data is received by the pad from the audio device. The received audio data can then be delivered to, for example, speakers or some sort of device to further utilize the audio data. The pad can be networked to a home or office network, such that received data can be distributed as needed. The data can also include information about the charging state of the receiver device. In a specific embodiment, the

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data can be transmitted at a rate of 50Mb-500Mb. In another specific embodiment, the data can be transmitted at a rate up to 1Gbps.

Figure 2 shows an embodiment of a platform in accordance with the present disclosure. Exemplary applications of this system include its use as a platform for wireless power charging and high data rate communication for portable devices, such as mobile phones and mp3 players. The system can be implemented in various locations, such as homes, airports, and hotel rooms. This adds convenience as it provides a universal charging interface and can reduce, or eliminate, the need to bring multiple chargers. In addition, it can serve as a high speed data link between devices so that data can be exchanged on the same platform, instead of separate ones. This can be integrated with a smart home or smart office space. The system can have simple hardware architecture so as to achieve low cost for mass production. In one embodiment, a wireless near-field high-speed data communication capability is implemented as part of the system.

Preferably, the magnetic flux generated by the transmitting coil pad is substantially uniform over at least a major part of the planar charging surface. In this way, the impact that the precise position and orientation of the electronic device on the charging surface has on the charging efficiency is reduced. The system illustrated in Figure 2 includes a power transmitter **4** that powers a power-transmitting coil pad **6**. The power transmitter **4** is powered by power source **2**. The transmitting coil pad **6** wirelessly sends power to a power receiver and energy harvesting circuit **8**. The power receiver is connected to the target electronic device **10**. In alternative embodiments, the power receiver and energy harvesting circuit can be attached or integrated with the target device, such that the target device can be placed on or near the coil pad for charging. In an exemplary embodiment, discussed later, the power receiver is formed as a back cover of the electronic device. In an exemplary embodiment, the equipment is charged simply by placing the power receiver on, or near, the transmitting coil pad surface.

In an exemplary embodiment, the system uses multiple lower powered transmitters, where each transmitter feeds a separate coil. The separate coils can be stacked so that the magnetic fields are substantially coextensive. The simultaneous driving of the multiple coils by the multiple transmitters can achieve similar power delivery as a single high powered transmitter. In a specific embodiment, the size of each lower powered transmitter can be

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reduced up to 80-90% compared with a single high-powered transmitted, such that the large transformer typically used to step up the voltage to a high voltage can be eliminated from the system. Removing the large transformer can enhance safety. Figure 3 shows a diagram of one embodiment incorporating a multiple-transmitter power delivery system for a multiple coil design having seven coils. Multiple stacked sets of coils can be integrated into a pad such that each stacked set of coils provides vertical magnetic fields over a section of the pad. Figure 4 shows a system block diagram of a multiple-transmitter power delivery system that can be used with a coil design having eight coils.

Figures 5A -5B show embodiments of a single transmitter coil for a wireless power system. The coils can have a variety of shapes. This coil can be integrated with a pad, or other object, for placing devices to be charged on or near the pad. In an embodiment, the coils are positioned such that the resulting magnetic field is normal to a surface of the pad, such that receiver coils can be located on the pad's surface to receive the magnetic fields. In a specific embodiment, the transmitter coil, such as the coil shown in Figure 5, can be driven by multiple transmitters, which can each be selectively turned on or off, and tuned. In a specific embodiment incorporating a stacked set of coils, each transmitter can be tuned independently, thereby achieving a wide tuning range. Individual tuning of the coils can be performed in near real time and increase energy transfer efficiency for different charging circumstances. Power control can be achieved by individually turning on and off the individual transmitters depending on the charging load, making it more energy efficient. The multiple-transmitter design enables the transmitter system to be more flexible and adaptive to a wider range of environmental situations while consuming less power. Thus, a significant improvement in efficiency can be attained. In a specific embodiment, each transmitter for the stacked set of coils is identical, or each transmitter for the multiple transmitters driving a single coil, allowing low cost for mass production. Since the transmitters are the same, additional transmitters can be easily added to the system to boost the maximum output, thereby offering a great advantage for scalability. Having multiple transmitters also gives the system many extra degrees of freedom for achieving a higher dynamic range. In a specific embodiment, the coils in the stacked configurations are driven in place by the plurality of transmitters.

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Referring to Figure 6, a device incorporating a coil design to receive power from surface magnetic fields that are substantially horizontal is shown. In accordance with current wireless power charging technology that uses horizontal magnetic fields for coupling of energy to charge portable electronic devices. The receiver coil used with the device to be charged receives magnetic field flux that is substantially parallel with the surface of the pad the device is placed on and does not extend very far above the surface of the pad. Such use of horizontal magnetic fields is inefficient because the cross sectional area of the receiver coil is limited; thus, the coupling factor is low. Embodiments of the subject invention can be designed to couple energy to the receiver coil of the device via magnetic fields that have a substantial vertical component. Examples of transmitter coil design that can be used to produce magnetic fields that have a substantial vertical component are shown in Figure 3 and Figure 5. Other designs can also be used in accordance with the invention.

Using a vertical field for coupling of energy can be more efficient. However, by mounting the receiver on the back of a portable device, the efficiency of such coupling can be reduced as the magnetic field must pass through the portable device in order to pass through the receiver coil. An embodiment of the present disclosure describes a receiver coil attached to a portable electronic device with a mechanical connection that allows the receiver coil to be positioned such that the vertical fields do not need to pass through a substantial portion of the device to pass through the receiver coil during charging and can allow the receiver coil to be conveniently positioned adjacent the device when not charging. In specific embodiments. the receiver coil can be positioned so that the magnetic fields pass through less than one half of the body of the device. In exemplary embodiments, the mechanical connection can be a flip or slide mechanism that allows the receiver coil to be positioned such that a vertical magnetic field does not need to pass through the portable device in order to pass through the receiver coil during charging, but allows the receiver coil to reside adjacent to the device when not charging in order to make the device with receiver coil easier to carry and store. The use of such a mechanical connection can enable efficient charging of the device without significant modification to the device's form factor, as shown in Figure 7.

The receiver can be designed as an add-on device or as part of a portable electronic device such as a mobile phone. In an exemplary application, a user need not replace an entire phone to take advantage of the new technology. For example, the user can replace the back

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panel or the battery cover of a phone or device to make the device compliant to this technology.

Figures 8A and 8B show a power charging receiver coil attached to a cell phone using a flip mechanism. In one embodiment, the flip mechanism includes a catch at one end of the device and a hinge on the other end of the device for allowing the receiver coil to flip open. The receiver coil can flip out, as shown by arrows in Figure 8B, such that the receiver coil is rotated 180 degrees and is parallel with the surface of the device from where it rotated from. In an alternative embodiment, the receiver coil can rotate 90 degrees and be used to receive horizontal magnetic fields for charging the device. Figure 9 shows a power charging receiver attached to a cell phone using a slide mechanism. In this embodiment, the receiver coil is slid out away from the phone body and placed on the charging pad so that the receiver coil is substantially parallel with the surface of the charging pad so as to allow the vertical portion of the magnetic field to pass through the receiver coil. Other mechanisms can be incorporated with embodiments of the invention to coordinate the relative position of the device body and the receiver coil.

The large cross-sectional area of the receiver coil provides for increased coupling for use with a near-field planar wireless power charger system. Positioning the receiver coil, for example, via the flip mechanism or the slide mechanism, such that the magnetic field flux does not pass through the body of the device enhances the charging efficiency. The device can be charged in the pre-flip or pre-slide position, but at a slower rate. To fully realize the benefits of the subject receiver coil design, the wireless power charger system can incorporate a vertical magnetic field for coupling of energy to the receiver coil. Such a vertical magnetic field achieves a higher efficiency coupling and, therefore, higher efficiency charging. Further, embodiments using vertical fields can allow the receiver coil to be positioned higher off of the pad having the transmitted coils than with systems using horizontal fields, while achieving the same coupling efficiency. In a specific embodiment, the receiver coil can be up to 5 inches above the pad.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

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It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

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CLAIMS

1. A wireless power transfer system, comprising:

a base station, wherein the base station comprises:

a transmitter coil;

a power transmitter, wherein the power transmitter is capable of driving the transmitter coil such that a first magnetic field is produced; and

a data receiver,

a receiver station, wherein the receiver station comprises:

a receiver coil, wherein the receiver coil inductively couples the first magnetic field to produce a received power signal; and

a data transmitter, wherein the data transmitter drives the receiver coil to produce a transmitted data signal,

wherein the transmitter coil inductively couples the transmitted data signal to produce a received RF data signal, wherein the data receiver receives the received RF data signal and outputs a received data signal.

2. The wireless power transfer system according to claim 1, where in the receiver station further comprises an energy harvesting circuit, wherein the energy harvesting circuit receives the received power signal and outputs DC power.

3. The wireless power transfer system according to claim 1, wherein the receiver station further comprises a target device, wherein the target device provides a data input signal to the data transmitter, wherein the data input signal is used by the data transmitter to produce the data signal.

4. The wireless power transfer system according to claim 1, wherein the base station further comprises:

a second data transmitter, wherein the second data transmitter drives the transmitter coil to produce a second transmitted data signal.

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wherein the receiver station further comprises a second data receiver, wherein the receiver coil inductively couples the second transmitted data signal to produce a second received RF data signal.

5. The wireless power transfer system according to claim 1, wherein the power transmitter and the data receiver are integrated as a first transceiver.

6. The wireless power transfer system according to claim 4, wherein the data transmitter and the second data receiver are integrated as a second transceiver.

7. The wireless power transfer system according to claim 4, wherein the second data transmitter is integrated with the power transmitter and the data receiver as the first transceiver.

8. The wireless power transfer system according to claim 4, wherein the second data receiver is integrated with the data transmitter and the second data receiver as the second transceiver.

9. The wireless power transfer system according to claim 4, wherein the power transmitter and the second data transmitter are capable of simultaneously driving the transmitter coil, wherein the power transmitter drives the transmitter coil at a first wavelength and the second data transmitter drives the transmitter coil at a second wavelength.

10. A wireless power transfer system, comprising:

a base station, wherein the base station comprises:

a transmitter coil;

a power transmitter, wherein the power transmitter is capable of driving the transmitter coil such that a first magnetic field is produced; and

a data transmitter,

a receiver station, wherein the receiver station comprises:

a receiver coil, wherein the receiver coil inductively couples the first magnetic

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field to produce a received power signal; and

a data receiver, wherein the data transmitter drives the transmitter coil to produce a transmitted data signal,

wherein the reciever coil inductively couples the transmitted data signal to produce a received RF data signal, wherein the data receiver receives the received RF data signal and outputs a received data signal.

11. A method of wireless power transfer, comprising:

providing a base station, wherein the base station comprises:

a transmitter coil;

a power transmitter; and

a data receiver,

providing a receiver station, wherein the receiver station comprises:

a receiver coil; and

a data transmitter,

driving the transmitter coil with the power transmitter such that a first magnetic field is produced;

inductively coupling the first magnetic field to the receiver coil to produce a received power signal;

driving the receiver coil with the data transmitter to produce the transmitted data signal;

inductively coupling the transmitted data signal to the transmitter coil to produce a received RF data signal;

receiving the received RF data signal by the data receiver; and

outputting a received data signal by the data receiver.

12. The method according to claim 11, where in the receiver station further comprises an energy harvesting circuit, further comprising receiving the received power signal by the energy harvesting circuit and outputting DC power by the energy harvesting circuit.

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13. The method according to claim 11, wherein the receiver station further comprises a target device, further comprising providing a data input signal from the target device to the data transmitter, wherein the data input signal is used by the data transmitter to produce the data signal.

14. The method according to claim 11, wherein the base station further comprises:

a second data transmitter and the receiver station further comprises

a second data receiver, the method further comprising:

driving the transmitter coil with the second data transmitter to produce a second transmitted data signal; and

inductively coupling the second transmitted data signal to the receiver coil to produce a second received RF data signal.

15. The method according to claim 11, wherein the power transmitter and the data receiver are integrated as a first transceiver.

16. The method according to claim 14, wherein the data transmitter and the second data receiver are integrated as a second transceiver.

17. The method according to claim 14, wherein the second data transmitter is integrated with the power transmitter and the data receiver as the first transceiver.

18. The method according to claim 14, wherein the second data receiver is integrated with the data transmitter and the second data receiver as the second transceiver.

19. The method according to claim 14, wherein the power transmitter and the second data transmitter are capable of simultaneously driving the transmitter coil, wherein the power transmitter drives the transmitter coil at a first wavelength and the second data transmitter drives the transmitter coil at a second wavelength.

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20. A method of wireless power transfer, comprising:

providing a base station, wherein the base station comprises:

a transmitter coil;

a power transmitter; and

a data transmitter,

providing a receiver station, wherein the receiver station comprises:

a receiver coil; and

a data receiver,

driving the transmitter coil with the power transmitter such that a first magnetic field is produced;

inductively coupling the first magnetic field to the receiver coil to produce a received power signal;

driving the transmitter coil with the data transmitter to produce the transmitted data signal;

inductively coupling the transmitted data signal to the receiver coil to produce a received RF data signal;

receiving the received RF data signal by the data receiver; and

outputting a received data signal by the data receiver.

21. A wireless power transfer system, comprising:

a plurality of transmitters;

a corresponding plurality of transmitter coils, wherein each transmitter delivers power to a corresponding transmitter coil, so as to produce a corresponding plurality of magnetic fields, wherein the plurality of transmitter coils are positioned such that corresponding plurality of magnetic fields are substantially coextensive.

22. The system according to claim 21, wherein the plurality of transmitter coils are positioned such that the plurality of magnetic fields are normal to a surface.

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23. The system according to claim 22, further comprising at least one receiver coil, wherein the at least one receiver coil is positionable with respect to the surface such that the at least one receiver coil is substantially parallel with the surface.

24. The system according to claim 22, wherein the plurality of transmitter coils are integrated in a pad, wherein the surface is on the pad.

25. The system according to claim 21, wherein each of the plurality of transmitters can be tuned independently.

26. The system according to claim 21, wherein the plurality of transmitters can be individually turned on and off depending on a needed charging load.

27. The system according to claim 21, wherein the plurality of transmitters drive the plurality of transmitter coils in phase.

28. An electronic device, comprising:

a body;

a receiver coil; and

a connector, wherein the connector moveably connects the receiver coil to the body such that the receiver coil can transition between at least two positions relative to the body, wherein at least one of the at least two positions the receiver coil can receive magnetic fields normal to the receiver coil without the received magnetic fields passing through a substantial portion of the body.

29. The device according to claim 28, wherein the connector allows the receiver coil to slide relative to the body to transition between the at least two positions.

30. The device according to claim 28, wherein the connector allows the receiver coil to rotate relative to the body to transition between the at least two positions.

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31. The device according to claim 28, wherein in at least one other of the at least two positions the receiver coil is adjacent the body such that magnetic fields normal to the receiver coil pass through a substantial portion of the body.

32. The device according to claim 31, wherein the connector comprises a hinge locateded at an end of the body, wherein the hinge allows the receiver coil to rotate from a first position adjacent the body to a second position that is an approximately 180° rotation of the receive coil with to the hinge.

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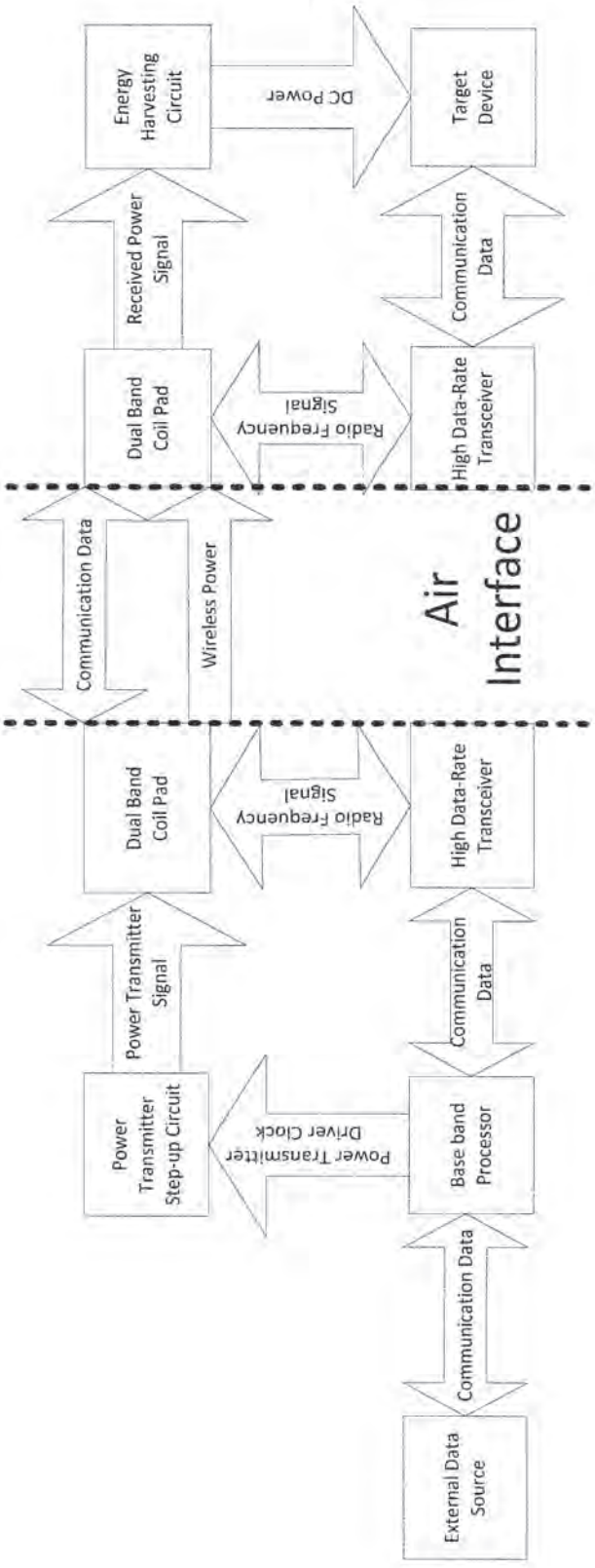

Energy Harvesting Circuit
DC Power
Target Device
Received Power Signal
Communication Data
Dual Band Coil Pad
Radio Frequency Signal
High Data-Rate Transceiver
Communication Data
Wireless Power
Air Interface
Dual Band Coil Pad
Radio Frequency Signal
High Data-Rate Transceiver
Power Transmitter Signal
Communication Data
Power Transmitter Step-up Circuit
Power Transmitter Driver Clock
Base band Processor
Communication Data
External Data Source

FIG. 1

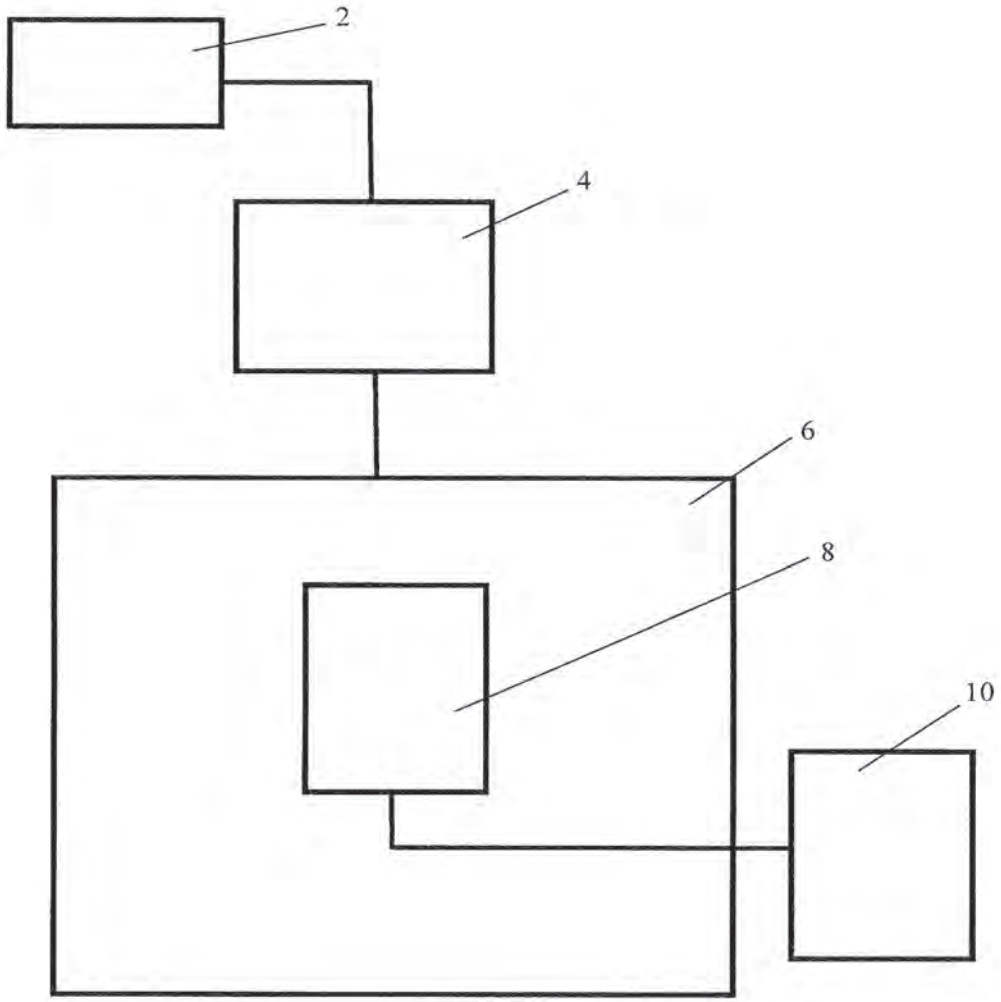


FIG. 2


Input from
multiple
transmitters

FIG. 3

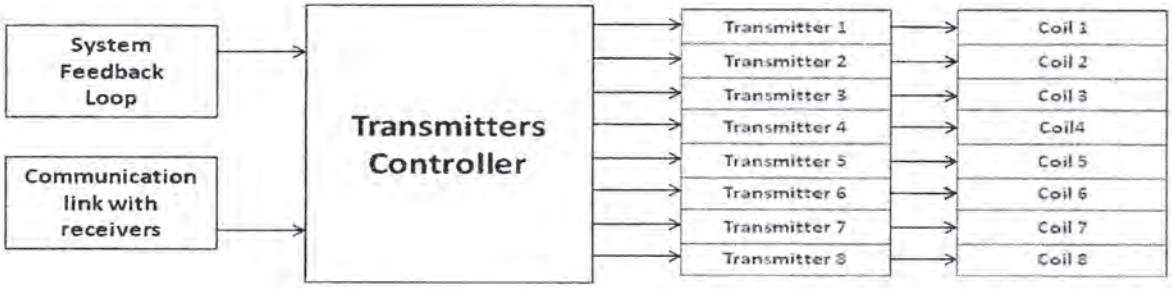

System
Feedback
Loop
Communication
link with
receivers
Transmitters
Controller
Transmitter 1
Transmitter 2
Transmitter 3
Transmitter 4
Transmitter 5
Transmitter 6
Transmitter 7
Transmitter 8
Coil 1
Coil 2
Coil 3
Coil4
Coil 5
Coil 6
Coil 7
Coil 8

FIG. 4

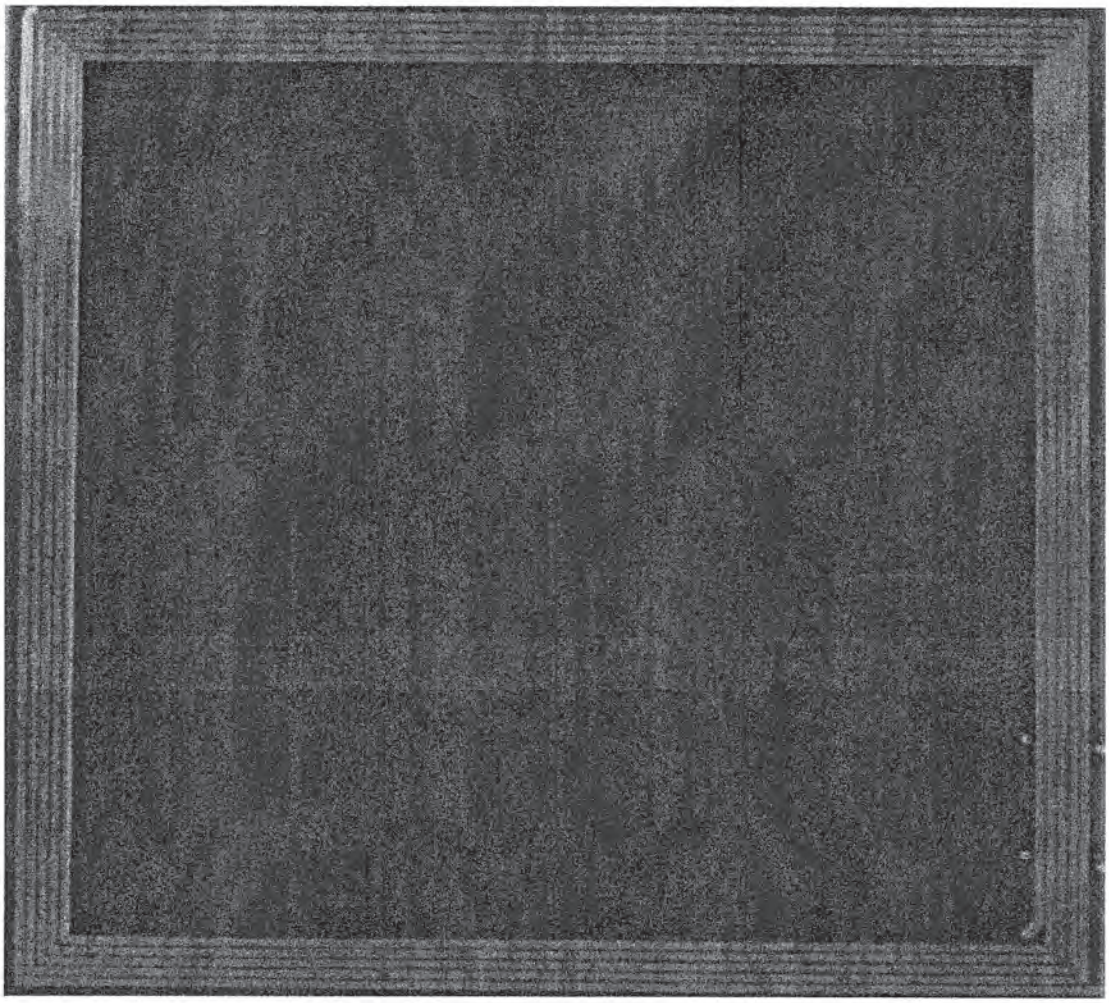


FIG. 5A

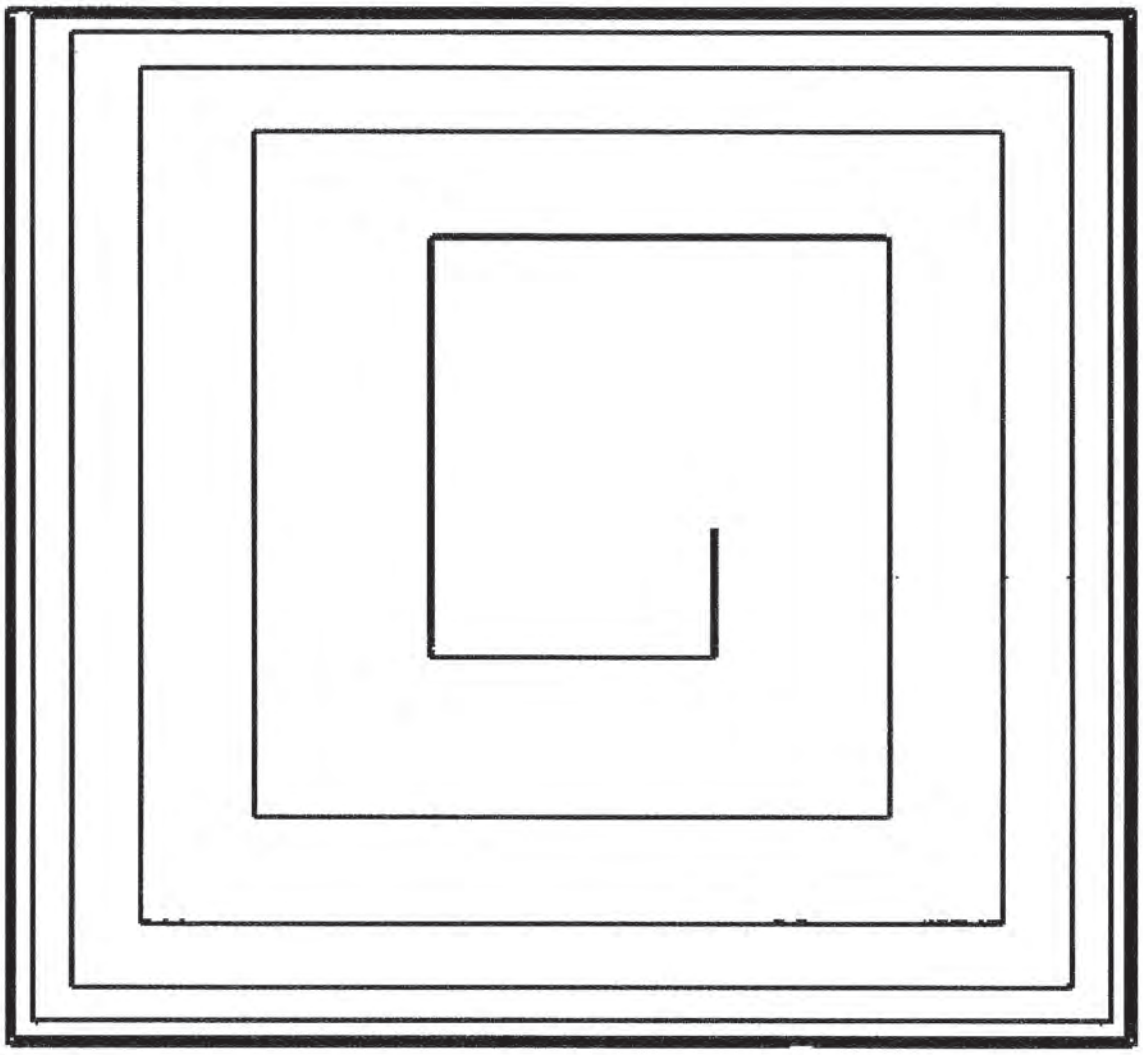


FIG. 5B

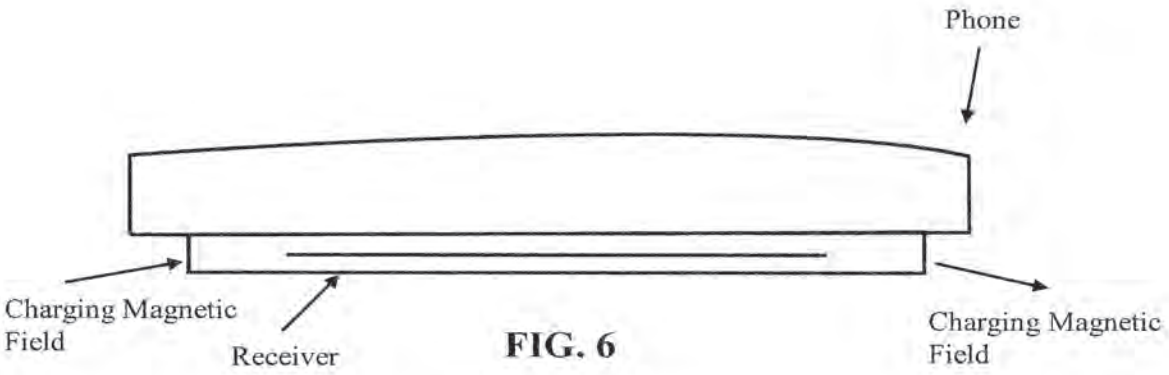


FIG. 6

(Prior Art)

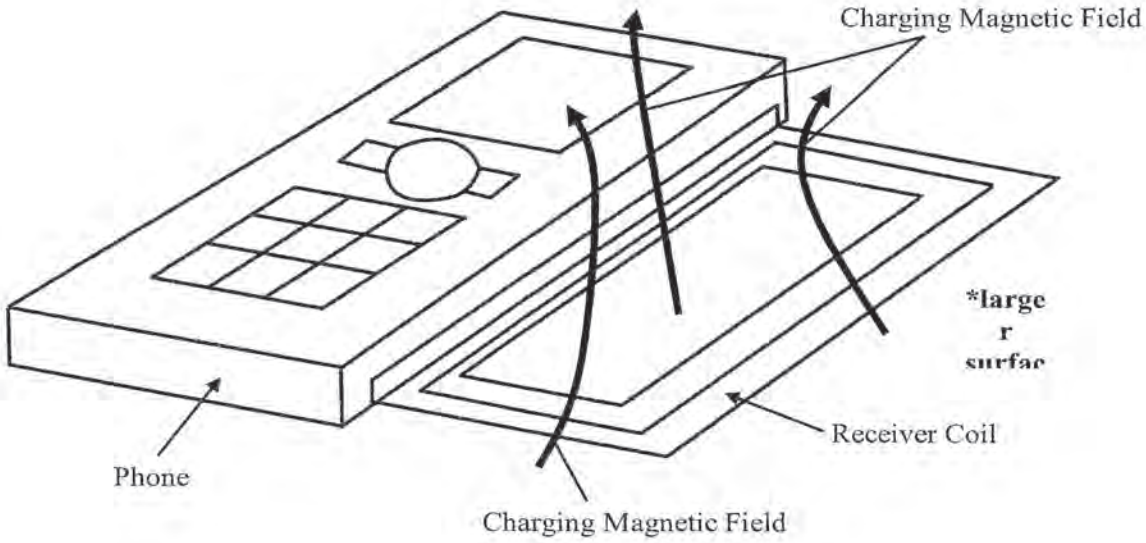


FIG. 7

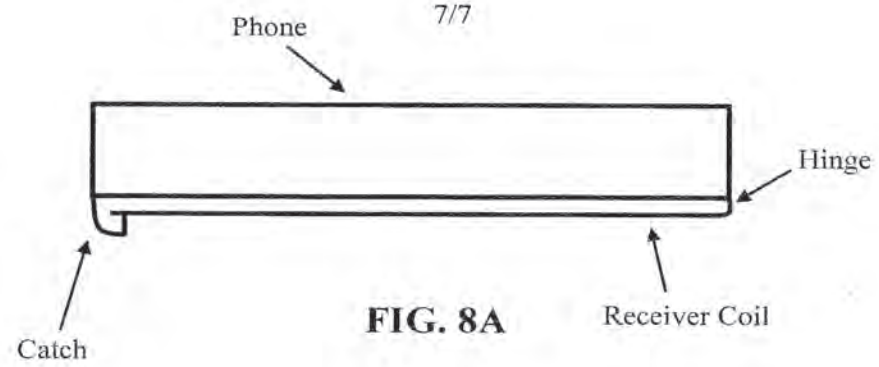


FIG. 8A

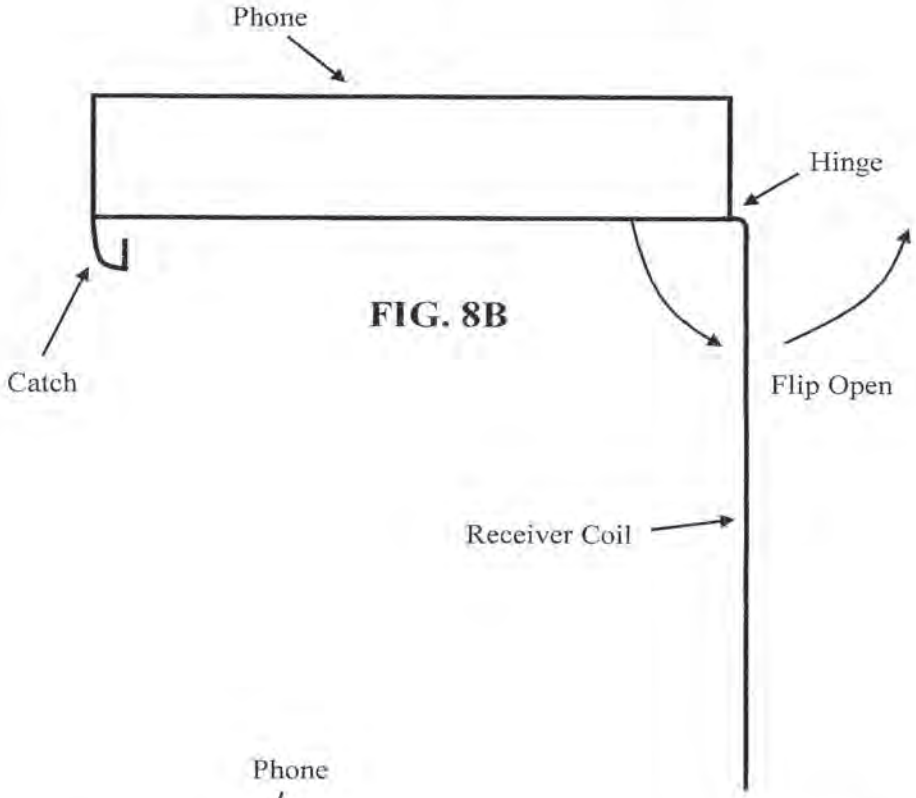


FIG. 8B

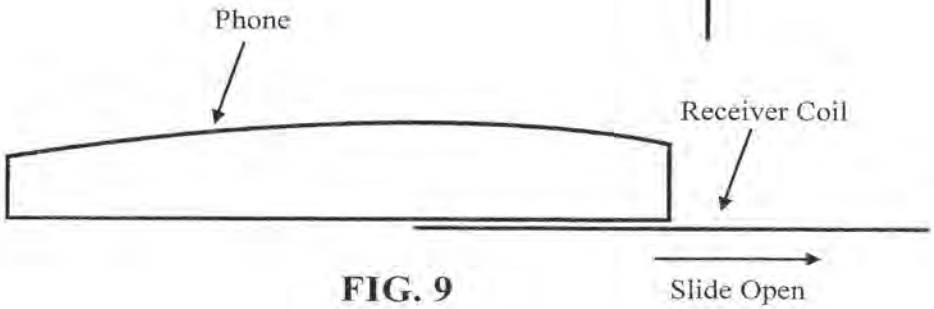


FIG. 9

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(74) Agents: **PARKER, James, S.** et al.; Saliwanchik, Lloyd, Saliwanchik, P.O. Box 142950, Gainesville, FL 32614-2950 (US).

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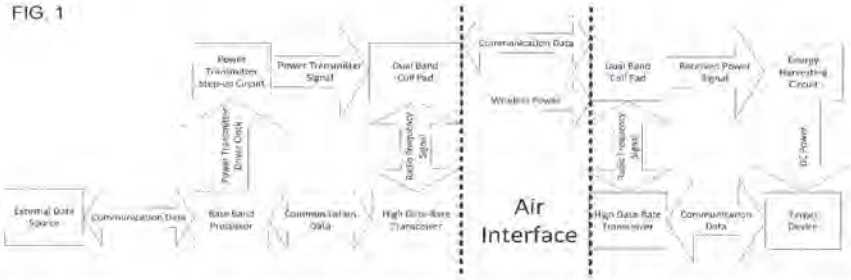
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(54) Title: PLANAR NEAR-FIELD WIRELESS POWER CHARGER AND HIGH-SPEED DATA COMMUNICATION PLATFORM

FIG. 1



(57) Abstract: In one aspect, the present disclosure describes a planar near-field wireless power charging system that is capable of charging small portable devices. Embodiments can incorporate coils for generating time-varying magnetic fields into a pad. In an exemplary embodiment, the charging system incorporates a charging pad that can act as an electrically small coil antenna for the low frequencies and long wavelengths, used for charging, and long wavelengths, and which can also be used for communication purposes by treating it as an electrically large antenna at higher frequencies, and shorter wavelengths, used for communications. In an exemplary embodiment, the system uses multiple lower powered transmitters, where each transmitter feeds a separate coil. The separate coils can be stacked so that the magnetic fields are substantially coextensive. The simultaneous driving of the multiple coils by the multiple transmitters can achieve similar power delivery as a single high powered transmitter. Multiple stacked sets of coils can be integrated into a pad such that each stacked set of coils provides vertical magnetic fields over a section of the pad. Embodiments of the subject invention can be designed to couple energy to the receiver coil of the device via magnetic fields that have a substantial vertical component. An embodiment of the present disclosure describes a receiver coil attached to a portable electronic device with a mechanical connection that allows the receiver coil to be positioned such that the vertical fields do not need to pass through a substantial portion of the device to pass through the receiver coil during charging and can allow the receiver coil to be conveniently positioned adjacent the device when not changing.

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A. CLASSIFICATION OF SUBJECT MATTER

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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
KOREAN UTILITY MODELS AND APPLICATIONS FOR UTILITY MODELS SINCE 1975

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKIPASS, DELPHION, ESPACENET & Keywords : wireless power transfer, data transmission, and similar terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KR 2006-0080320 A (BIZMODELINE CO., LTD.) 10.07.2006 See the abstract, page 4 line 17 - page 8 line 5, claims 1,2,5,6,9-11 and 16, figures 1-3	1-32
A	US 6960968 B2 (ODENDAAL WILLEM G. et al.) 01.11.2005 See the abstract, column 6 lines 27-67, figures 11 and 12	1-32

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 FEBRUARY 2009 (26.02.2009)	**26 FEBRUARY 2009 (26.02.2009)**

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Korean Intellectual Property Office
Government Complex-Daejeon, 139 Seonsa-ro, Seo-gu, Daejeon 302-701, Republic of Korea
Facsimile No. 82-42-472-7140

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JEONG Heon Ju
Telephone No. 82-42-481-8356

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2008/075429

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
KR 2006-0080320 A	10.07.2006	NONE	
US 6960968 B2	01.11.2005	AU 2003-239738 A1	19.01.2004
		CN 1663118 A	31.08.2005
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		WO 2004-004118 A1	08.01.2004

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Published:
— *without international search report and to be republished upon receipt of that report*

(54) Title: METHOD AND APPARATUS FOR HIGH EFFICIENCY SCALABLE NEAR-FIELD WIRELESS POWER TRANSFER

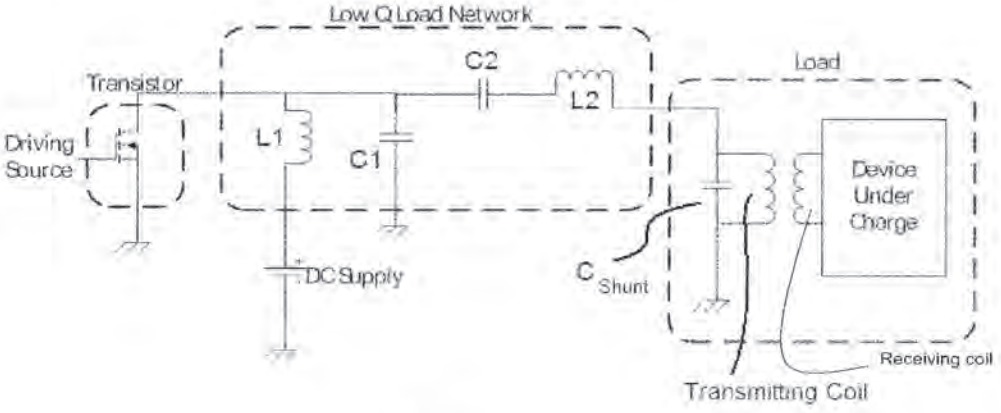


FIG. 1

(57) Abstract: Wireless power transfer systems are provided. A wireless power transmitter can include a transistor block providing a switching mode amplifier, and a low-Q output network including a tunable supply voltage. The transistor block can be scalable. Multiple scalable transistor blocks can be incorporated in a power transfer system using a single tunable supply voltage and transmitting coil. The tunable supply voltage can be controlled by an adaptive power supply tuning circuit to accommodate for a range of loading conditions. Embodiments of the subject invention are capable of achieving high efficiency across a wide range of output power levels.

WO 2009/070730 A2

DESCRIPTION

METHOD AND APPARATUS FOR HIGH EFFICIENCY SCALABLE NEAR-FIELD WIRELESS POWER TRANSFER

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 60/990,377, filed November 27, 2007, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

Portable electronic devices such as laptop computers, LCD digital photo frames, mobile phones, and mp3 players require power to operate. Often, these devices use rechargeable batteries to provide power. The batteries are typically recharged by plugging a charger into the portable device or by removing the battery from the portable device and separately recharging the battery using a wired charger.

The cables that once restricted electronic devices are gradually being rendered unnecessary by wireless communication technology, and as the circuits that constitute the electronic devices shrink, only the power cords and batteries continue to restrict the portability of mobile electronic devices.

Current trends are leading towards going completely wireless. This means that portable devices can remain portable and can avoid having to 'plug-in' for power charging. Electro-magnetic inductive charging uses a coil to create an electromagnetic field across a charging station surface. The device then converts power from the electromagnetic field back into usable electricity, which is put to work charging the battery. Two coils are brought close to each other and when current is passed through one, the generated magnetic flux causes electromotive force to be generated in the other.

For charging of portable electronic devices and/or powering the portable electronic devices at close proximity, radio frequency charging appears to be a viable option. Recent improvements in efficiency have made it possible to consider radio frequency charging technology for commercial applications. However, there still exists a need in the art for a high efficiency low cost wireless power charging platform and components.

BRIEF SUMMARY

Embodiments of the present invention relate to a method and apparatus for wireless power transfer. Wireless power transfer systems in accordance with embodiments of the invention are capable of transmitting power to devices under charge through radio frequency charging. According to an embodiment, the wireless power transfer system of the present invention includes a switching mode amplifier and a low-Q output network. Embodiments of the present invention can follow class E amplifier designs while focusing on providing a low Q load.

In one embodiment of the present invention, a wireless transmitter includes a transistor block, a supply voltage block, and a transmitting coil block. The transistor block can include a transistor, load network capacitor, and a load network inductor. The transistor block can be scalable. The supply voltage block can include an RF choke inductor and a DC supply voltage. The supply voltage can provide tunable output power. The transmitting coil block can include a second load network capacitor, a transmitting coil, and a coil shunt capacitor.

In a further embodiment, multiple transistor blocks sharing the same load current can be used. Advantageously, the multiple transistor blocks can use a single DC supply voltage and transmitting coil block. Additional RF choke inductors can be added for each transistor block. The multiple transistor blocks can be incorporated to increase output power.

In yet another embodiment, the DC supply voltage can be tuned to achieve high efficiency for a wide range of load conditions through adaptive power supply tuning. This can be accomplished though a feedback circuit involving a current monitor network, a voltage monitor network, and a receiver for receiving charging data of a device under charge.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 shows a planar wireless power transfer system according to an embodiment of the present invention.

Figure 2 shows ideal voltage and current waveforms to prevent simultaneous high voltage and high current in a transistor of a planar wireless power transfer system according to an embodiment of the present invention.

Figure 3 shows a schematic of a transmitter according to an embodiment of the present invention with three scalable transistor blocks.

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Figure 4 shows a power delivery and efficiency plot of a two-scalable transistor block transmitter according to an embodiment of the present invention at 24 V, 36 V and 48 V supply voltage.

Figure 5 shows a power delivery and efficiency plot of a two-scalable transistor block transmitter according to an embodiment of the present invention with adaptive power control.

Figure 6A shows a system block diagram of a planar wireless power transfer system using adaptive power supply tuning according to an embodiment of the present invention.

Figure 6B shows a planar wireless power transfer system according to an embodiment of the present invention including current and voltage monitoring.

Figures 7A and 7B show measurement results with different loads according to an embodiment of the present invention, where Figure 7A shows efficiency vs. power delivered to a load, and Figure 7B shows power supply voltage vs. power delivered to a load.

Figure 8 shows the efficiency at different power levels at a fixed power supply voltage of 48 V according to an embodiment of the present invention with no adaptive power supply tuning.

DETAILED DISCLOSURE

Embodiments of the present invention provide a method and apparatus for wireless power transfer. Specific embodiments of the present invention utilize radio frequency (RF) charging techniques. According to an embodiment of the present invention, a wireless power transmitter includes a transistor block providing a switching mode amplifier, and a low-Q output network including a tunable supply voltage. The combination of a switching mode amplifier and the low-Q output network provides high efficiency for power charging.

Potential uses for the subject invention include, but are not limited to, high efficiency and low cost wireless power charging platform for all portable devices such as laptop computers, LCD digital photo frames, mobile phones, mp3 players. With its high efficiency, energy loss via heating could be reduced. Further, embodiments of the subject invention can be implemented at home, in airports, and in hotel rooms. This would bring great convenience to general consumers, especially frequent travelers, as it would provide a universally charging interface and eliminate the need to bring multiple chargers. In addition, the scalable transmitter and power control design enables the transmitter system to be more flexible and adaptive to wider range of environmental situations while maintaining high energy efficiency.

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Further, impedance tuning design enables the transmitter system to be more flexible and adaptive to wider range of loading conditions while maintaining high efficiency.

Figure 1 shows a schematic for a planar wireless power transfer system according to an embodiment of the present invention. Referring to Figure 1, a transmitter of the power transfer system includes a transistor block and a low Q load network. A transmitting coil with shunt capacitor is connected to the low Q load network to transmit the signal from the power transfer system to a device under charge. The device under charge should include a receiving coil for receiving the signal transmitted by the transmitter. Advantageously, the low Q network is insensitive to a change in load. In particular, the transmitter is capable of providing a range of frequencies for the transmitted signal without causing a problem with respect to load matching.

The transistor block can receive a driving power source as input. For example, a wall outlet providing ac power can provide the driving power to the transistor block. In an embodiment, the transistor block can receive the input at the gate of a transistor. A variety of transistors can be utilized in the transistor block in accordance with embodiments of the invention. In a specific embodiment, the transistor can be an n-channel metal oxide semiconductor field effect transistor (NMOSFET). In another specific embodiment, an NPN BJT transistor can be used. The transistor block can amplify an input signal and operate as an on/off switch. The output network shapes the voltage and current waveforms to prevent a simultaneous high voltage and high current in the transistor. Figure 2 shows the ideal voltage and current waveforms to prevent simultaneous high voltage and high current in the transistor. This effect minimizes power dissipation, especially during the switching transitions. Unlike a conventional amplifier using a high-Q output network to reduce harmonics in wireless communications systems, embodiments of the present invention can use a low-Q output network to provide successful operation regardless of load condition. In a specific embodiment, the low-Q output network can also be dynamic.

According to embodiments of the present invention, a maximum value for Q can be about 10. In one embodiment, Q can be selected to be less than or equal to 10. In other embodiments, Q can be selected to be less than or equal to 8 or less than or equal to 5. In further embodiments, Q can be a range of 10-20, 2-4, or 1.8-5.

In one embodiment a single transistor is used for the transistor block. The single-transistor amplifier can be used to significantly reduce the circuit complexity. Although a

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single transistor is illustrated in the embodiment shown in Figure 1, multiple transistors can also be used.

Embodiments of the subject invention may ensure that a low cost amplifier is able to operate at a wide dynamic range of frequency and load impedance. This is important because the load condition of the planar wireless power transfer system varies over a huge range depending on the device or devices it is powering/charging as well as the charging stage. Embodiments of the present invention have very simple hardware architecture and are able to work for a wide dynamic range of load impedance variation.

Embodiments of the subject invention provide a planar wireless power transfer system that is capable of charging portable devices as well as powering them at close proximity attaining 78% efficiency while delivering 68 W of power to an ideal load. A peak power of 132 W has been achieved using a planar wireless power transfer system according to an embodiment of the present invention. Another specific embodiment has achieved a peak power of 300W. Further, an embodiment can incorporate litz wire and achieve an efficiency of about 80%. Current existing products have not been able to achieve this level of efficiency and power output. The power capability with high efficiency makes the wireless power transmission system of the present invention suitable for charging laptop computers wirelessly.

According to an embodiment of the present invention, as illustrated in Figure 1, the transmitter is designed in a hybrid class-E parallel amplifier topology.

The class E amplifier design equations provide:

$$P = 0.576801\left(\frac{V_{CC}^{\ 2}}{R}\right)\left(1.001245 - \frac{0.451759}{Q_L} - \frac{0.402444}{Q_L^{\ 2}}\right)$$

$$R = 0.576801\left(\frac{V_{CC}^{\ 2}}{P}\right)\left(1.001245 - \frac{0.451759}{Q_L} - \frac{0.402444}{Q_L^{\ 2}}\right)$$

$$C1 = \frac{1}{34.2219fR}\left(0.99866 + \frac{0.91424}{Q_L} - \frac{1.03175}{Q_L^{\ 2}}\right) + \frac{0.6}{(2\pi f)^2 L1}$$

$$C2 = \frac{1}{2\pi fR}\left(\frac{1}{Q_L - 0.104823}\right)\left(1.00121 + \frac{1.01468}{Q_L - 1.7879}\right) + \frac{0.2}{(2\pi f)^2 L1}$$

$$L2 = \frac{Q_L R}{2\pi f}$$

$$Q_L = \frac{2\pi fL2}{R},$$

where P is the power delivered to the load of resistance R, R is the load resistance (related to the transmitting coil and shunt capacitor), V_{CC} is the supply voltage, Q_L is the load quality factor, and f is the operating frequency.

Assuming that the amplifier is ideal,

$$P = V_{CC} \times I_{DD}$$

$$PeakV_{DS} = \frac{3.56 \times V_{CC}}{SF}$$

$$PeakI_{DS} = \frac{2.86 \times I_{DD}}{SF}$$

$$\frac{t_{f/r}}{T} = \frac{\sqrt{12\left(\frac{P_{Dissipation\ of\ f}}{P}\right)}}{2\pi\left(1 + \frac{0.82}{Q_L}\right)},$$

where I_{DD} is the supply current, V_{CC} is the supply voltage, Q_L is the load quality factor, SF is the safety factor for the off nominal load condition range (typical value 0.75), $\frac{P_{Dissipation\ of\ f}}{P}$ is the fraction of turn off power dissipation (typically < 1%), T is the period of the operating frequency, $PeakV_{DS}$ is the peak drain to source voltage (the rating of the transistor), $PeakI_{DS}$ is the peak drain to source current (the rating of the transistor), and $t_{f/r}$ is the fall time and rise time of the transistor (typically of similar value or order of magnitude).

Depending on the requirements, the transmitter can be designed for various maximum power output. In addition, by varying the supply voltage, the transmitter can tune its instantaneous power output to maintain its high efficiency while powering smaller devices such as PDA or cellular phone.

In a further embodiment of the present invention, the transistor block and low Q network of the power transfer system can be modified to achieve higher power output. In particular, the transistor block and low Q network can be provided as a scalable transistor block, tunable supply voltage block, and coil block, where the scalable transistor block

ock and C1 and L2 from the low Q load

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network, the tunable supply voltage block incorporates the DC supply and L1 from the low Q load network, and the coil block incorporates C2 from the low Q load network, the coil shunt capacitor, and the transmitting coil. Although the coil block is described as including the capacitor C2 from the low Q load network, the capacitor C2 can be considered part of the load network. The transmitting coil block, not including a receiver coil for a device under charge, can be viewed as part of the load network of the transmitter.

According to embodiments of the present invention, the power supplied from the transmitter can be increased by increasing the number of scalable transistor blocks while lower cost can be achieved by decreasing the number of scalable transistor blocks. Advantageously, a single tunable supply voltage block and coil block can be used for multiple scalable transistor blocks. For example, 2-5 scalable transistor blocks can be used, sharing the load current, with a single tunable supply voltage, load network capacitor (C2), transmitting coil and coil shunt capacitor.

Figure 3 shows a schematic of a transmitter with three scalable transistor blocks according to an embodiment of the present invention. Each scalable transistor block includes a transistor, a load capacitor C1, and a load inductor L1. The transistor can be a NMOSFET. In one embodiment the NMOSFET can be an active device IRFP264NPbF. The load capacitor C1 can have a value of, for example, 3.3 nF, and the load inductor can have a value of, for example, 100 μH. A single variable DC supply can be used for tunable output power. The tunable supply voltage block includes the DC supply and an inductor for each scalable transistor block acting as an RF choke. The inductor acting as an RF choke can have a value of, for example, 500 μH.

A single coil block is connected to the three scalable transistor blocks. The coil block includes a transmitting coil, a coil shunt capacitor, and a load network capacitor C2. The load network capacitor C2 and the coils shunt capacitor can each have a value of, for example, 100 nF. In the embodiment shown in Figure 3, a buffer and input clock oscillator can be included as input to the scalable transistor blocks.

Although each scalable transistor block illustrated in Figure 3 is indicated as having an RF choke inductor, embodiments of the present invention are not limited thereto. For example, a single RF choke inductor can be shared by the scalable transistor blocks to reduce cost.

As indicated by Figure 3, the DC supply can provide tunable output power. The

can be affected by the voltage of the DC

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supply voltage. Figure 4 shows a power delivery and efficiency plot of a two scalable block transmitter at 24 V, 36 V and 48 V supply voltage. In particular, in Figure 4, the lower curve shows the 48V supply voltage results, the middle curve shows the 36V supply voltage results, and the upper left curve shows the 24V supply voltage results. As illustrated by the plots of Figure 4, an efficiency of about 78% is possible over a range of supply voltage. Figure 5 shows a power delivery and efficiency plot of a two scalable block transmitter according to an embodiment of the present invention with tunable power control. As illustrated by the plot shown in Figure 5, a high efficiency is possible over a large range of power.

This system has simple hardware architecture and each scalable block is a duplicate of each other that maintains the architecture of the transmitter. In addition, the power control enables high efficiency across a wide band power level. Therefore, it is able to achieve low cost for future custom design to meet various needs. Embodiments can also incorporate blocks that have different parameters, and that can be utilized together in various combinations. In this way, power delivery can be unevenly distributed.

Further embodiments of the present invention can include adaptive power supply tuning. The adaptive power supply tuning can be performed on a modified switching-mode amplifier with low-Q output network. According to one embodiment of the present invention, the power supply voltage of a wireless transmitter is tuned based on the feedback from a receiver load, which is the device under charge, to optimize the efficiency. Referring back to Figures 1 and 3, since the power supply (labeled as DC supply) has a direct path to the transmitting coil via the switching mode amplifier, the input impedance of the transmitter seen by the power supply is related to the impedance of the transmitting coil. The impedance of the transmitting coil is related to the coupling coefficient of the coils as well as the receiver load impedance. The receiver load impedance varies with the input voltage to the receiver load's voltage regulator. By adjusting the load impedance, by tuning the power supply voltage, the load impedance seen by the transmitter can be closer to an optimal value. Accordingly, varying the DC supply in the embodiments shown in Figures 1 and 3, the voltage at the input of the receiver's voltage regulator will change, so as to change the impedance looking into the input port of the voltage regulator. According to embodiments of the present invention incorporating an adaptive power supply, the tuning system measures the voltage and current delivered to the receiver load and attempts to tune its impedance via varying the power supply voltage. Therefore, by tuning the power supply voltage, power

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control as well as impedance tuning can be achieved. The adaptive tuning method can be implemented using a low cost microprocessor as well as a programmable switching regulator.

A block diagram of a planar wireless power transfer system using adaptive power supply tuning according to an embodiment of the present invention is shown in Figure 6A. Referring to Figure 6A, a wireless charger according to any embodiment of the present invention can be connected to an adaptive power control circuit. The adaptive power control circuit can include a programmable regulator and feedback network to set programmable regulator output voltage; a voltage monitor network and current monitor network that each receive the output voltage as input; and a microprocessor that receives input from the current monitor network and the voltage monitor network, and provides feedback to the feedback network. The microprocessor can also receive charging data from a device under charge. Examples of charging data that can be provided from the device under charge includes, but is not limited to, charge status, voltage provided to receiver, and/or current into the receiver. The device under charge can provide receiver charging data to a wireless transmitter. In other embodiments, other types of data links than wireless can be used. The charging data can then be received by a receiver of the adaptive power supply tuning circuit and provided to the microprocessor. The current monitor network can provide the power supply to the wireless charger. As examples, the output of the current monitor network in Figure 6A can be the DC supply of Figure 1 or the DC supply variable of Figure 3.

In an embodiment, tuning of the transmitter can be accomplished using voltage and current monitoring. For example, as illustrated in Figure 6B, the voltage across the drain of the transistor and the voltage and current across the transmitting coil can be monitored. These monitored values can be used as input in a feedback system for tuning control. In another specific embodiment, the supply DC current and the voltage across the transmitting coil can be monitored and provided for tuning of the power supply, such as a DC power supply. The power supply can then be tuned by, for example, inputting the monitored data into a lookup table created based on a determination of desired efficiency and the output of the power supply tuned accordingly.

Figures 7A and 7B show measurement results for the embodiment of Figure 6A with different loads. Referring to Figure 7A, it is possible to maintain efficiency at over 75% in all conditions. Figure 7B shows power supply voltage vs. power delivered to the load. Power supply voltage is tuned to achieve high efficiency at each load condition.

As a comparison, Figure 8 shows the efficiency at different power levels when no adaptive power supply tuning is included. Here the power supply voltage is fixed at 48 V.

Previous planar wireless power transfer systems tend to suffer low efficiency at low output power, even though the efficiency at higher output power is higher. In contrast, embodiments of the present invention are capable of maintaining a high efficiency of over 75% across a wide range of output power levels. Current existing products cannot achieve this level of efficiency and power output. The adaptive power supply tuning according to embodiments of the present invention enables high efficiency across a wide range of output power levels. Therefore, embodiments of the present invention are able to achieve low cost for future custom designs to meet various needs.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

CLAIMS

What is claimed is:

1. A wireless power transfer system, comprising:

a transistor, wherein the transistor has an on state and an off state;

an output network, wherein the output network is low Q; and

a transmitting coil block, wherein the transmitting coil block is coupled to the output network, wherein the transmitting coil block comprises a transmitting coil,

wherein when the transistor is in the on state the transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the transistor is in the on state the transistor has a low voltage and high current across the transistor, wherein when the transistor is in the off state the transistor has a low current and high voltage across the transistor.

2. The system according to claim 1, wherein Q is less than 20.

3. The system according to claim 1, wherein Q is less than 10.

4. The system according to claim 1, wherein Q is less than 8.

5. The system according to claim 1, wherein Q is in the range of 10-20.

6. The system according to claim 1, wherein Q is in the range of 1.8-5.

7. The system according to claim 1, wherein Q is in the range of 2-4.

8. The system according to claim 1, further comprising:

a receiver coil, wherein the receiving coil is inductively coupled to the transmitting coil, wherein the receiver coil is capable of delivering power to a load.

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9. The system according to claim 1, further comprising: a first choke inductor coupled between the drain of the transistor and a power supply, wherein the output network comprises:

a first load network capacitor coupled between a drain of the transistor and ground;

a first load network inductor, wherein the first load inductor is in series between the drain of the transistor and the transmitting coil block.

10. The system according to claim 9, wherein the power supply is a DC power supply.

11. The system according to claim 9, wherein the transmitting coil block comprises a series capacitor in series with the transmitting coil.

12. The system according to claim 11, wherein the transmitting block comprises a shunt capacitor in parallel with the transmitting coil.

13. The system according to claim 9, wherein the output network comprises a series capacitor in series with the first load network inductor.

14. The system according to claim 10, wherein the DC power supply is a variable DC supply.

15. The system according to claim 14, further comprising a tuning circuit capable of receiving charging data from a device under charge for adaptive power supply tuning of the variable DC supply.

16. The system according to claim 9, wherein the output network further comprises:

a second transistor, wherein the second transistor has a second on state and a second off state;

a second load network capacitor coupled between a drain of the second transistor and ground; and

a second load network inductor, wherein the second load network inductor is in series between the drain of the second transistor and the transmitting coil block

wherein when the second transistor is in the second on state the second transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the second transistor is in the second on state the second transistor has a low voltage and high current across the second transistor, wherein when the second transistor is in the second off state the second transistor has a low current and high voltage across the second transistor.

17. The system according to claim 16, further comprising:

a second choke inductor coupled between the drain of the second transistor and the DC supply.

18. The system according to claim 9, wherein the output network further comprises:

at least one additional transistor, wherein the at least one additional transistor has an at least one additional on state and an at least one additional off state;

at least one additional load network capacitor coupled between a drain of a corresponding at least one additional transistor and ground; and

at least one additional load network inductor, wherein the at least one additional load network is in a series between the drain of the at least one additional transistor and the transmitting coil block,

wherein when the at least one additional transistor is in the at least one additional on state the at least one additional transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the at least one additional transistor is in the at least one additional on state the at least one additional transistor has a low voltage and high current across the at least one additional transistor, wherein when the at least one additional transistor is in the at least one additional off state, the at least one additional transistor has a low current and high voltage across the at least one additional transistor.

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19. The system according to claim 18, further comprising:

at least one additional choke inductor coupled between the drain of the corresponding at least one additional transistor and the DC supply.

20. The system according to claim 1, wherein the transmitting coil block further comprises:

a coil shunt capacitor coupled in parallel with the transmitting coil.

21. The system according to claim 1, further comprising a tuning circuit capable of receiving charging data from a device under charge for adaptive power supply tuning.

22. The system according to claim 1, further comprising a tuning circuit capable of receiving voltage and current data from across the transmitting coil and voltage data from across the transistor as input for adaptive power supply tuning.

23. The system according to claim 9, further comprising a tuning circuit capable of receiving output current of the power supply and voltage across the transmitting coil for adaptive supply tuning.

24. The system according to claim 1, further comprising:

a driving source coupled to a gate of the transistor.

25. The system according to claim 24, wherein the driving source is an ac power source.

26. A method for wireless power transfer, comprising:

providing a transistor, wherein the transistor has an on state and an off state;

providing an output network, wherein the output network is low Q;

providing a transmitting coil block, wherein the transmitting coil block is coupled to the output network, wherein the transmitting coil block comprises a transmitting coil; and

driving a gate of the transistor with a driving source,

wherein when the transistor is in the on state the transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the transistor is in the on state the transistor has a low voltage and high current across the transistor, wherein when the transistor is in the off state the transistor has a low current and high voltage across the transistor.

27. The method according to claim 26, wherein Q is less than 20.

28. The method according to claim 26, wherein Q is less than 10.

29. The method according to claim 26, wherein Q is less than 8.

30. The method according to claim 26, wherein Q is in the range of 10-20.

31. The method according to claim 26, wherein Q is in the range of 1.8-5.

32. The method according to claim 26, wherein Q is in the range of 2-4.

33. The method according to claim 26, further comprising:

providing a receiver coil, wherein the receiving coil is inductively coupled to the transmitting coil, wherein the receiver coil is capable of delivering power to a load.

34. The method according to claim 26, further comprising: providing a first choke inductor coupled between the drain of the transistor and a power supply, wherein the output network comprises:

a first load network capacitor coupled between a drain of the transistor and ground;

a first load network inductor, wherein the first load inductor is in series between the drain of the transistor and the transmitting coil block.

35. The method according to claim 34, wherein the power supply is a DC power supply.

36. The method according to claim 34, wherein the transmitting coil block comprises a series capacitor in series with the transmitting coil.

37. The method according to claim 36, wherein the transmitting block comprises a shunt capacitor in parallel with the transmitting coil.

38. The method according to claim 34, wherein the output network comprises a series capacitor in series with the first load network inductor.

39. The method according to claim 35, wherein the DC power supply is a variable DC supply.

40. The method according to claim 39, further comprising providing a tuning circuit capable of receiving charging data from a device under charge for adaptive power supply tuning of the variable DC supply; and

tuning the variable DC supply base on the received charging data.

41. The method according to claim 34, wherein the output network further comprises:

providing a second transistor, wherein the second transistor has a second on state and a second off state;

providing a second load network capacitor coupled between a drain of the second transistor and ground;

providing a second load network inductor, wherein the second load network inductor is in series between the drain of the second transistor and the transmitting coil block; and

driving a second gate of the second transistor with the driving source,

wherein when the second transistor is in the second on state the second transistor supplies current to the output network and the output network drives the transmitting coil. wherein when the second transistor is in the second on state the second transistor has a low voltage and high current across the second transistor, wherein when the second transistor is in the second off state the second transistor has a low current and high voltage across the second transistor.

42. The method according to claim 41, further comprising:

providing a second choke inductor coupled between the drain of the second transistor and the DC supply.

43. The method according to claim 34, wherein the output network further comprises:

providing at least one additional transistor, wherein the at least one additional transistor has an at least one additional on state and an at least one additional off state;

providing at least one additional load network capacitor coupled between a drain of a corresponding at least one additional transistor and ground;

providing at least one additional load network inductor, wherein the at least one additional load network is in a series between the drain of the at least one additional transistor and the transmitting coil block; and

driving the at least one additional gate of the at least one additional transistor with the driving source,

wherein when the at least one additional transistor is in the at least one additional on state the at least one additional transistor supplies current to the output network and the output network drives the transmitting coil, wherein when the at least one additional transistor is in the at least one additional on state the at least one additional transistor has a low voltage and high current across the at least one additional transistor, wherein when the at least one additional transistor is in the at least one additional off state, the at least one additional transistor has a low current and high voltage across the at least one additional transistor.

44. The method according to claim 43, further comprising:

providing at least one additional choke inductor coupled between the drain of the corresponding at least one additional transistor and the DC supply.

45. The method according to claim 26, wherein the transmitting coil block further comprises:

a coil shunt capacitor coupled in parallel with the transmitting coil.

46. The method according to claim 26, further comprising providing a tuning circuit capable of receiving charging data from a device under charge for adaptive power supply tuning; and

tuning the power supply based on the received charging data.

47. The method according to claim 26, further comprising providing a tuning circuit capable of receiving voltage and current data from across the transmitting coil and voltage data from across the transistor as input for adaptive power supply tuning; and

tuning the power supply based on the voltage and current data from across the transmitting coil and voltage data from across the transistor.

48. The method according to claim 34, further comprising providing a tuning circuit capable of receiving output current of the power supply and voltage across the transmitting coil for adaptive supply tuning; and

tuning the power supply based on the output current of the power supply and voltage across the transmitting coil.

49. The method according to claim 26, wherein the driving source is an ac power source.

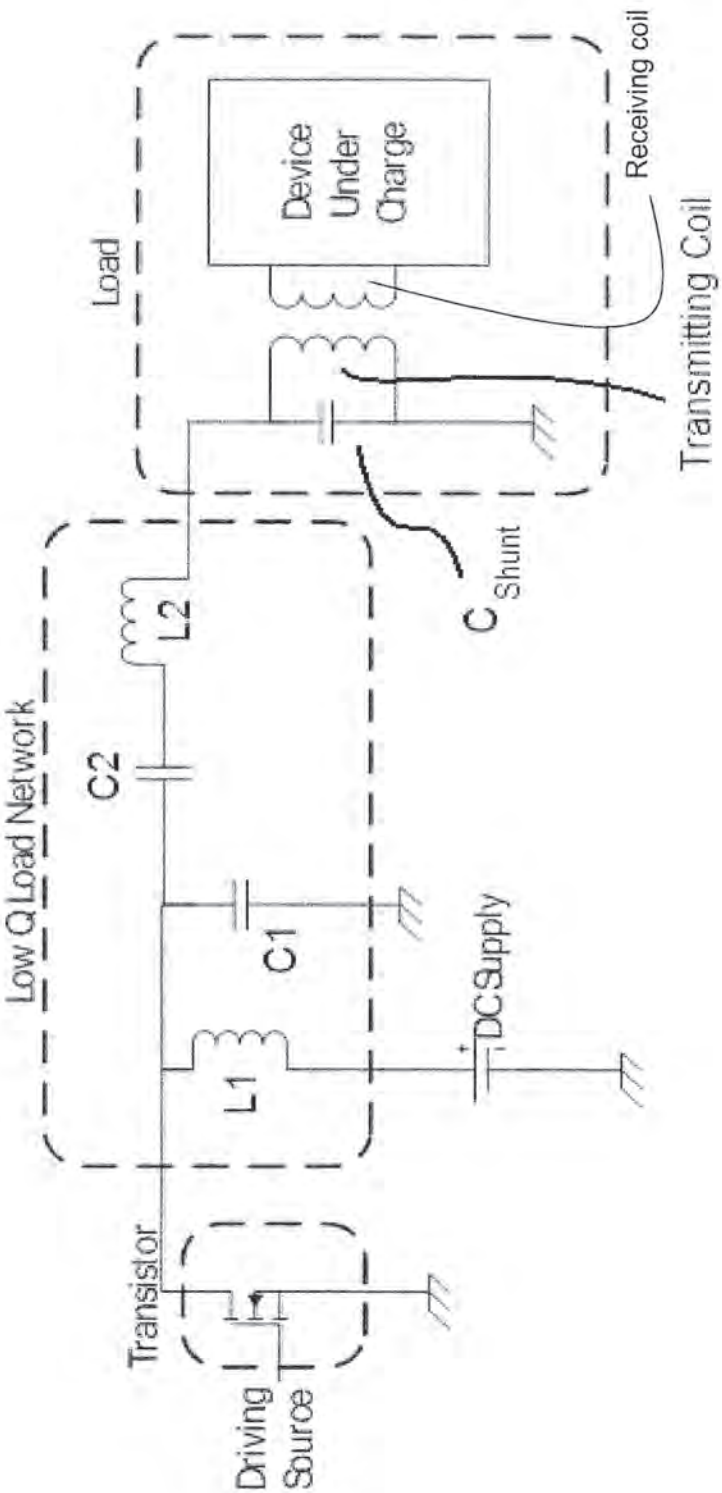


FIG. 1

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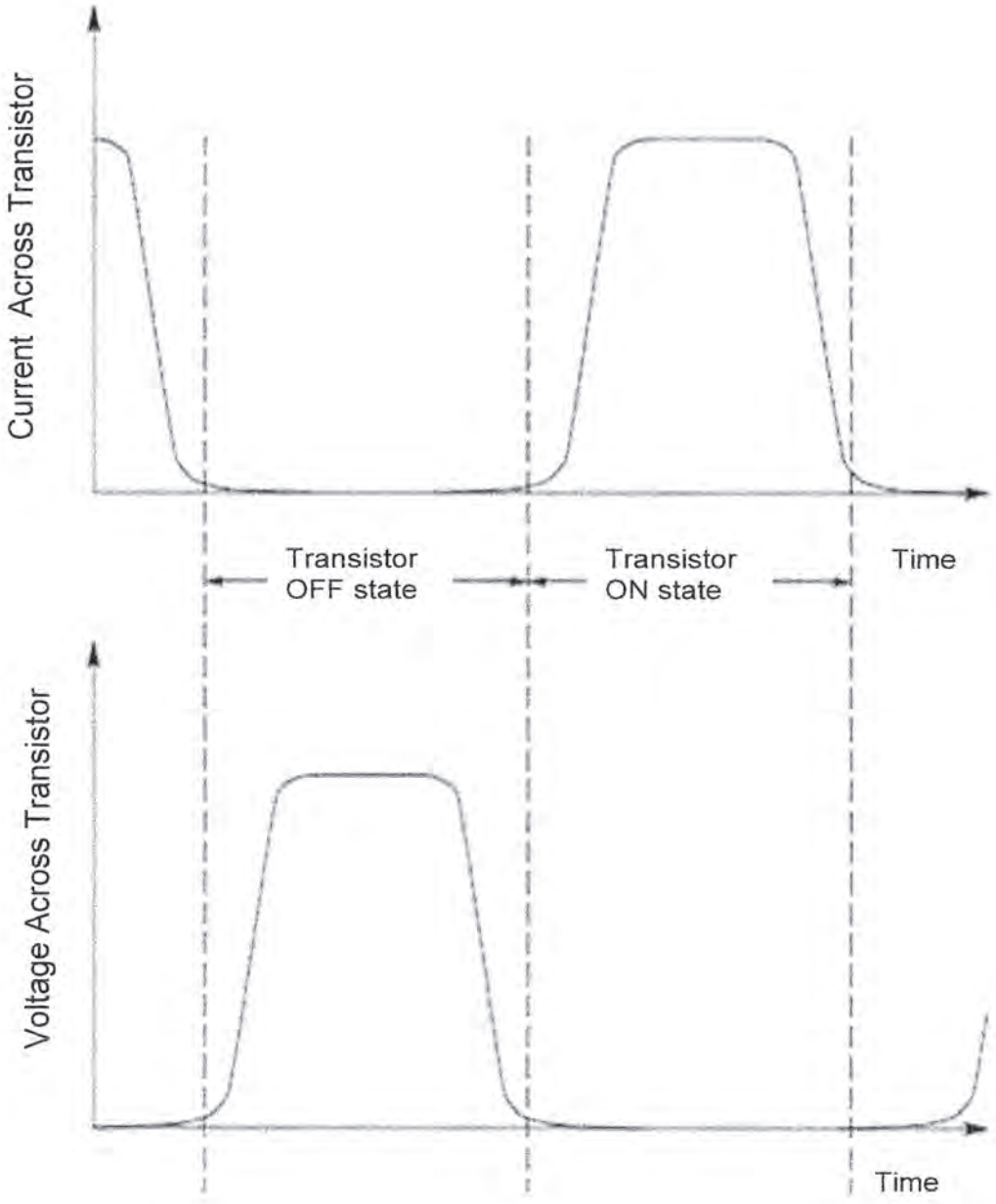

Current Across Transistor
Transistor OFF state
Transistor ON state
Time
Voltage Across Transistor
Time

FIG. 2

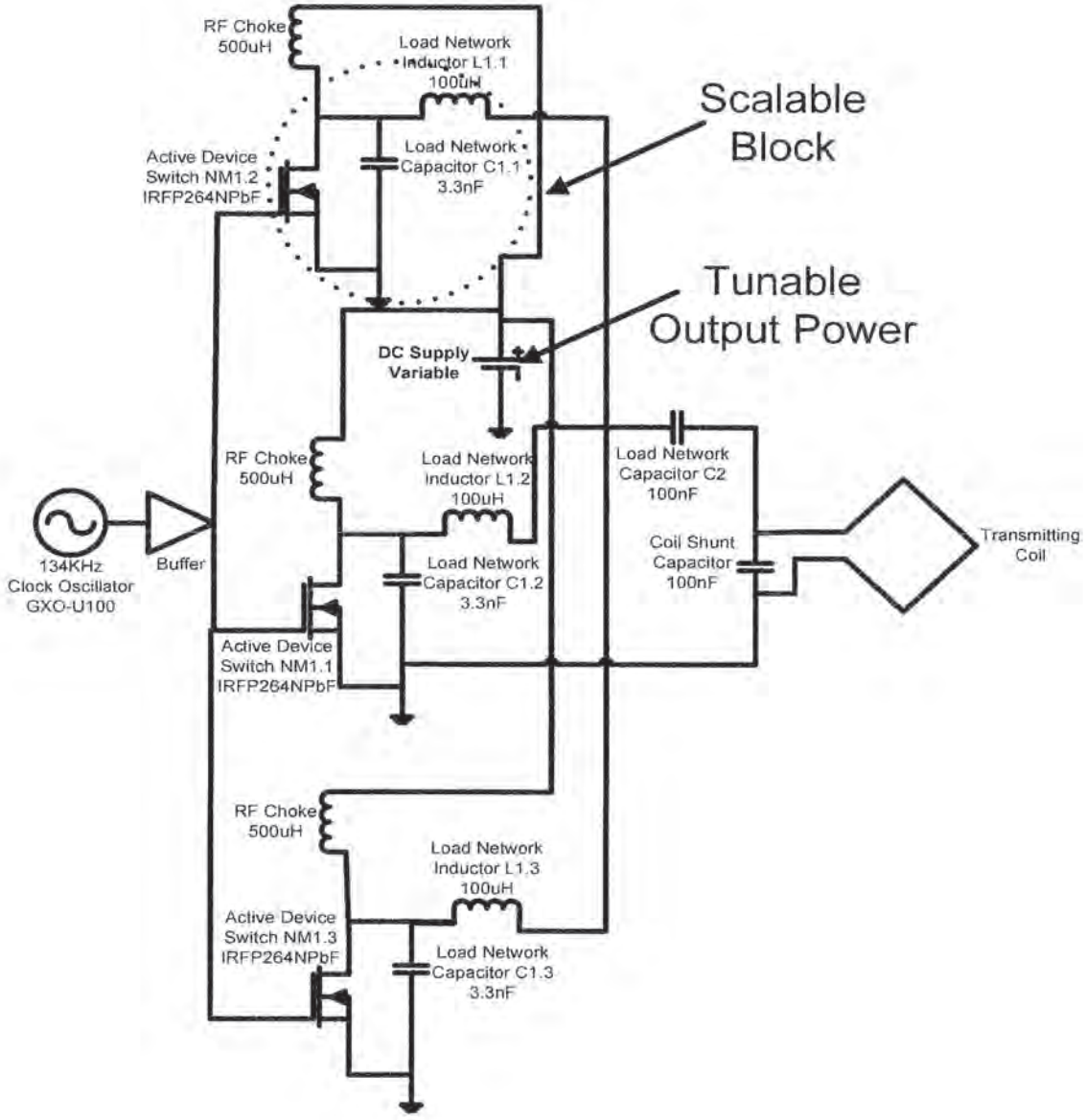

RF Choke
500uH
Load Network
Inductor L1.1
100uH
Scalable
Block
Active Device
Switch NM1.2
IRFP264NPbF
Load Network
Capacitor C1.1
3.3nF
Tunable
Output Power
DC Supply
Variable
RF Choke
500uH
Load Network
Inductor L1.2
100uH
Load Network
Capacitor C2
100nF
Transmitting
Coil
134KHz
Clock Oscillator
GXO-U100
Buffer
Coil Shunt
Capacitor
100nF
Load Network
Capacitor C1.2
3.3nF
Active Device
Switch NM1.1
IRFP264NPbF
RF Choke
500uH
Load Network
Inductor L1.3
100uH
Active Device
Switch NM1.3
IRFP264NPbF
Load Network
Capacitor C1.3
3.3nF

FIG. 3

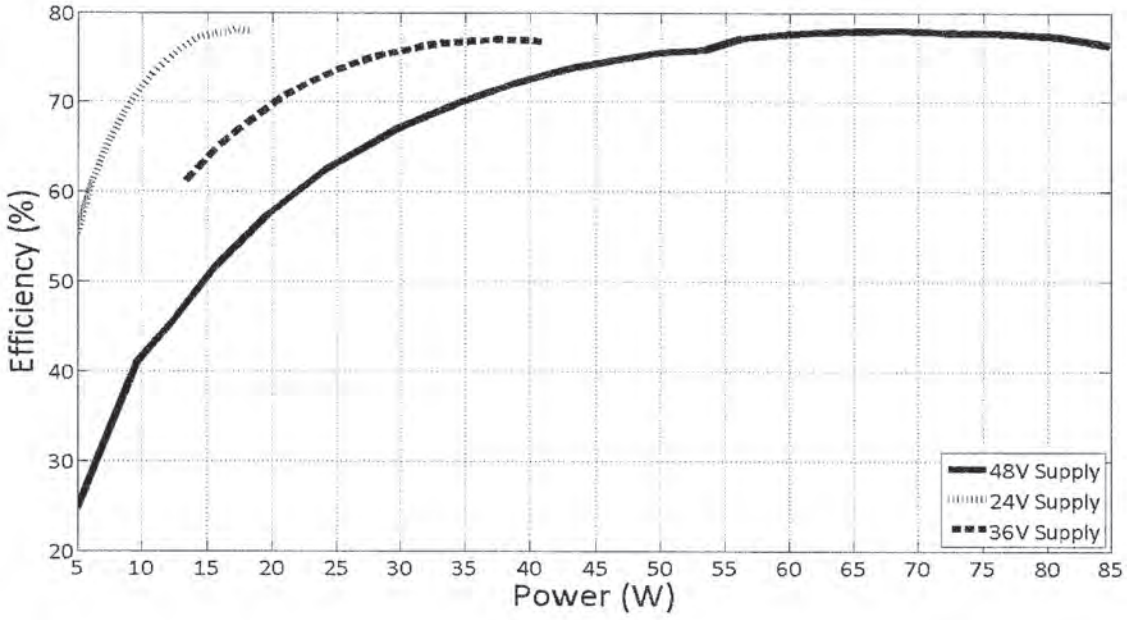

Efficiency (%)
Power (W)
48V Supply
24V Supply
36V Supply

FIG. 4

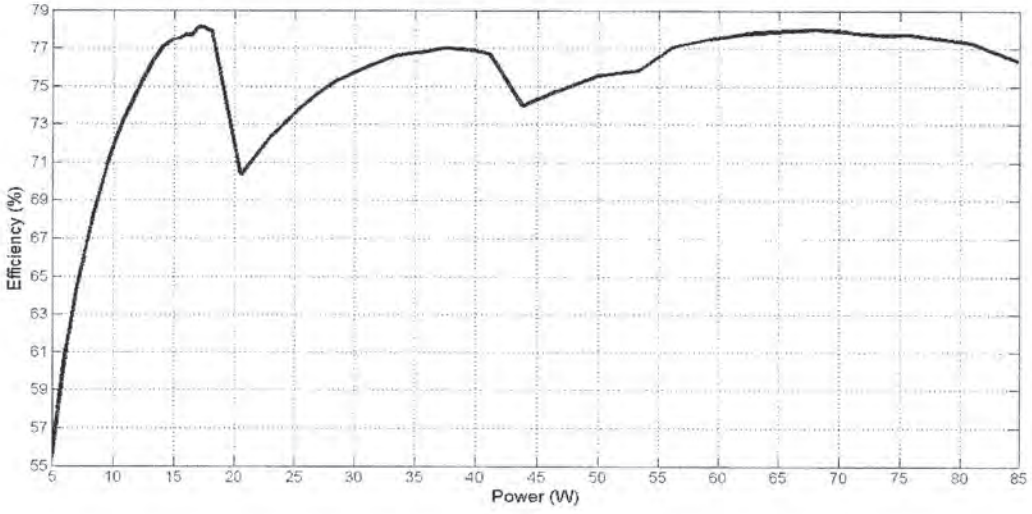

Efficiency (%)
Power (W)

FIG. 5

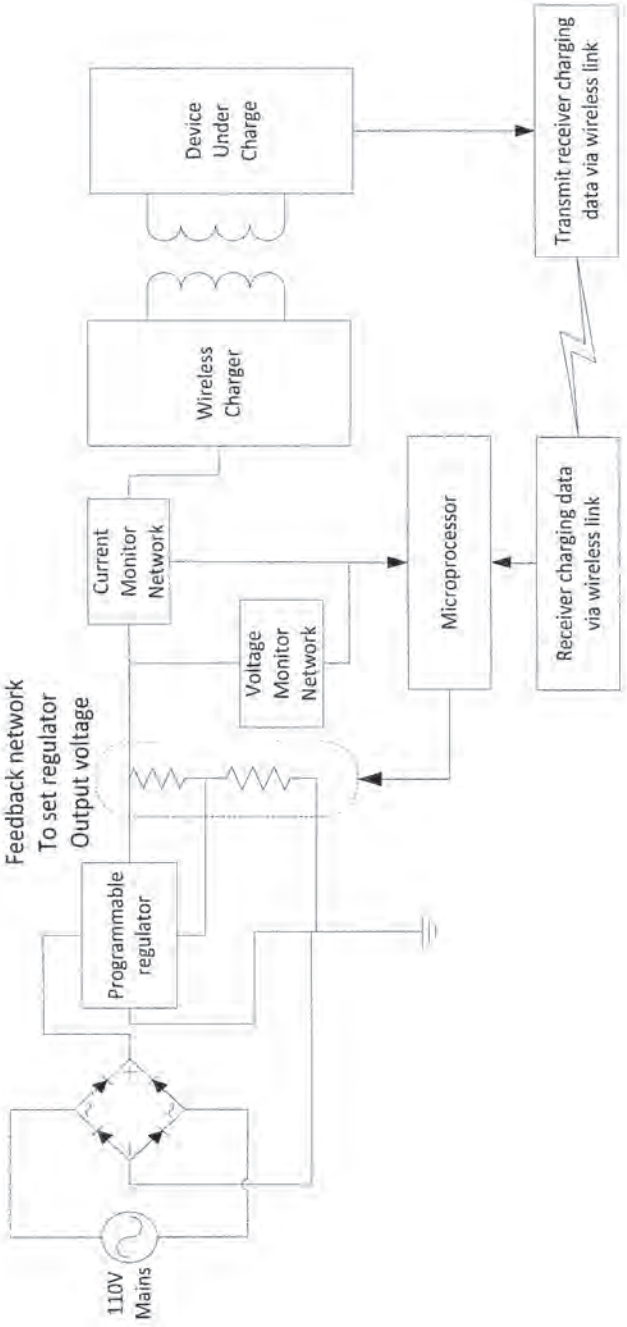

Device Under Charge
Transmit receiver charging data via wireless link
Wireless Charger
Current Monitor Network
Microprocessor
Receiver charging data via wireless link
Voltage Monitor Network
Feedback network
To set regulator
Output voltage
Programmable regulator
110V Mains

FIG. 6A

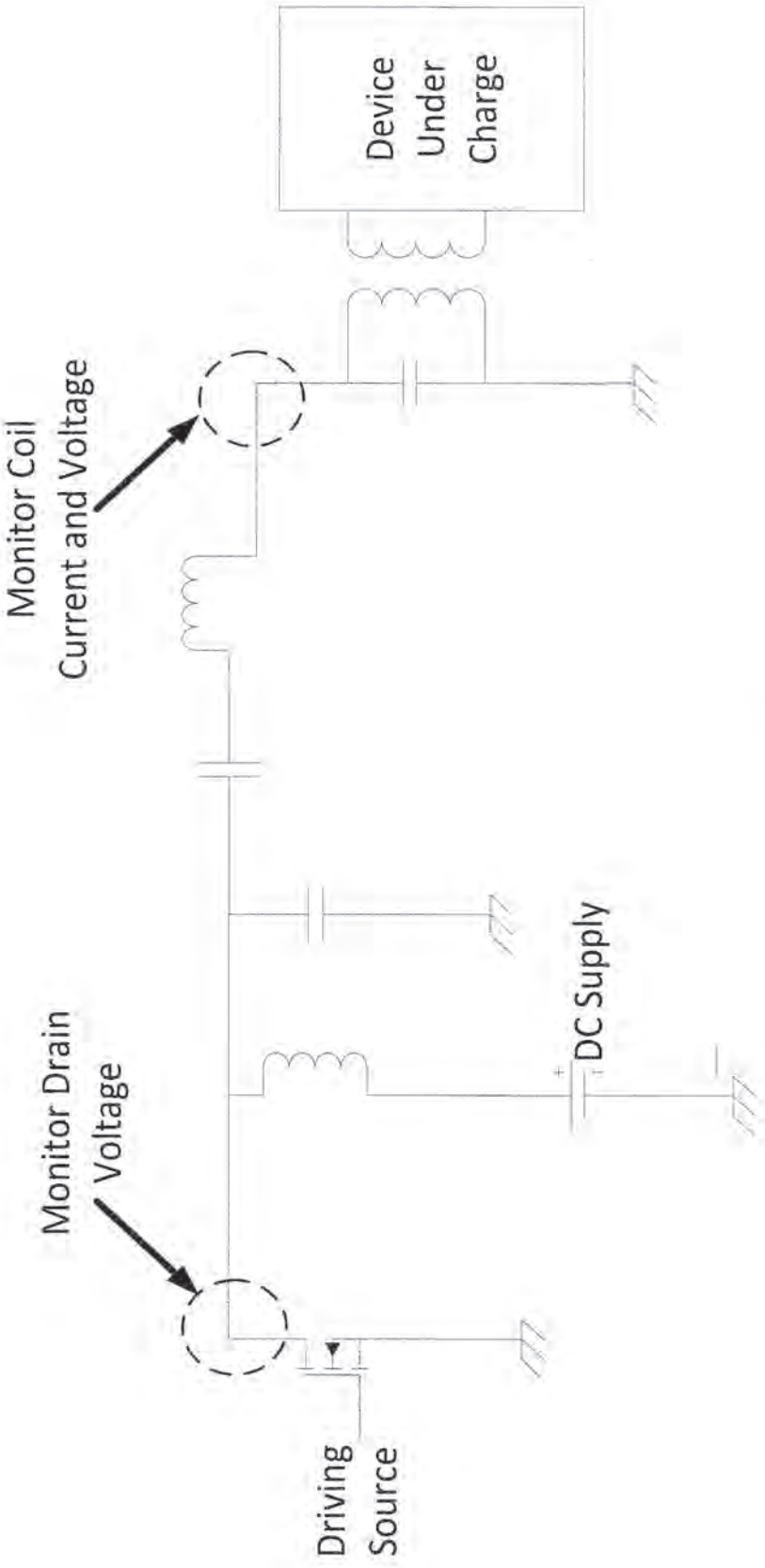

Device Under Charge
Monitor Coil Current and Voltage
Monitor Drain Voltage
DC Supply
Driving Source

FIG. 6B

FIG. 7A

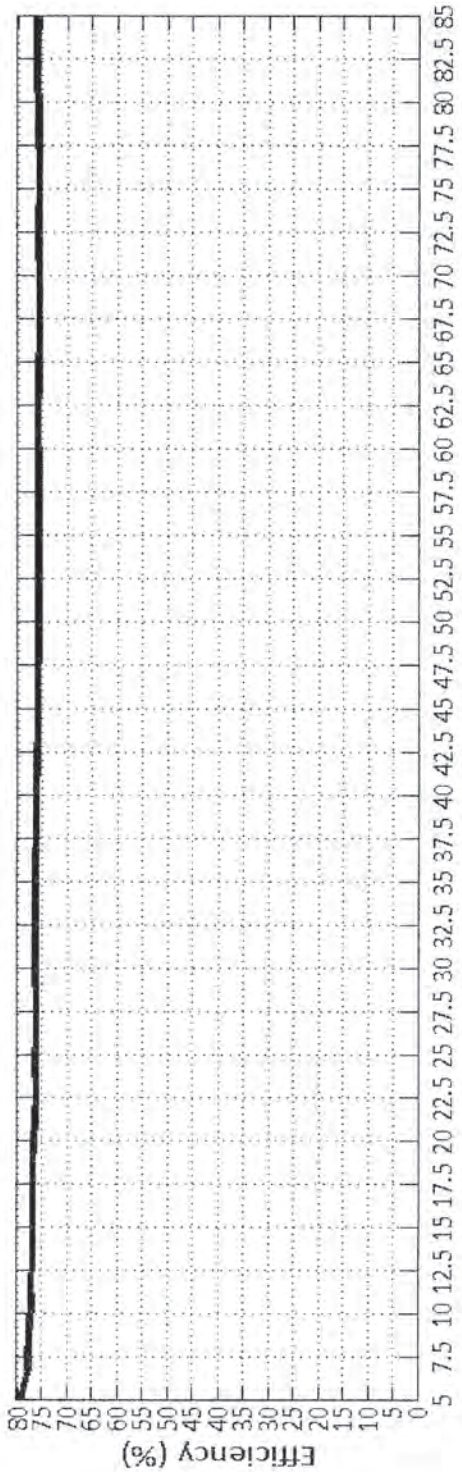
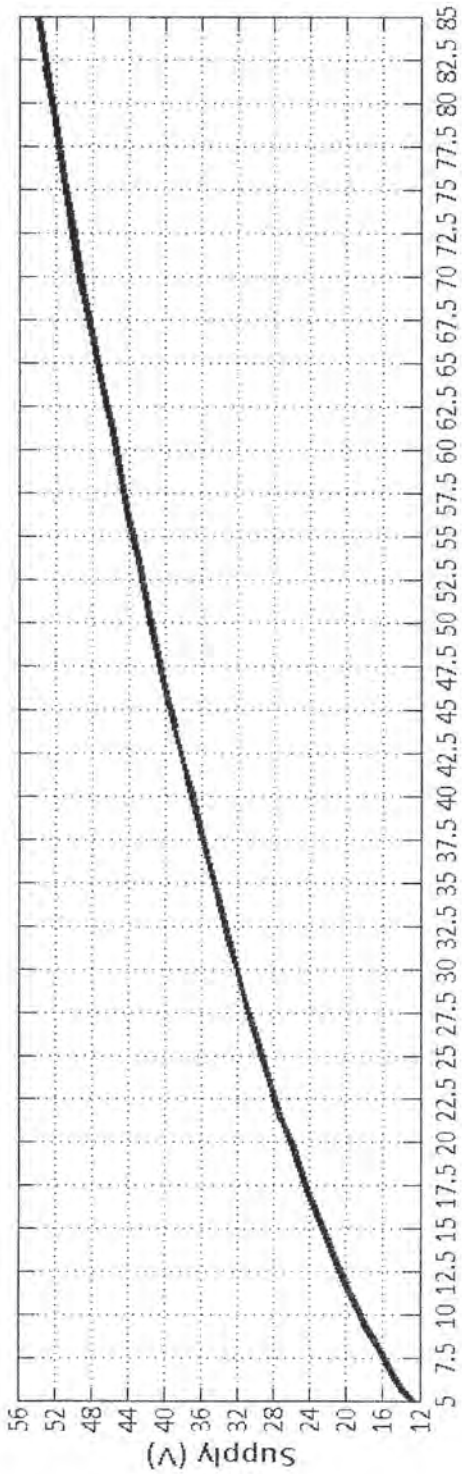


FIG. 7B



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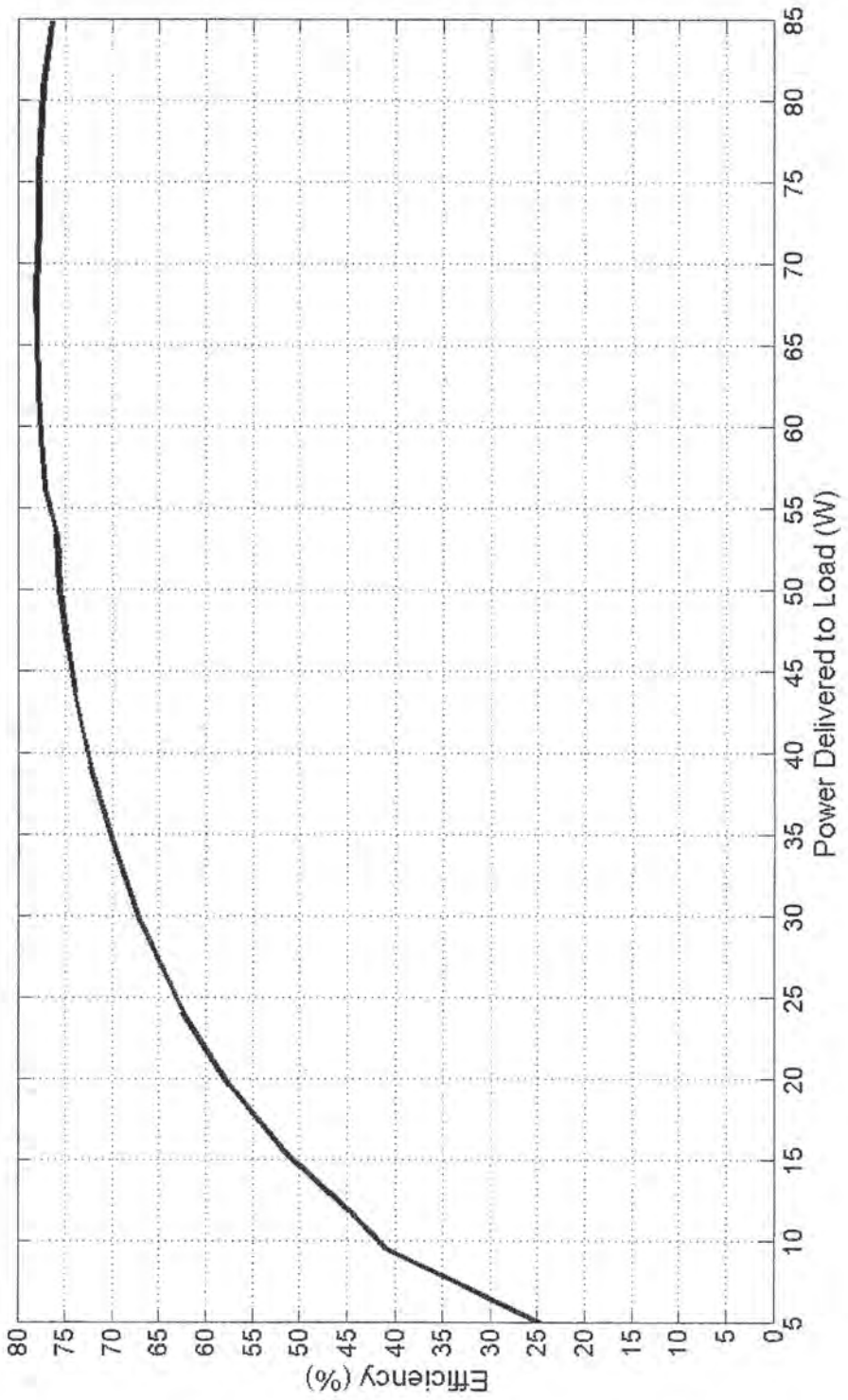

Efficiency (%)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
Power Delivered to Load (W)

FIG. 8

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(74) Agents: **PARKER, James, S.** et al.; Saliwanchik, Lloyd, Saliwanchik, P.o. Box 142950, Gainesville, FL 32614-2950 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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27 August 2009

(54) Title: METHOD AND APPARATUS FOR HIGH EFFICIENCY SCALABLE NEAR-FIELD WIRELESS POWER TRANSFER

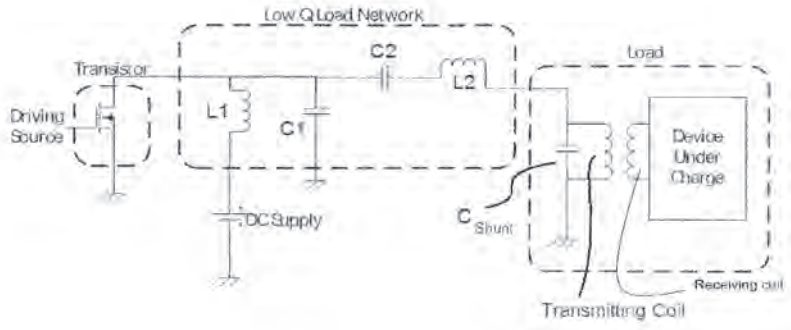


FIG. 1

(57) Abstract: Wireless power transfer systems are provided. A wireless power transmitter can include a transistor block providing a switching mode amplifier, and a low-Q output network including a tunable supply voltage. The transistor block can be scalable. Multiple scalable transistor blocks can be incorporated in a power transfer system using a single tunable supply voltage and transmitting coil. The tunable supply voltage can be controlled by an adaptive power supply tuning circuit to accommodate for a range of loading conditions. Embodiments of the subject invention are capable of achieving high efficiency across a wide range of output power levels.

WO 2009/070730 A3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2008/084970

A. CLASSIFICATION OF SUBJECT MATTER

H02J 17/00(2006.01)i, H02J 15/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC8 H02J 17/00, H02M 3/335

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean Utility models and applications for Utility models since 1975
Japanese Utility models and applications for Utility models since 1975

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PAJ, FPD, USPAT, eKIPASS "Keyword: wireless, transfer, load, quality factor, safety factor"

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2002-320347 A (SHINKO ELECTRIC CO LTD) 31 October 2002 See the abstract; claim 1; figure 1.	1-49
A	US 2003-0214821 A1 (DEMETRI GIANNOPOULOS et al.) 20 November 2003 See the abstract; claim 11; figure 1.	1-49
A	JP 2006-230032 A (DAIHO NOBORU) 31 August 2006 See the abstract; claim 1; figure 1.	1-49

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
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Name and mailing address of the ISA/KR Korean Intellectual Property Office Government Complex-Daejeon, 139 Seonsa-ro, Seo-gu, Daejeon 302-701, Republic of Korea Facsimile No. 82-42-472-7140	Authorized officer WEE Jae Woo Telephone No. 82-42-481-8540

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Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 2002-320347 A	31.10.2002	None	
US 2003-0214821 A1	20.11.2003	AU 2003-230103 A1	02.12.2003
		EP 1506606 A1	16.02.2005
		JP 2005-526474 A	02.09.2005
		KR 10-2005-0005480 A	13.01.2005
		US 0684-04702B2	18.01.2005
		WO 2003-098773 A1	27.11.2003
JP 2006-230032 A	31.08.2006	None	

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(54) **Title**: POWER CONTROL DUTY CYCLE THROTTLING SCHEME FOR PLANAR WIRELESS POWER TRANSMISSION SYSTEM

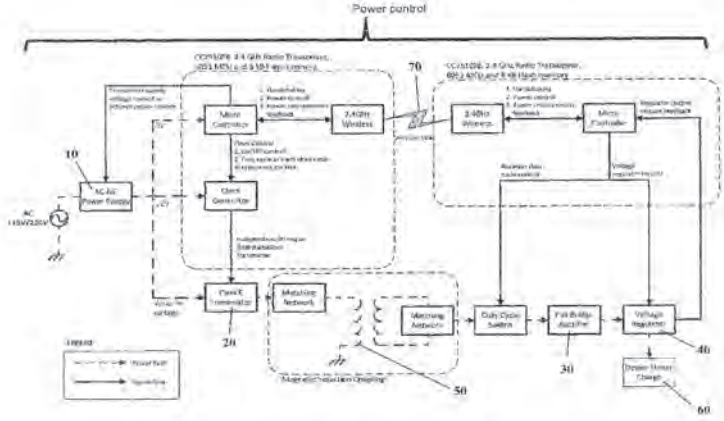


FIG. 1

(57) **Abstract**: Embodiments of a power transmission system and power control scheme are provided. The power control scheme utilizes the power requirements for each receiver of a device on a charging pad for highly efficient charging of multiple devices. According to an embodiment, each receiver transmits its power requirement to the transmitter, and based on this power requirement, the most power hungry device is used to set the duty cycle of the transmitter. Each individual receiver can continue to monitor its power requirement and make necessary adjustments to ensure efficient power transfer. Once all the devices are fully charged, the transmitter can be powered off or have its duty cycle reduced to performance trickle charging. The transmitter can continue to access the load conditions while in standby to detect any new device being placed on the charging pad.

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DESCRIPTION

POWER CONTROL DUTY CYCLE THROTTLING SCHEME FOR PLANAR WIRELESS POWER TRANSMISSION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 61/044,327, filed April 11, 2008, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

Wireless power transmission is an emerging technology as trends move toward completely wireless devices. Currently, power control can be achieved via changing the operating frequency of a transmitter, tuning the transmitter's matching network, and changing the transmitter's supply voltage. However, limited dynamic range can be attained by changing the operating frequency. It can be difficult and costly to find tunable components to operate at such high power level. In addition, system performance tends to degrade when the supply voltage deviates too far from it nominal operating voltage.

BRIEF SUMMARY

Embodiments of the present invention relate to a method and apparatus for power control in wireless power transmission. According to an embodiment, multiple receivers can be used with a single transmitter. In an embodiment, a low cost microprocessor can be used to perform timing control for the transmitter output. Embodiments of the present invention have a significantly wider power dynamic range than other competing solutions. In addition, it is possible to scale the timing control technique to charge a large number of devices concurrently, thus becoming more flexible.

In an embodiment, an intelligent power control technique is implemented that attends to the power requirement for the receiver of each device on a charging pad. According to an embodiment, each receiver transmits the power requirement of the receiver to the transmitter, and based on this power requirement, the most power hungry device is used to set the duty cycle of the transmitter. Each individual receiver can continue to monitor its power requirement and make necessary adjustments to ensure efficient power transfer. Once all the devices are fully charged, the transmitter can be powered off or have its duty cycle reduced to

perform trickle charging. The transmitter can continue to access the load conditions while in standby to detect any new device being placed on the charging pad.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 shows a system overview according to an embodiment of the present invention.

Figure 2 shows a duty cycling throttling scheme according to an embodiment of the present invention.

Figure 3 shows a timing scheme according to an embodiment of the present invention for three receivers of significantly different per-unit area power requirement (75W, 25W, 5W) placed on a 100W transmitting pad.

Figure 4 shows an optimum duty cycling throttling scheme according to an embodiment of the present invention.

DETAILED DISCLOSURE

Embodiments of the present invention provide a method and apparatus for power control in wireless power transmission. Embodiments of the subject invention can be utilized in a planar power transmission system that is capable of charging multiple portable devices as well as powering them at close proximity. Since different devices have different power requirements that can span across a large dynamic range, embodiments of the present invention provide an intelligent power control scheme that allows contemporaneous charging of multiple devices that may span across a large dynamic range. According to an embodiment, multiple receivers can be used with a single transmitter. Certain embodiments of the present invention can attain 81% efficiency while delivering 68W of power to an ideal load. A peak power of 132W has been achieved using a specific embodiment of the present invention. In a further embodiment, a peak power of 300W has been achieved.

Figure 1 illustrates a power transmission system according to an embodiment of the present invention that can utilize one or more power control schemes. The power-related systems of this example are shown, following a power path. Power control techniques according to embodiments of the present invention can be applied to the power-related systems. In the transmitter portion of the system, the amplifier supply voltage **10** and the duty cycle can be tuned. In a specific embodiment, a duty cycle of driving square pulses can be tuned. In addition, in a system where the class E transmitter portion **20** includes two transistors, one of the two transmitting transistors can be shut down to reduce power output.

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In one embodiment, two independent clocks can be used to separately drive the two transistors, such that a power control scheme is capable of shutting down one transistor when the power requirement is low. Synchronization between the independent clocks can be provided.

In an embodiment of the power control scheme, the system duty cycle for the transmitter can be controlled. On the receiver end, the system duty cycle can also be controlled as part of a power scheme according to an embodiment of the present invention. In an embodiment, receivers from different devices can have different duty cycles. Receivers from different devices can communicate with each other and coordinate such that the receivers reduce the amount of the duty cycle where no receiver is receiving power and/or the more than one, or more than two, receivers are receiving power, so as to enhance the charging of the two or more devices.

In one embodiment, the system duty cycle of a receiver can be controlled using, for example, discrete rectifying diodes **30** with a voltage regulator **40**. For example, the voltage regulator part LM5574 for 500mA output current and part LM5576 for 3A output current can be used. In another example, voltage regulation can be performed by a microprocessor having an RF receiver such as the Chipcon CC2510F8.

Figure 2 shows a power control scheme according to an embodiment of the present invention. As shown in Figure 2, the transmitter (e.g., reference **20** of Figure 1) excites the coil (e.g., reference **50** of Figure 1) for a short period of time (X/Y seconds) to access a pad's load condition so as to determine if any device (e.g., reference **60** of Figure 1) is on or near the pad and to power down for X seconds if no load is detected. Values of X and Y are determined by the settling time of the system and the response time requirement once the receiver(s) is/are placed on the pad. In a specific embodiment, X can be about one second and X/Y can be from about 500 μsec to about 1 msec, so as to promptly start charging a device placed in appropriate position and avoid wasting power.

The load condition can be monitored, in order to determine when a device to be charged is put in an appropriate position by, for example, comparing one or more of the following with values that occur when no load is present: transmitter supply current, transmitter coil voltage, and transmitter coil current. The transmitter is also able to detect a device on the pad via a near field wireless communication link (e.g., reference **70** of Figure 1) if there is still charge left in the receiver's battery. However, if there is not sufficient charge left in the battery, the transmitter can power up at full 100% duty cycle to transmit power to the power depleted receiver(s). In another embodiment, the transmitter is powered up to at

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least 50% duty cycle. Upon receiving sufficient power to power the near field communication module, the receiver can then transmit its power requirement to the transmitter. Based on the power requirement of the receiver(s), the transmitter can then determine a duty cycle that is, for example, sufficient to power the most power hungry device without wasting extra energy. In specific embodiments, the selected duty cycle can optimize the efficiency of charging.

When there is a single device to be charged the transmitter can detect the presence of the device to be charged by detecting load conditions, and can then adjust the duty cycle of the transmitter appropriately. In embodiments having two or more devices to be charged the transmitter can detect the devices to be charged by detecting load conditions and then receiving communications from the receiver(s) of the device(s) to be charged as to the charging requirements. In a specific embodiment, the devices to be charged can communicate with each other as to what portions of the transmitters duty cycle to receive power.

The receiver can determine the transmitter duty cycle. In a specific embodiment, the receiver can determine the transmitter duty cycle via the envelope detect technique. In addition, clock synchronization can also be performed during the process of determining the transmitter duty cycle. Depending on the power requirement of the receiver, the receiver can transmit its requirement if insufficient power is being transmitted or perform further duty cycling on the transmitter duty cycled power transmission to obtain the required power level. In a specific embodiment, a device placed on charging pad is recognized by the transmitter as a change in load. If a battery is drained, then the near field communication module is powered-up using power from the transmitter.

Figure 3 shows a duty cycle scheme according to an embodiment of the present invention. In a specific embodiment, a duty cycle scheme for a 100 W per unit area transmitter is provided with examples of three receivers' per unit area power requirement of 75 W, 25 W and 5 W respectively. The shaded portions show when the transmitter is transmitting or when the receivers are receiving, while the dark line shows when the receivers are on. The transmitter is shown as having a 75% duty cycle, as turning the transmitter off for a portion of the cycle can be helpful. Other percentage duty cycles can also be used. Each receiver can determine its duty cycle and turn on charging in accordance with its power requirement. Other than the most power hungry device, which is reflected in the scheme shown by receiver 1 in Figure 3, all other receivers (receiver 2 and receiver 3 of Figure 3) can stop receiving power by disengaging the coil during the beginning of the next cycle of power

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transmission from the transmitter. Each individual receiver can continue to monitor its power requirement and make necessary adjustments to ensure efficient power transfer. The scheme is capable of seamlessly letting any device receive power even if there are other devices under charge.

In another specific embodiment, the duty cycling scheme can be optimized as shown in Figure 4. The difference between the scheme illustrated by Figure 4 and the scheme illustrated by Figure 3 is the change in the window position of receiver 2. This change in window position can provide improved distribution of power transmission between lower power devices by reducing overlapping of receivers being on. However, synchronization between receivers can be important. If desired, the receivers can be turned off while the transmitter is off. In addition, the window of when the receivers are turned on can be moved to reduce the amount of overlapping of receiver charging in order to further improve charging efficiency.

Then, once all the devices are fully charged, which can be determined via feedback from the receiver(s), the transmitter can be powered off or its duty cycle can be reduced to performance trickle charging. The transmitter can continue to access the load conditions while in standby to detect any new device being placed on the transmitting pad.

Through using a duty cycle scheme according to embodiments of the present invention, it is possible to provide a high efficiency and low cost wireless power charging platform that is capable of concurrent charging/powering of one or more portable devices such as mobile phones, mp3 players, and laptop computers. Embodiments of the present invention can be implemented, for example, at home, at airports, hotel rooms, or any public location. Accordingly, this would bring great convenience to general consumers, especially frequent travelers, as it would provide a universally charging interface and eliminate the need to carry multiple chargers. In addition, the user is able to charge all of his portable devices at the same time without significant impact on charge time.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

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CLAIMS

What is claimed is:

1. A method for wireless power transmission, comprising:

(a) exciting a transmitter coil of a transmitter of a wireless power transmission system for X/Y seconds, wherein the transmitter coil transmits an RF magnetic field when the transmitter coil is excited;

(b) determining a load condition so as to determine if a device is positioned to be charged, wherein each device to be charged comprises a receiver coil inductively coupled to the transmitter coil when the device is positioned to be charged and a receiver for receiving a receiver current from the receiver coil, wherein if there is no device positioned to be charged, then after a delay of X seconds returning to (a);

(c) if there is a device positioned to be charged, then exciting the transmitter coil so as to transmit power to the device positioned to be charged.

2. The method according to claim 1, further comprising receiving at the transmitter a power requirement for the device positioned to be charged provided by the receiver of the device positioned to be charged.

3. The method according to claim 2, wherein when there are two or more devices positioned to be charged, receiving at the transmitter the power requirement for each device positioned to be charged provided by the receiver of each device positioned to be charged.

4. The method according to claim 2, wherein the receiver comprises a near field communication module for providing the power requirement, wherein when a battery of the device positioned to be charged is not sufficiently charged to power the near field communication module of the receiver to provide the power requirement the receiver of the device positioned to be charged provides the power requirement to the transmitter upon receiving sufficient power from the transmitter to power the near field communication module of the receiver.

5. The method according to claim 3, further comprising:
detecting at the receiver a transmitter duty cycle.

6. The method according to claim 5, wherein the transmitter duty cycle is detected by using an envelope detect technique.

7. The method according to claim 5, wherein each of the two or more devices positioned to be charged detects the transmitter duty cycle and charges according to the power requirement of the device.

8. The method according to claim 1, wherein X is less than or equal to 1 second.

9. The method according to claim 1, wherein X/Y is in the range of 500 μsec to 1 msec.

10. The method according to claim 1, further comprising adjusting a duty cycle of the transmitter based on the load condition.

11. The method according to claim 2, further comprising adjusting a duty cycle of the transmitter based on the power requirement provided by the receiver of the device positioned to be charged.

12. The method according to claim 1, wherein determining the load condition comprises determining a transmitter supply current.

13. The method according to claim 1, wherein determining the load condition comprises determining a transmitter coil voltage.

14. The method according to claim 1, wherein determining the load condition comprises determining a transmitter coil current.

15. A system for wireless power transmission, comprising:

a transmitter having a transmitter coil, wherein the transmitter coil transmits an RF magnetic field when the transmitter coil is excited;

a device having a receiver and a receiver coil, wherein the receiver coil is inductively coupled to the transmitter coil when the device is positioned to be charged, wherein the receiver receives a receiver current from the receiver coil;

a means for exciting the transmitter coil for X/Y seconds; and

a means determining a load condition after exciting the transmitter coil for X/Y seconds so as to determine if the device is positioned to be charged, wherein if the device is not positioned to be charged, then after a delay of X seconds initiating the means for exciting the transmitter coil for X/Y seconds, wherein if the device is positioned to be charged, then exciting the transmitter coil so as to transmit power to the device positioned to be charged.

16. The system according to claim 15, wherein the receiver further comprises a means for transmitting to the transmitter a power requirement for the device.

17. The system according to claim 16, wherein the system comprises two or more devices.

18. The system according to claim 16, wherein the means for transmitting to the transmitter the power requirement comprises a near field communication module for providing the power requirement, wherein when a battery of the device is not sufficiently charged to power the near field communication module to provide the power requirement the receiver of the device positioned to be charged provides the power requirement to the transmitter upon receiving sufficient power from the transmitter to power the near field communication module of the receiver.

19. The system according to claim 17, wherein at least one device further comprises:

a means for detecting a transmitter duty cycle.

20. The system according to claim 19, wherein the transmitter duty cycle is detected by using an envelope detect technique.

21. The system according to claim 19, wherein each of the two or more devices detect the transmitter duty cycle and charges according to the power requirement of the device.

22. The system according to claim 15, wherein X is less than or equal to 1 second.

23. The system according to claim 15, wherein X/Y is in the range of 500 μsec to 1 msec.

24. The system according to claim 15, wherein the transmitter further comprises a means for adjusting a duty cycle of the transmitter based on the load condition.

25. The system according to claim 16, wherein the transmitter further comprises a means for adjusting a duty cycle of the transmitter based on the power requirement provided by the receiver of the device.

26. The system according to claim 15, wherein the means for determining the load condition comprises a means for determining a transmitter supply current.

27. The system according to claim 15, wherein the means for determining the load condition comprises a means for determining a transmitter coil voltage.

28. The system according to claim 15, wherein the means for determining the load condition comprises a means for determining a transmitter coil current.

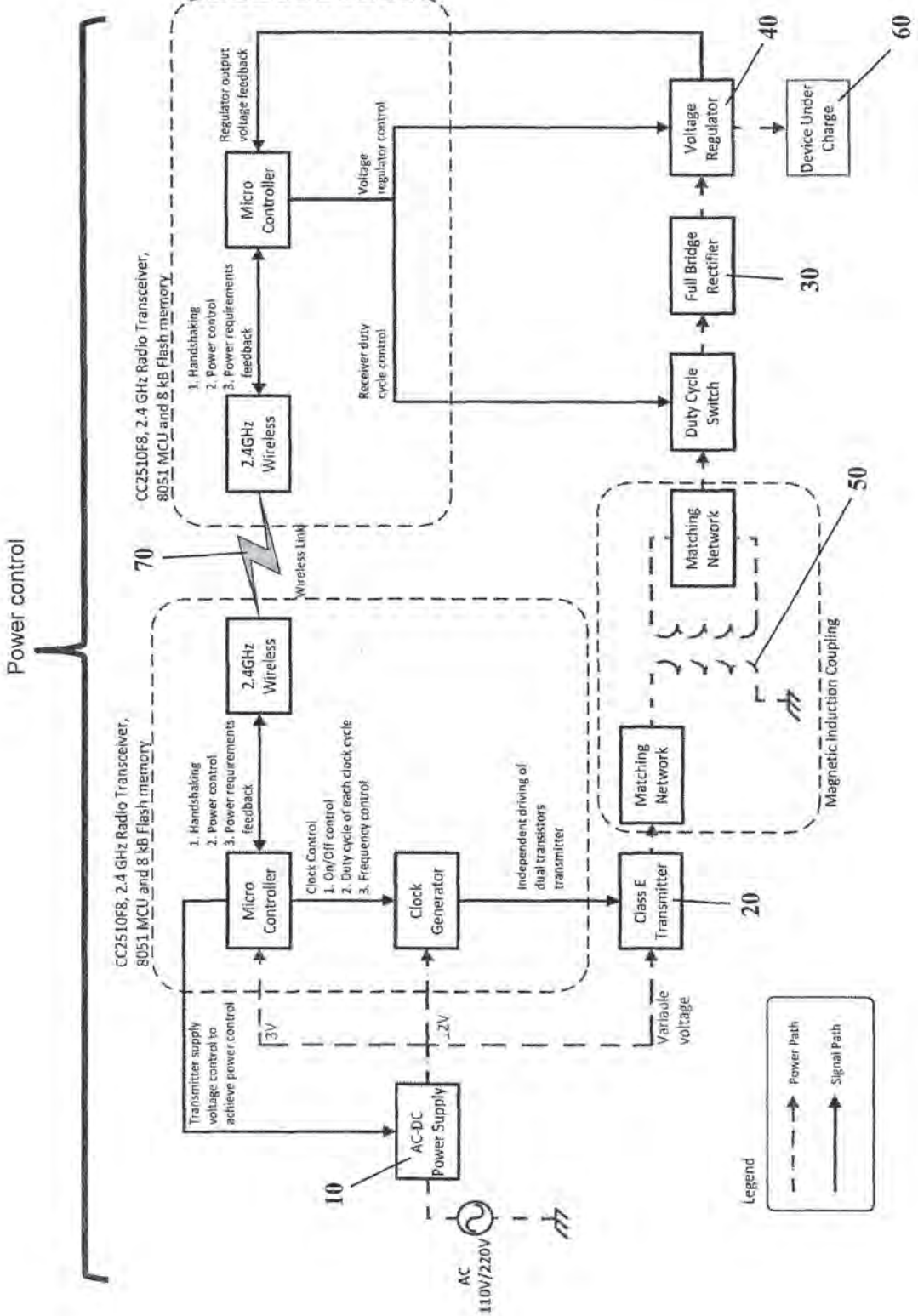

Power control
CC2510F8, 2.4 GHz Radio Transceiver, 8051 MCU and 8 kB Flash memory
1. Handshaking
2. Power control
3. Power requirements feedback
Micro Controller
2.4GHz Wireless
Regulator output voltage feedback
Voltage regulator control
Receiver duty cycle control
Wireless Link
70
Clock Control
1. On/Off control
2. Duty cycle of each clock cycle
3. Frequency control
Clock Generator
Independent driving of dual transistors transmitter
Class E Transmitter
20
Matching Network
Magnetic Induction Coupling
50
Duty Cycle Switch
Full Bridge Rectifier
30
Voltage Regulator
40
Device Under Charge
60
Transmitter supply voltage control to achieve power control
3V
2V
Variable voltage
AC-DC Power Supply
10
AC 110V/220V
Legend
Power Path
Signal Path

FIG. 1

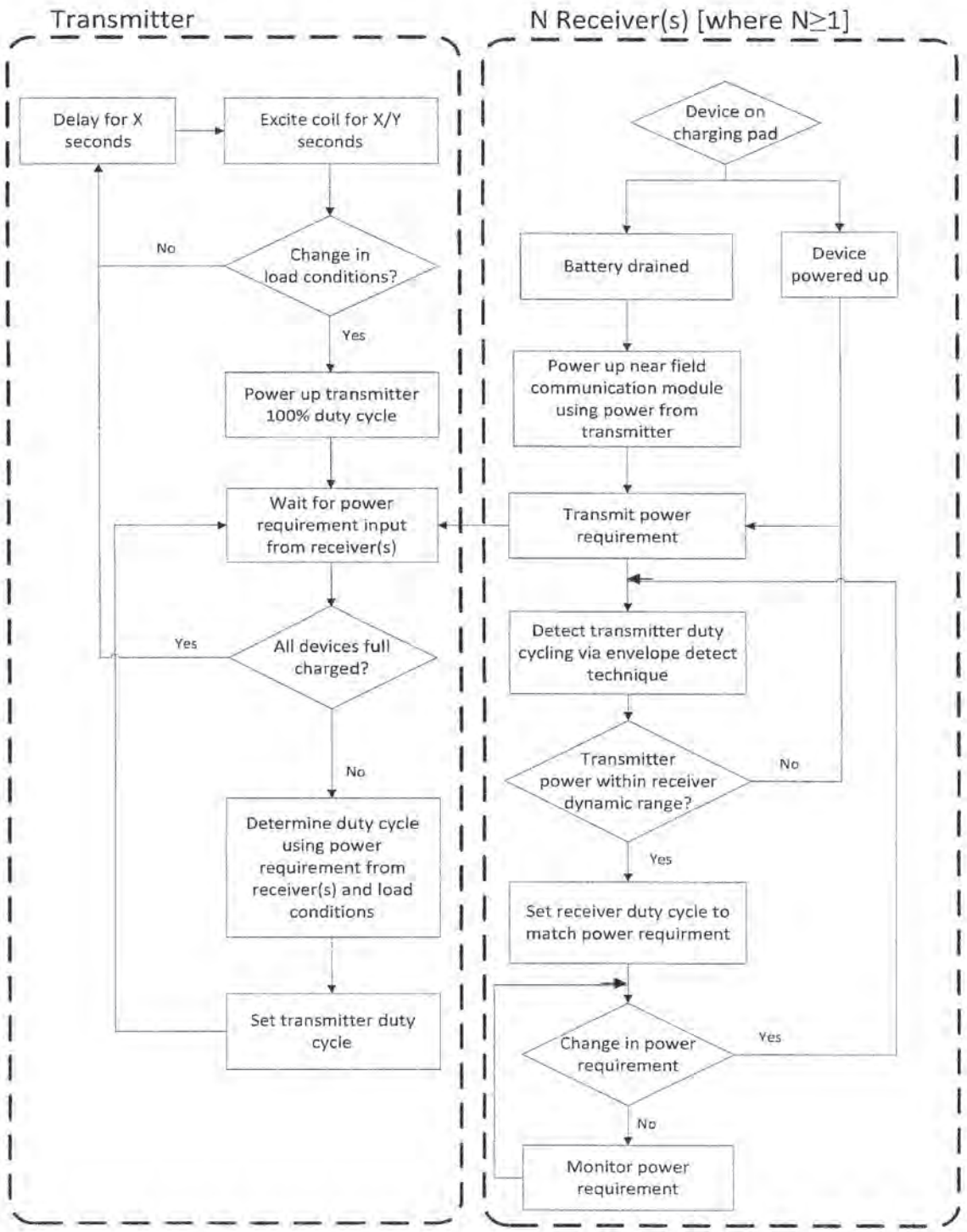

Transmitter
N Receiver(s) [where N≥1]
Delay for X seconds
Excite coil for X/Y seconds
Change in load conditions?
No
Yes
Power up transmitter 100% duty cycle
Wait for power requirement input from receiver(s)
All devices full charged?
Yes
No
Determine duty cycle using power requirement from receiver(s) and load conditions
Set transmitter duty cycle
Device on charging pad
Battery drained
Device powered up
Power up near field communication module using power from transmitter
Transmit power requirement
Detect transmitter duty cycling via envelope detect technique
Transmitter power within receiver dynamic range?
No
Yes
Set receiver duty cycle to match power requirment
Change in power requirement
Yes
No
Monitor power requirement

FIG. 2

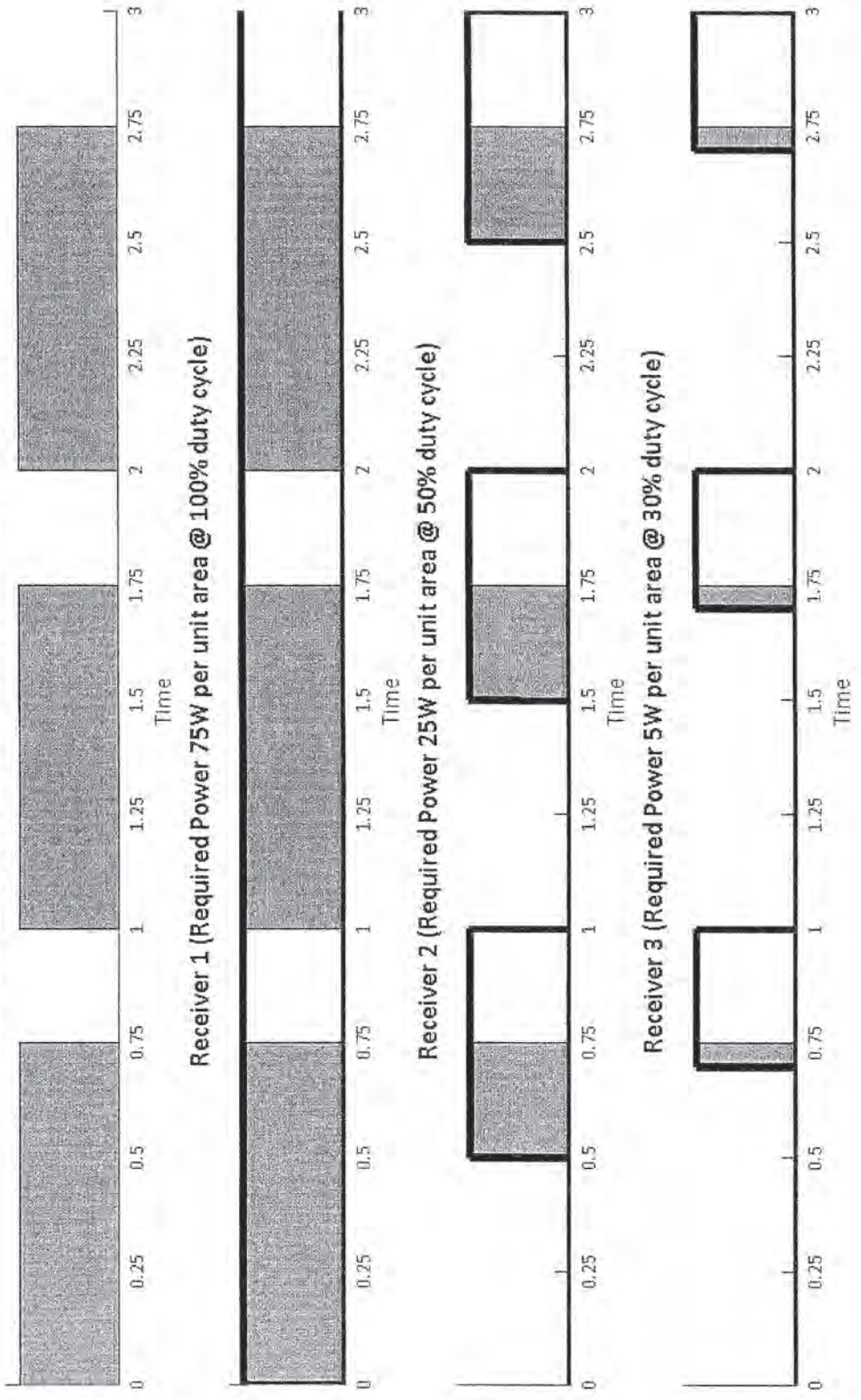


FIG. 3

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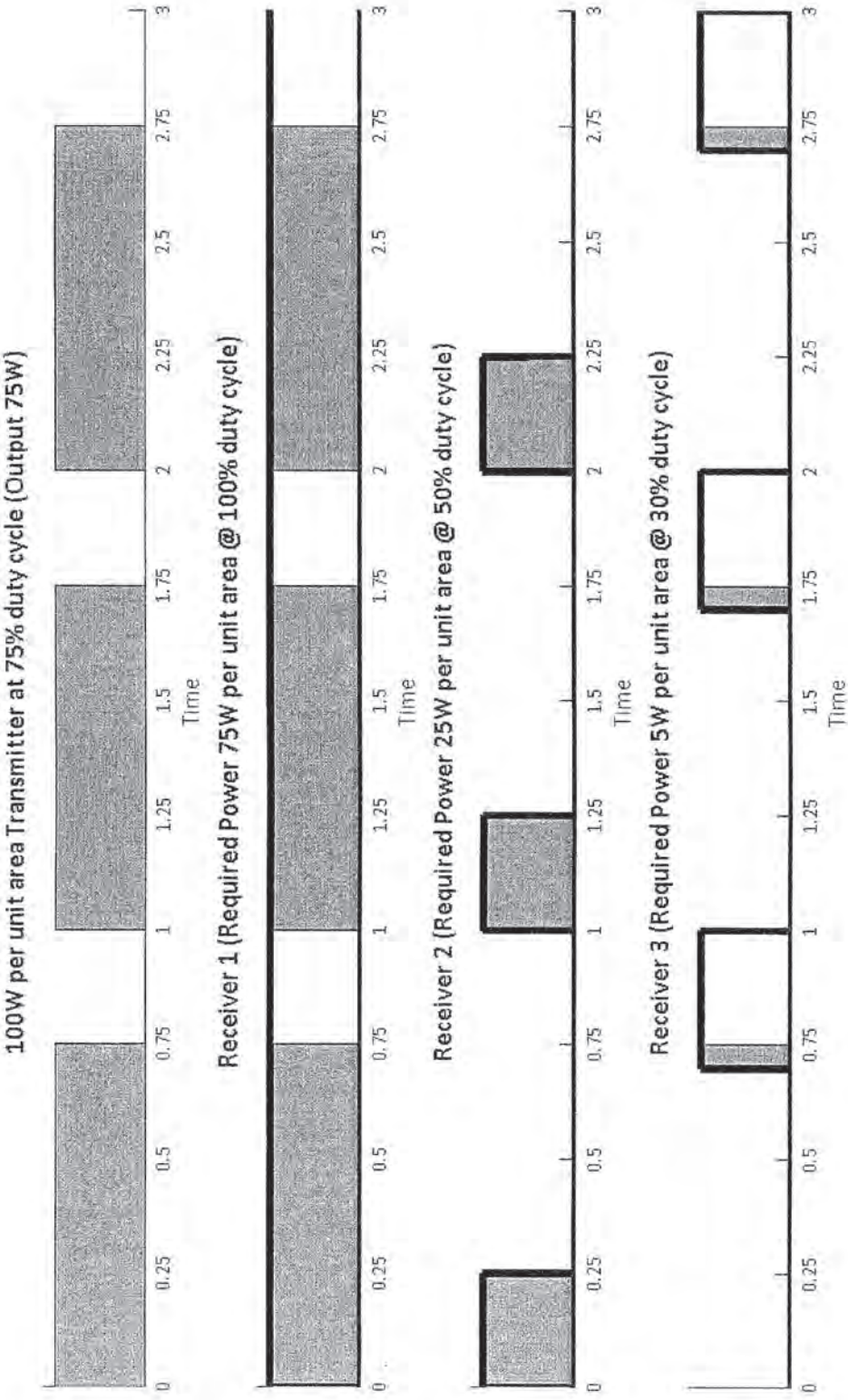

100W per unit area Transmitter at 75% duty cycle (Output 75W)
Receiver 1 (Required Power 75W per unit area @ 100% duty cycle)
Receiver 2 (Required Power 25W per unit area @ 50% duty cycle)
Receiver 3 (Required Power 5W per unit area @ 30% duty cycle)
Time
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3

FIG. 4

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(75) Inventors/Applicants *(for US only)*: **LOW, Zhen, Ning** [SG/US]; 712 S.w. 16th Avenue, #311, Gainesville, FL 32601 (US). **LIN, Jenshan** [US/US]; 910 S.W. 105th Terrace, Gainesville, FL 32607 (US).

(74) Agents: **PARKER, James, S.** et al.; Saliwanchik, Lloyd, Saliwanchik, P.O. Box 142950, Gainesville, FL 32614-2950 (US).

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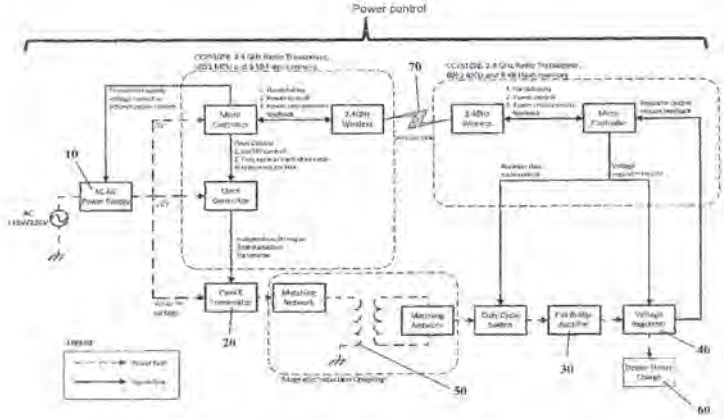


FIG. 1

(57) Abstract: Embodiments of a power transmission system and power control scheme are provided. The power control scheme utilizes the power requirements for each receiver of a device on a charging pad for highly efficient charging of multiple devices. According to an embodiment, each receiver transmits its power requirement to the transmitter, and based on this power requirement, the most power hungry device is used to set the duty cycle of the transmitter. Each individual receiver can continue to monitor its power requirement and make necessary adjustments to ensure efficient power transfer. Once all the devices are fully charged, the transmitter can be powered off or have its duty cycle reduced to performance trickle charging. The transmitter can continue to access the load conditions while in standby to detect any new device being placed on the charging pad.

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean Utility models and applications for Utility models since 1975
Japanese Utility models and applications for Utility models since 1975

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) "wireless", "power", "coil", "trans", "induct", "duty"

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2007-015599 A1 (LS CABLE LTD.) 08 February 2007 See abstract; paragraphs [0039]-[0074]; claims 1,4,5,8,10,13,14,16,23,33; figures 1-4.	1-28
Y	US 2008-0067874 A1 (RYAN TSENG) 20 March 2008 See abstract; paragraphs [0044]-[0079]; claims 7,11,12,14,18,19; figures 1,9,13,32.	1-28
A	US 2007-0103110 A1 (JOHN CHARLES CALHOON et al.) 16 June 2005 See abstract; paragraphs [0031]-[0052]; claims 1,2,10,14; figures 2-4.	1-28
A	US 2005-0127868 A1 (DAVID W. BAARMAN) 08 July 2004 See abstract; paragraph [0030]-[0034]; figures 2,3.	1-28

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
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"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 NOVEMBER 2009 (30.11.2009)	**30 NOVEMBER 2009 (30.11.2009)**
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Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2007-015599 A1	08.02.2007	CN 101233666 A	30.07.2008
		JP 2009-504117 A	29.01.2009
		KR 10-2007-0015264 A	02.02.2007
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(74) Agent: **PARKER, James, S.**; Saliwanchik, Lloyd, Saliwanchik, P.O. Box 142950, Gainesville, FL 32614-2950 (US).

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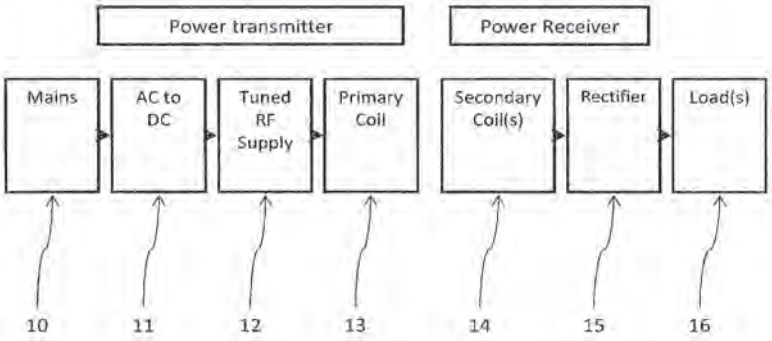


FIG. 1

(57) Abstract: Embodiments of the subject invention pertain to a method and apparatus for contactless power transfer. A specific embodiment relates to an impedance transformation network, a new class of load network for application to a contactless power system. Embodiments of the impedance transformation network enable a contactless power system to operate without encountering the common problems of: 1) over-voltage and/or under-voltage conditions; 2) over-power and/or under-power conditions; 3) power oscillations; and 4) high heat dissipation.

DESCRIPTION

METHOD AND APPARATUS FOR CONTACTLESS POWER TRANSFER

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 61/059,663, filed June 6, 2008, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

In recent years, inductive charging technology has become a leading candidate to eliminate power cables. Inductive power systems and other contactless power systems typically use one or more transmitters to send power to one or more receivers. Electronic devices with contactless power receivers can be powered or charged by being positioned in close proximity to a contactless power transmitter. Such systems have been designed and implemented.

Contemporary contactless power systems are make use of switch-mode inverters, such as the Class, D, DE, E, E^{-1}, F, F^{-1}, EF, EF2, EF3, Phi. The switch-mode inverter converts DC voltage that is provided by a DC voltage source to into a high frequency signal that enables efficient coupling of one or more primary coils to one or more secondary coils. The secondary coils are ultimately connected to one more loads. In the case of a contactless power transfer system the load of an inverter is typically a portable electronic device or some other load device with a variable power requirement. In many instances the load has an input impedance that is variable. The load can use energy or it can be designed to store energy. The load can comprise a voltage regulator and / or a power management system for regulating and relaying the power to an energy consuming or energy storing element. The impedance of the load helps determine the loading condition.

A typical switch-mode inverter comprises an active device, a supply network, and a load network with output terminals for connecting to a load.

The active device is typically a transistor and operates as a switch. The switch alternates between a conductive and non-conductive state. A control signal from a gate drive or clock can be used to operate the switch. The switch is connected to a supply network and a load network. The switching of the active devices helps form an AC signal at the output of the load network.

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The supply network relays power from a source the DC voltage source to a terminal of the active device. The DC voltage source can have an output voltage that is variable. The supply network can be a simple inductor and typically comprises passive components. In some cases it may comprise an active device or variable elements for active reconfiguration of the supply network. A reconfiguration of the supply network can be performed depending on the load conditions in order to optimize efficiency or regulate the power which is delivered from the source.

The load network relays power to the load device from a terminal of the active device and supply network. The load network typically comprises passive components. In some cases it may contain an active device or variable for active reconfiguration of the load network. A reconfiguration of the load network may be performed depending on the load conditions in order to optimize efficiency and / or regulate the power delivered to the load.

The load network includes one or more primary coils for inductively coupling to one or more secondary coils. Because of size mismatches and restrictions on the use of bulky core materials, the coupling between the primary and secondary coils can be weak thereby reducing efficiency, power delivery, or both.

In order to compensate for weak coupling between primary and secondary coils, typical inductive charge systems typically operate at frequencies greater than 50kHz. At these higher operating frequencies soft-switching inverters, such as the Class E, E^{-1}, are preferred because they are more efficient than hard-switching inverters. High efficiency is preferable for environmental and regulatory reasons as well as practical reasons such as minimizing heat dissipation.

Soft-switching describes a mode of operation where an active device, such as a transistor, will switch when either the voltage or current across the transistor is zero. Soft-switching eliminates losses that normally occur with hard switching due to switch capacitance and the overlap of voltage and current in the switch. For example, in the case of zero voltage switching, the voltage across a transistor to swings to zero before the device turns on and current flows. Likewise, at turn-off, the voltage differential across the active device swings to zero before it is driven to a non-conductive state.

A practical system is preferably capable of matching the power supplied to the power demanded by a load device. This is important because many load devices have variable power requirements. If the power delivered does not match power required, the excess energy can be dissipated as heat. A load device can have an input impedance that is variable because of a power requirement that is variable (see Figure 5 for a graph of resistance versus changing

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time for a typical cell phone battery). The input impedance of the load device can change by an order of magnitude. The input impedance of a voltage regulator connected to a portable electronic device can change by two orders of magnitude. The variable impedance of a load device makes the implementation of contactless power system difficult.

The following two characteristics of soft-switched inverters found in typical contactless power system make the adaptation to a load device with a variable impedance challenging: 1. Most switch-mode inverters have high efficiency over a narrow range of impedances. As an example, a class E inverter typically operates under, high-efficiency soft-switched conditions over a factor of two in load impedance (see Figure 3) (Raab, 1978). (see Figure 2 for a graph of efficiency versus normalized resistance for typical switch-mode inverters); 2. The output power vs. load impedance relationship of a switch-mode inverter is different than the output power vs. load impedance relationship of a DC supply (See figure 4 for a graph of power delivery vs. load resistance for a DC supply and an inverter). Because of this, a load device's pre-existing power management control system can fail to appropriately regulate the power delivered to the load device which can lead to component failure.

Due to the above described characteristics a contactless power system is likely to encounter one or more of the following problems: 1) over-voltage and/or under-voltage conditions throughout the circuit; 2) excess or inadequate power delivery to individual loads 3) power oscillations; 4) heat problems; and 5) low efficiency.

Notably, a class D inverter architecture does not share the unfavorable characteristics and resulting problems of the other soft-switched inverters. Class D inverters are optimized for driving an impedance looking into the load network that has zero-phase angle (ZPA), and works for positive phase angles. Zero phase angle operation can be maintained by eliminating the reactance in a circuit of by using a combination of control functionalities, including, but not limited to, frequency, and tank circuit control (see Figures 7 and 8). A contactless power system with other soft-switched inverter architectures would be expected to make use of similar control functionality because of their sensitivity to the input impedance of the load(s). (Laouamer, R., *et al.*, " A multi-resonant converter for non-contact charging with electromagnetic coupling," in *Proc. 23rd International Conference on Electronics, Control and Instrumentation*, Nov 1997, Vol. 2, pp. 792 – 797; Abe, H., *et al.*, "A non-contact charger using a resonant converter with parallel capacitor of the secondary coil," in *Proc. Applied Power Electronics Conference and Exposition*, 15-19 Feb 1998, Vol. 1, pp. 136 – 141; Joung, G. B. *et al.*, "An energy transmission system for an artificial heart using leakage inductance compensation of transcutaneous transformer," *IEEE Transactions on Power*

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Electronics, Vol. 13, pp. 1013 – 1022 Nov 1998; Lu, Y., *et al.*, "Gapped air-cored power converter for intelligent clothing power transfer," in *Proc. 7th International Conference on Power Electronics and Drive Systems,* 27-30 Nov. 2007, pp. 1578 – 1584; Jang, Y., *et al.*, "A contactless electrical energy transmission system for portable-telephone battery chargers," *IEEE Transactions on Industrial Electronics*, Vol. 3, pp. 520 – 527, June 2003; Wang, C., *et al.*, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer system," *IEEE Transactions on Industrial Electronics*, Vol. 51, pp. 148 – 157, Feb. 2004; Wang, C., *et al.*, "Investigating an LCL load resonant inverter for inductive power transfer applications," *IEEE Transactions on Power Electronics*, Vol. 19, pp. 995 – 1002, July 2004; Wang, C., *et al.*, "Design consideration for a contactless electric vehicle battery charger," *IEEE Transactions on Industrial Electronics*, Vol. 52, pp. 1308 – 1314, Oct. 2005) Control functionality adds to the cost and complexity of a system and detracts from the commercial viability.

To enable better control functionality and to ensure proper operation of the system, communication systems between the power supply and the load have been proposed (see Figures 6 and 9). Such communication systems also add undesirable cost to the system.

The previously described control functionality has been implemented in both contactless power transmitters and contactless power receivers. Control functionality in the receiver has been considered of particular importance when multiple loads require power from the same transmitter. To support multiple loads, it has been proposed that receiver units incorporate mechanisms such as, but not limited to, variable inductance and duty cycling. These mechanisms allow multiple loads to receive power from the same source by giving load devices a mechanism to protect themselves from over-voltage and/or current conditions (Figure 6). These mechanisms are of high importance because loads without such mechanisms will continue to receive power even when they no longer require power. The power will be dissipated as heat in the load device. Contemporary batteries will not charge at temperatures over 50°C. These systems also add undesirable cost to the system.

SUMMARY OF THE INVENTION

Embodiments of the subject invention pertain to a method and apparatus for contactless power transfer. A specific embodiment relates to an impedance transformation network, a new class of load network for application to a contactless power system. Embodiments of the impedance transformation network enables a contactless power system to operate without encountering the common problems of: 1) over-voltage and/or under-

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voltage conditions; 2) over-power and/or under-power conditions; 3) power oscillations; and 4) high heat dissipation.

Embodiments of the impedance transformation network enables the contactless power system to avoid one or more of the four common problems described above, without any feedback, communication, and/or control functionality. The pre-existing power and battery charge management circuitry for a load, which may include a voltage regulator, can regulate the power output of a contactless power system under normal modes of operation. In accordance with embodiments of the invention, contactless power systems can be combined with very simple controls to improve the performance of the system. In this preferred mode of operation, a contactless power system can predictably and reliably deliver power to a load across a wide range of load impedances.

Embodiments of the invention provide one or more of, and a preferred embodiment of the invention provides each of, the following four functions:

1) Reactance shifting and phase angle control: a reactance is added to the resistance looking from the switch-mode supply through the load network. The reactance is shifted such that the phase angle looking from the switch-mode inverter into the load network is within a range that provides substantially soft-switching operation of the active device either when connected to or disconnected from one or more loads. Embodiments of the invention use the phase angle to control the power delivered by the inverter. Such embodiments can take advantage of the correlation between phase angle and load resistance. Changes in load resistance are transformed into a shift in the phase angle looking into the impedance transformation network. The output power response is more pronounced with respect to phase than with respect to load resistance (see Figure 12). This enables the invention to match power delivery and more closely mimic the response of a traditional DC supply (see Figure 13). In this method of operation, the contactless power system can deliver the necessary amount of power to the load. The soft-switching operation of the active device is preferably maintained for all load impedances.

If the inverter is designed for soft switching when the impedance looking into the load network from the active device is inductive, then the impedance transformation network is configured such that the impedance of the phase angle looking from the active device into the load network is positively correlated with the effective resistance of the load(s). If the effective resistance of the load increases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network increases. If the effective resistance of the load decreases, then the impedance transformation

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network is configured such that the phase angle looking from the active device through the load network decreases. In a specific embodiment the reference phase angle is 40 degrees or greater, and in another 45 degrees or greater. In further embodiments, increases in load resistance can increase the phase angle up to 85 degrees.

If the inverter is designed for soft switching when the impedance looking into the load network from the active device is capacitive, than the impedance transformation network can be configured such that impedance of the phase angle looking from the active device into the load network is negatively correlated with the effective resistance requirement of the load. If the effective resistance of the load increases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network decreases. If the effective resistance of the load decreases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network increases.

The effective resistance is a combination of the resistances of the loads looking from the terminals of the secondary coils toward the load. The loads can be seen as in series or parallel. The loads can be seen as the series or parallel combination of the inverse of the individual load resistances. In the generalized form, the effective load resistance of any close proximity contactless power system via magnetic induction that incorporates m primary coils and n secondary coils can be described by:

$$Z_{in} = \{1_{1M}[\mathbb{Z}^{IV} - (\mathbb{Z}^{II})^T(\mathbb{Z}^{I})^{-1}\mathbb{Z}^{II}]^{-1}1_{M1}\}$$

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}^{III} & (\mathbb{Z}^{II})^T \\ \mathbb{Z}^{II} & \mathbb{Z}^{I} \end{bmatrix}$$

$$\mathbb{Z}_{ab} = \begin{cases} j\omega L_a + R_a & \text{for } a = b \\ j\omega M_{ab} & \text{otherwise} \end{cases}$$

$$\mathbb{Z}^{IV} = \mathbb{Z}^{III} + Z_{in}1_{MM}$$

Zin: Input impedance looking into the primary coil

1_{1M}: Vector of 1's of length M

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1_{MM}: M X M matrix of 1's

Z: Impedance matrix

Z_{ab}: Element ab of the impedance matrix

Z^{I} : Sub-matrix of Z

Z^{II}: Sub-matrix of Z

Z^{III}: Sub-matrix of Z

M_{ab}: Mutual inductance between the a^{th} and b^{th} coil

j: imaginary number

a: coil index

b: coil index

ω: radian frequency

R_a: Parasitic resistance of the a^{th} coil

L_a: Self inductance of the a^{th} coil

Typically, the power requirement of the device is negatively correlated with load resistance. As the resistance of the load increases the power required by the load decreases.

2) Resistance isolation: the resistance looking from the switch-mode supply through the load network can be minimally affected by changes in load resistance (see Figure 10);

Embodiments of the invention can isolate the switch-mode supply from changes in load resistance in order to improve the predictability and stability of the output power. The isolation from changes can be accomplished by the implementation one or more filter networks such that the range of resistances presented by load appear much narrower at the output terminals of a switch-mode inverter. The switch-mode supply should see a resistance such that it is in a high efficiency mode of operation (see Figure 2).

3) Frequency filtering: a filter removes extra harmonics, effectively "cleaning" the power signal before it enters the primary or secondary coil. In one embodiment this frequency filter incorporates an inductor and a capacitor with a "low Q" value. In another embodiment this frequency filter incorporates an inductor and a capacitor, the filter being considered to have a high Q value.

4) Coupling: at least one primary coil in the load network is inductively coupled to one or more secondary coils of the same load network. The primary coils can be configured in a spiral configuration and maybe designed with a variable pitch in order to create an even

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magnetic field distribution. The primary coils can be arranged in an array pattern with each coil in the array wound with an irregular shape so that the array has a substantially even magnetic field distribution. The secondary coils can be coupled to the primary coil in any position or orientation. The secondary coil can be adapted to attach to a load. In a preferred embodiment the secondary coil is adapted to attach to a portable electronic device. In specific embodiments, both the primary coil and the secondary coil are the same size to maximize coupling. In this example, and other specific embodiments, the receiver coil is significantly smaller than the primary coil, in order to allow the user to place the device in any orientation. It is desirable for the secondary coil to be much smaller than the primary coil, but the efficiency and power transfer capabilities start to degrade significantly if the receiver is too small, due to poor coupling. In this example the secondary is wound along a single path with minimal spacing between turns in order to minimize the occupied volume and ease integration.

The voltage and current characteristics of the primary coil and the secondary coil can be described using the following equations [7][12]:

$$V_1 = M_{11}\frac{dI_1}{dt} + M_{12}\frac{dI_2}{dt} \quad (1)$$

$$V_2 = M_{21}\frac{dI_1}{dt} + M_{22}\frac{dI_2}{dt} \quad (2)$$

$$M_{12} = k\sqrt{M_{11}M_{22}} \quad (3)$$

Where

V_1 is the voltage at the transmitting coil

I_1 is the current at the transmitting coil

V_2 is the voltage at the receiving coil

I_2 is the current at the receiving coil

M_{11} is the self inductance of the transmitting coil

M_{22} is the self inductance of the receiving coil

$M_{12} = M_{21}$ is the mutual inductance of the two coils

k is the coupling coefficient between the two coils

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By Ohm's law:

$$Z_{in} = R_{tx} + jX_{tx} = \frac{V_1}{I_1} \quad (4)$$

$$Z_{rx} = R_{rx} + jX_{rx} = \frac{V_2}{I_2} \quad (5)$$

Solving equations (1-3)

$$Z_{in} = \frac{\omega^2 M_{12}^2 R_{rx}}{R_{rx}^2 + (\omega M_{22} + X_{rx})^2} + j\left(\omega M_{11} - \frac{\omega^2 M_{12}^2 (\omega M_{22} + X_{rx})}{R_{rx}^2 + (\omega M_{22} + X_{rx})^2}\right) \quad (6)$$

The above equations neglect any 2nd order effects such as skin depth and proximity effects. A more in-depth analysis accounting for the above effects can be utilized. In an embodiment, litz wires can be used to mitigate such effects to the extent that they do not create significant discrepancies.

By using the combination of resistance isolation and phase angle control, a reliable, stable transmitter can power a variable load. First, the inverter preferably will not fail or overheat when the secondary coil is removed from the primary coil. Although a load detection scheme can be used to turn off the transmitter and reduce unloaded power losses, it can still be desirable for the unloaded power consumption to be sufficiently low. Since the coil voltage is unique to each load resistance as shown in Figure 49, load detection and status can be easily acquired. To avoid false detection, the load detection and status can be verified by analyzing the supply current via a current sense resistor. Limiting unloaded power loss can be achieved by ensuring the unloaded transmitting load network has effective impedance similar to a high load resistance case (high impedance with large phase angle). From the schematic of the class E circuit in Figure 44, it can be deduced that most of the power lost is due to the primary coil and inductor parasitic resistances as they are in the path of power transfer. Therefore, one way to reduce the unloaded power loss is to use an inductor with lower parasitic resistance.

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BRIEF DESCRIPTION OF DRAWINGS

The foregoing and other objects, features, and advantages of the present invention, as well as the invention itself, will be more fully understood from the following description of various embodiments, when read together with the accompanying drawings.

Figure 1 shows a typical contactless power system that uses an inverter to drive a primary coil that may couple to one or more secondary coils and loads.

Figure 2 shows the operating efficiency versus load resistance seen by an inverter (Class E) that is driving load resistances from .1 to 10, a span that reaches two orders of magnitude, where the high efficiency operating range for the inverter is identified, and the operating range of a typical portable electronic device is identified.

Figure 3 shows the power in (Pi) and power out (Po) versus load resistance seen by an inverter (Class E) that is driving load resistances from .1 to 10, a span that reaches two orders of magnitude, where the high efficiency operating range for the inverter is identified, and the operating range of a typical portable electronic device is identified.

Figure 4 shows the power delivered to a variable load resistance from two different sources: a tuned switch-mode inverter supply and a fixed voltage DC supply, illustrating that power delivered to the load across a range of impedances is very different depending on the source, and that the range of output power can be much smaller with switch-mode inverters.

Figure 5 shows the load resistance of a Motorola Razr during the charge cycle, illustrating that during the charge cycle, the resistance can change by greater than one order of magnitude.

Figure 6 shows a block diagram of a typical prior art contactless power system, including commonly proposed and implemented communication and control functionality.

Figure 7 shows a logic diagram, which is continued in Figure 8, of a typical prior art contactless power system, including commonly proposed and implemented control functionality.

Figure 8 shows a continuation of the logic diagram of Figure 7.

Figure 9 shows a block diagram of a typical prior art wireless power system with communication capability.

Figure 10 shows the correlation between load resistance and the resistance looking from the inverter in accordance with an embodiment of the subject method, where the load resistance is transformed such that the resistance seen by the switch-mode supply is relatively constant, and in particular, the resistance from the supply is seen as between 2 and 6 ohms while the resistance of the load is varied from 5-500 ohms.

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Figure 11 shows the operating efficiency and power output of a class E inverter that is driving a fixed resistance with a phase angle ranging from -90 to 90 degrees, where the operating region for an embodiment of the invention is indicated.

Figures 12A and 12B show the power output of a class E inverter in response to variable load resistance and variable phase, respectively, showing a calculation of output range and compares them against each other.

Figure 13 shows the power delivered to a variable load resistance from three different sources: an inverter, a fixed voltage DC supply, and a switch-mode inverter operating in accordance with an embodiment of the invention.

Figure 14 shows the decoupling, or degradation of coupling efficiency between the load and the transmitter for various filter networks.

Figure 15 shows a block diagram of a system in accordance with an embodiment of the subject invention, where the block diagram shows the direction of power flow and the various networks that can be used.

Figure 16 shows a typical load resistance vs. time plot as seen from the input of a rectifier feeding into a device.

Figure 17 shows the real and reactive components of the impedance as seen looking into the receiver side impedance transformation network, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 18 shows the real and reactive components of the impedance as looking into the primary coil, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention .

Figure 19 shows the real and reactive components of the impedance as seen from the transmitter side load-transformation network, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 20 shows the real and reactive components of the impedance as seen from the transmitter-side, phase shift network, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 21 shows the phase angle of the impedance as it is seen from the inverter, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

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Figure 22 shows the actual power delivery and efficiency of a system that is operating in accordance with a preferred embodiment of the invention.

Figures 23A-23C show the actual power delivery and efficiency for another system in accordance with the invention. The experimental results are from a 12V supply system. Efficiency peaks at main power delivery band, which is approximately 25-100Ω load resistance, are shown. Power delivery drops rapidly after 100Ω, when the system goes into low load condition or trickle charge condition. Although the efficiency at high load resistance is poor, the absolute power loss is kept at about 1.75W, while power delivery continues to drop. This power loss is distributed in the system and little or no heat issues are observed (especially at the receiver) during the low load operation.

Figure 24 shows the phase angle of the impedance as it is seen from the inverter, where the impedance characteristic at this point is measured from a system operating in the non-preferred mode of operation.

Figure 25 shows the actual power delivery and efficiency of a system that is operating in the non- preferred mode of operation.

Figures 26A-26B show the instantaneous peak power loss for hard switching topologies, known in the art, as they are compared to soft-switching topologies, known in the art, where Figure 26A shows a "hard switching" topology power loss waveform for a bridge MOSFET (320 W/div) showing high instantaneous peak power loss during each switching cycle, and Figure 26B shows a "soft switching" topology power supply with the same rating as that in Figure 26A.

Figure 27 shows the real and reactive components of the impedance as seen looking into the receiver side impedance transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 28 shows the real and reactive components of the impedance as looking into the primary coil, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 29 shows the real and reactive components of the impedance as seen from the transmitter side load-transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 30 shows the real and reactive components of the impedance as seen from the transmitter-side, phase shift network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

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Figure 31 shows the circuitry shown in Figure 68 with dotted lines, labeled A and B, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 32 shows the block diagram of Figure 15 with dotted lines, labeled A and B, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 31.

Figure 33 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 34 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 33.

Figure 35 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 36 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 35.

Figure 37 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 38 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 37.

Figure 39 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 40 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram

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elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 39.

Figure 41 shows a typical inductive coupling system.

Figure 42 shows some of the possible topologies for a single-element transformation network.

Figure 43 shows some of the possible topologies for a single-element transformation network.

Figure 44 shows a typical Class E driver using parallel-parallel transformation network.

Figure 45 shows a dual channel class E driver that can be used in accordance with an embodiment of the invention.

Figure 46 shows an impedance response looking into receiver with different parallel capacitor value.

Figure 47 shows an optimum receiver capacitor value across a range of load resistances to achieve maximum R looking into the transmitter coil.

Figures 48A-48B show a coupling efficiency and transformed impedance looking into the primary coil.

Figure 49 shows a normalize primary coil voltage across a range of load resistances.

Figure 50 shows a load network reactance with different transmitter capacitor.

Figure 51 shows an amplitude and phase of impedance of unloaded transmitter load network with different C_{tx}.

Figure 52 shows an impedance looking into transmitter load network.

Figure 53 shows a phase looking into transmitter load network.

Figure 54 shows a power delivered into the transmitting load network if transmitter is an ideal sine voltage source.

Figure 55 shows a transistor drain voltage where C_{shunt} = 19nF.

Figure 56 shows a dual channel class E driver.

Figure 57 shows a primary coil – 10 turns (embedded into the table top) and secondary coil – 5 turns (taped up).

Figure 58 shows a power delivery and efficiency of 120V system with a peak power of 295W.

Figure 59 shows a temperature of transistor and inductor with natural convection cooling and forced cooling.

Figure 60 shows a dual channel class E with forced air cooling.

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Figure 61 shows a waveform of the class E driver.

Figures 62A-62B show power delivered to load with respect to load resistance. Peak power occurs at approximately 50Ω load resistance for dual channel at 69W for dual channel and 75Ω for single channel at 10W for single channel.

Figure 63 shows system efficiency with respect to load resistance with both peak efficiency of 64.5% for single channel and 76% of dual channel at approximately 70Ω load resistance.

Figure 64 shows transmitter efficiency with respect to load resistance. Peak transmitter efficiency occurs across the band of 60Ω to 100Ω load resistance at 90% for dual channel and 79% for single channel.

Figure 65 shows system efficiency with respect to load resistance with both cases achieving high efficiency at heavy load and also illustratin that a single channel mode is more efficient at low power delivery state.

Figure 66 shows primary coil RMS voltage having a unique load resistance for each value.

Figure 67 shows receiver DC voltage converging to approximately 70V for dual channel and 37V for single channel.

Figure 68 shows a generalized contactless power system with a single transistor power amplifer in a single ended configuration.

Figure 69 shows a generalized contactless power system with two, single transistor power amplifiers in a push-pull configuration.

Figure 70 shows a generalized contactless power with a two transistor power amplifier in a single ended configuration.

Figure 71 shows a generalized contactless power system with two, two transistor power ampliferrs in a push-pull configuration.

Figure 72 shows different supply network configurations that are used to connect a DC supply voltage to a terminal of the active device of a power amplifier.

Figure 73 shows the functions of a impedance transformation network for a single ended system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 74 shows the functions of a impedance transformation network for a push-pull system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

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Figure 75 shows various circuit elements arranged to achieve the fuction of reactance shifting. These circuit elements, or variants thereof, can add or remove the mangitude of reactance looking into the impedance transformation network. Inductive elements increase reactance. Capacitive elements decrease reactance.

Figure 76 shows various circuit elements arranged to achieve the fuction of frequency filtering. Two notch filters are shown that can remove unwanted harmonics from the signal. A combination of other filter types can be used to achieve frequency filtering.

Figure 77 shows various circuit elements arranged to adjust the correlation between the equivelent resistance and the phase of the load. Inductive elements will tend to result in a positive correlation between phase and load resistance. Capacitive elements will tend to result in a negative correlation between phase and load resistance. These elements can also serve the purpose of resistance compression.

Figure 78 shows primary to secondary coil configurations. The impedance transformation network may comprise a single primary and a single secondary. Alternatively, the impedance transformation network may comprise one or more primary coils coupled to one or more secondary coils. The inductance of the primary and/or secondary coil(s) can be used to compress resistance and change the phase vs. resistance relationship.

Figure 79 show various circuit elements arranged to compress the resistance seen looking into the impedance transformation network. Either capacitive or inductive elements can be used.

Figure 80 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 81 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 82 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 83 shows a typical configuration of an impedance tranformation network connected to an active device.

DETAILED DISCLOSURE

Contactless power systems typically use high frequency power electronics to deliver power to one or more loads. Figure 1 shows the fundamental components of many contactless power systems. A contactless power supply generally draws its power from the electrical grid through a standard wall outlet **10**. The power from the wall is typically AC so it is generally

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converted to DC voltage by an AC to DC converter 11. In order to shrink the size of components it is desirable to work at a high frequency, so the DC voltage is switched by an inverter **12**. The high frequency signal, such as a high frequency voltage signal or high frequency current signal, is fed into one or more primary coils **13**. The high frequency signal may pass through one or more filters before it feeds in to the primary **13**. The primary coil **13** couples with one or more secondary coils **14**. The secondary coil **14** will receive the high frequency power signal and will feed that into a rectifier **15**, which will then output power to the load **16**. One or more filter networks may be present between the secondary coil **14**, rectifier **15**, and load **16**. Voltage regulation and battery charge management circuitry may be considered part of load **16**.

The incorporation of a switch-mode inverter can make it difficult to deliver the correct amount of power to the load or loads. This is partially attributable to the limited range of load resistances that enable high-efficiency operation. Figure 2 shows the high efficiency operating range **20** of an inverter as it compares to the operating range **21** of a typical battery operated device. The operating range of resistances of the battery operated device is substantially wider than the high efficiency operating range or the inverter. Figure 3 shows the relation of input power **34** and output power **33** of an inverter across a range of resistances. The lost power can be calculated by subtracting output power **33** from input power **34**. The power loss is significant outside the high efficiency operating region **31**.

Switch-mode inverters are difficult to implement in contactless power systems with variable loads because the output power response relative to load resistance is very different than a DC supply's output power response relative to load resistance. Figure 3 shows output power **33** increasing with load resistance until it reaches a center value and decreases again. This is different than a typical constant-voltage DC supply whose power delivery follows the relationship P=V^2/R. The difference is illustrated in Figure 4 where we can see that the power delivery from a DC supply **41** will decrease rapidly with an increase in load resistance. By contrast, the output power from an inverter **42** will increase with load resistance and will later drop as load resistance continues to increase. The drop in power delivery **42** is markedly slower than the drop in power delivery **41**. Although Figure 4 shows the curve for one example of a tuned switch-mode inverter supply, other tuned inverters can have different curves.

Portable electronic devices display a wide range of input resistances. Figure 5 shows the effective resistance **51** looking into a Motorola Razr during the charge cycle. Figure 5

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shows the wide dynamic range of the load **52**, and in this case it is greater than one order of magnitude.

The aforementioned challenges of efficiency and power delivery can be overcome by implementing a variety of communications and controls. Figure 6 shows a contactless charging system that is an elaboration of the basic components and systems show in Figure 1. The grayed blocks are components that are found in a basic contactless power system. The white boxes are components that enhance the performance of a typical contactless power system. It show a transmitter control **60** which can alter the phase, duty cycle, frequency, tank circuit impedance, or rail voltage depending on loading conditions. There is a detection circuit **61** that draws information from various parts of the circuit and feeds that information back into the controller **60**. It show contactless communication links **62** on both the transmitter side **66** and receiver side **67**. The communication link can work in conjunction with the detection mechanisms **61** to help the controller **60** make the most appropriate adjustments to the system. The receiver side **67** also has a controller **63** which can adjust the resonant frequency, duty cycle **65**, or perform other functionality to regulate power being delivered to the load. A front end regulator **64** is added to provide an additional level of protection to the load.

With a system such as the one in Figure 6 in place, designers can implement control logic such as that shown in Figure 7 and Figure 8 taken from a prior art system. We can see from Figure 8 **433**, **434**, **436**, **438**, **440**, **442** some of the logic functionality that designers have built into contemporary contactless power systems. We can see from **432** that this system includes memory in order to achieve the desired functionality. Figure 9 shows another prior art system that uses a communication mechanism **91** on the receiver and a communication mechanism **90** on the transmitter. The communication, logic, and use of memory add additional cost to the system and require a large number of sensing points to be considered.

In order to stay within the high-efficiency operating region **20** and to match the power delivery of DC supply **41** several steps can be taken. Figure 10 shows the resistance seen by the switch-mode supply **100** as it compares to actual load resistance. From **100**, we can see that the resistance appears to vary from 2 to 6 ohms over a range from 5 to 500 ohms. This enables the switch-mode supply to stay in the high efficiency region **20** shown in Figure 2, regardless of load resistance.

Compressing the resistance will not solve the problem of improper power delivery. Figure 2 shows that if we keep the resistance in a narrowband, power output changes

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minimally. In fact, the compression would exacerbate the power delivery discrepancy shown in Figure 4 where we see that power output response to load resistance from a switch-mode supply **42** does not match the power output response to load resistance from a constant voltage, DC supply. If too much power is delivered, the device may be destroyed, if too little is delivered it may not function.

In order to address the challenge, the phase angle of the load can be affected in order to affect the power output of the switch-mode supply, in accordance with embodiments of the invention. Figure 11 shows, for class E inverters, that an increase or decrease in phase correlates with an increase or decrease in output power. Input power **111** and output power **110** matched closely for a phase angle in the range of about +45 to +80 degrees. Even though efficiency **112** drops considerably as the phase angle approaches +90 degrees, the absolute power lost remains low. The use of phase angle control enables a +/-70% usable range of output power **113** with very low absolute power loss.

Embodiments of the invention use phase angle control to power a battery operated device. Conventional voltage regulators increase the resistance so that the power output of a DC supply is reduced **41**. Figures 12A-12B show, for class E inverters, the difference between using traditional resistance controlled output power vs. using phase controlled output power in accordance with embodiments of the invention. Referring to Figure 12A, in a resistance controlled scheme, input power **122** matches power out **123** for a very small dynamic range **125** of output power. This shows that varying the resistance is an ineffective way of controlling output power. The usable range of power levels for a resistance controlled scheme is only about +/- 9% **125** of the center value. Outside of this range the high absolute losses are high and can create harmful heat and wear and tear on components. Referring to Figure 12B, in a phase controlled scheme, input power **121** matches power out **120** for a much wider dynamic range of output power **124**. This shows that varying the phase dramatically increases the output power range. The usable range of power levels is +/- 70% **124** of the center value. Even though resistance may drop over this range, the absolute power losses are relatively low in this band **124**. Efficiency can be low, but total dissipated power is very low. The low absolute power loss avoids the problem of overheating and device damage.

By combining the resistance compression and the phase control, the contactless system can achieve a power output response to load resistance that is very similar to that of a conventional DC supply. Figure 13 shows the power output response of a DC supply **130**, an inverter **131**, and an inverter in accordance with an embodiment of the subject method of

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operation **132**. The output power in response to load resistance of the inverter in accordance with the embodiment of the subject method of operation **132** is much closer to the output power a device should expect from a constant voltage DC supply **130**.

An additional challenge to designing and implementing a contactless power system is that multiple loads may draw power from a single source. This is problematic when different devices have different power requirements. For instance, a fully discharged cell phone may require 10-15 times the power of a fully charged cell phone. Embodiments of the subject method of operation can provide a mechanism to protect individual devices from damage if the power output exceeds the device requirement. Loads that no longer require power can be decoupled from the primary coil. De-coupling can include degradation in coupling efficiency so that the load is effectively isolated from the transmitter. This can be accomplished by using pre-existing voltage regulator behavior. As a voltage regulator increases the effective input resistance, coupling efficiency drops and vice-versa.

Figure 14 shows the decoupling effect for various receiver circuits. A parallel capacitor can be selected to tune the decoupling point, which is the point when efficiency of receiver is at 50%. For this case, the decoupling point for 100nF capacitor is at 700Ω, whereas the decoupling point for 150nF capacitor is at 320Ω. We can see that for various configurations **141**,**142**, **143** the rate of decoupling occurs at varying rates. **143** shows a curve that is a good fit for a single device charger that can regulate power output from the transmitter. **141** shows a curve that is good fit for a multi-device charger where individual loads may need to be isolated from the source. Although not shown in Figure 14, when the capacitor valve is changed the power received is also changed.

In order to accomplish this method of operation without any communication and control functionality, other than the pre-existing control found in today's voltage regulators, embodiments of the subject system can use a series of carefully tuned transformation networks that transform, compress, and shift the impedance of the load. Through these filter networks the resistance can be compressed, the phase angle manipulated, and the loads allowed to decouple from the primary.

Example 1:

A high power, high-efficiency contactless power transfer system using the impedance transformation network and has been designed and fabricated using the subject impedance transformation network. The contactless transfer system requires minimal control to achieve the desired power delivery profile across a wide range of load resistances, while maintaining high efficiency to which helps to prevent overheating of components. This embodiment of the

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subject system includes more than one active device with independent gate drive to control power delivery. The system is able to achieve power delivery of 295W to a load of 50Ω with a DC voltage of 121.5V and current of 2.43A. The input current was current-limited at 3.25A. The system efficiency at maximum power output is 75.7%. The system operates at a minimum of 77% efficiency across load resistances ranging from 60Ω to 140Ω which corresponds to a high output power state. The system can be scaled to achieve higher output power if the current limit is removed. Higher efficiency and better power delivery can be achieved by using components with lower parasitic resistance.

The DC source voltage is the 600W CSI12005S power supply by Circuit Specialists, Inc rated at 120V at 5A. The active devices are transistors, specifically the transistors are part IRFP21N60L from International Rectifier.

A pair of coils was fabricated using 16 AWG magnet wire for the set-up. The primary coil is 21cm by 21cm with 10 turns with variable spacing between turns while the secondary coil is 13cm by 13cm with 5 turns wound along the same path. Figure 57 shows the primary coil embedded in plastic with the secondary coil placed on top. The primary and secondary coils are separated by a gap of 10mm. The primary coil is designed with the appropriate spacing between the turns to achieve only 5% power variation of the received power at all different locations. In this example, the coupling is approximately constant regardless of the receiver position provided that the entire secondary coil is within the outer perimeter of the primary coil. The self inductance of the primary coil is 31.95μH with a parasitic resistance of 0.32Ω and secondary coil is 12.52μH with a parasitic resistance of 0.2Ω. Mutual inductance between the coils is 7.454uH with a coupling coefficient of 0.373. The measurements were taken using the HP4192A LF Impedance Analyzer.

In order to reduce losses through parasitic resistance, low loss Polypropylene capacitors are used. In order to strike a balance between size and efficiency, 1140-101K-RC by Bourns Jw Miller is selected to be L_{out}. Since most of the losses of the transmitter are from the parasitic resistance of L_{out}, a larger and more efficient inductor can be replaced, if space permits. The fabricated dual channel driver with a dimension of 10cm x 8.5cm is shown in Figure 56. There are a lot of empty spaces; therefore its size can be further reduced. L_{out} takes up a significant amount of space due to the requirement for low parasitic resistance so as to maintain sufficiently high efficiency and power delivery.

Peak drain voltage is only 460V, which is approximately 25% lower than the rated voltage of the transistor used. Figure 58 shows the efficiency and power delivery of the 120V system with respect to load resistance. The power delivery of the system can be scaled by

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varying the supply voltage as long as the DC power supply driving system is able to provide sufficient power and the drain voltage across the transistor stays within its breakdown voltage.

The efficiency of the single channel is approximately 10-15% lower for the same load resistance because the current is flowing through a single L_{out} inductor instead of a pair of them, which means the parasitic resistance is doubled, thus resulting in a low system and transmitter efficiency as shown in Figure 63 and Figure 64, respectively. However, when the system goes into light load mode or trickle charge mode, it would be desirable to go into the single channel mode. It can be seen from Figure 65 that the system efficiency is approximately 15% higher than the dual channel mode for delivering the same amount of power below 10W. Instead of operating at high load resistance for a dual channel mode resulting in high receiver DC voltage as shown in Figure 67, it is possible to achieve similar power delivery at much lower load resistance for a single channel mode resulting in lower receiver DC voltage as lower load resistance would result in higher system efficiency. In addition, a typical buck regulator has higher DC-DC efficiency when the input voltage is lower. Therefore, a load resistance detection scheme can be used to determine the switch over point from dual channel to single channel. It can be seen from Figure 62 that a power delivery of 10W occurs at 500Ω load resistance of the dual channel mode making it a good switch over point. It can be concluded that a 500Ω load resistance would translate to an approximate primary coil RMS voltage of 20V for the dual channel mode as shown in Figure 66. Likewise, if the power requirement for the single channel mode is too high, it can be switched to dual channel mode. It can be inferred from Figure 62 that the switch over point would be approximately 75Ω, which translates to a RMS coil voltage of 22V from Figure 65. The coil voltage can be read using an ADC where the DC voltage at the input of the ADC can be transformed from the coil voltage by rectification and stepping down using a potential divider.

In a specific embodiment, for size and efficiency considerations, capacitors can be used for the network. This is because resistors dissipate power and a low loss inductor would be large in size. Alternative embodiments can incorporate resistors and inductors. Although, a multi-element transformation network might achieve a more appropriate response, for simplicity and low components count, an embodiment of the system uses a single-element transformation network. Four topologies are shown in Figures 42 and 43.

A series capacitor only introduces a negative reactance and does not change the real part of the impedance. A parallel capacitor affects both the real and imaginary part of the

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impedance. For simplicity, the receiver input impedance can be modeled using a variable resistor load such that equation (7) illustrates the transformation performed by the parallel capacitor.

$$Z_{in} = \frac{R}{1+\omega^2 C^2 R^2} - j\frac{\omega C R^2}{1+\omega^2 C^2 R^2} \qquad (7)$$

Equation (7) shows that the resistance is "compressed" non-linearly by a factor of $1/(1+\omega^2 C^2 R^2)$. Thus, the effective resistance decreases with increasing load resistance. At high load resistance, the transformed resistance is small. Therefore, a significant part of the power received is dissipated across the secondary coil as heat. This phenomenon is actually desirable if the receiver is in a state that requires very little power or during trickle charge. Therefore, it has a "decoupling" effect regulating the power delivery with increasing load resistance. However, this should preferably occur only when the transmitter is designed to use limited power at this state of operation as heating would become an issue if too much power is being dissipated across the secondary coil. By using a parallel capacitor, a reactive term can be introduced. The reactive term decreases nonlinearly from null with increasing load resistance with an asymptote of $-1/\omega C$, which can be useful in compensating the secondary coil inductance.

From equation (6) it can be observed that the resistance looking into the transmitter coil can be reduced significantly with the increase of resistance looking from the receiver coil into the receiver. Due to loose coupling between the coils, the resistance looking into the primary coil can be further reduced as the mutual inductance can be relatively low. If the total resistance looking into the primary coil is comparable to the parasitic resistance of the primary coil, limited power is transmitted to the receiver as most of the power would be dissipated across the primary coil as heat. Therefore, it would be preferred for a power transmission via loosely coupled coils to have a parallel capacitor on the secondary coil. By substituting equation (7) into equation (6),

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$$Z_{in} = \left(\frac{\omega^2 M_{12}^2 \left(\frac{R}{1+\omega^2 C^2 R^2} \right)}{\left(\frac{R}{1+\omega^2 C^2 R^2} \right)^2 + \left(\omega M_{22} - \frac{\omega C R^2}{1+\omega^2 C^2 R^2} \right)^2} \right) + j \left(\omega M_{11} - \frac{\omega^2 M_{12}^2 \left(\omega M_{22} - \frac{\omega C R^2}{1+\omega^2 C^2 R^2} \right)}{\left(\frac{R}{1+\omega^2 C^2 R^2} \right)^2 + \left(\omega M_{22} - \frac{\omega C R^2}{1+\omega^2 C^2 R^2} \right)^2} \right) \quad (8)$$

For the transmitter transformation network, a series or parallel topology can be used. However, to maintain an ideal efficiency above 95%, the allowable variation of load resistance of an ideal class E inverter can be kept within +55% and -37% [F. H. Raab, "Effects of circuit variations on the class E tuned power amplifier," *IEEE Journal of Solid-State Circuits*, vol. 13, pp. 239 – 247, Apr 1978.]. Therefore, if the variation of resistance with respect to load resistance looking into the transmitter is too large, it can be preferable to use a parallel capacitor instead of a series capacitor. A capacitor value can be selected that ensures that the transmitter would not suffer immediate failure when there is no secondary coil as well as having an increasing reactance trend with increasing load resistance. Having an increasing reactance trend with increasing load resistance can ensure the preferred power delivery trend.

Figure 15 shows an example configuration of a system that can work in this mode of operation in accordance with an embodiment of the subject invention. Other circuit configurations can also be utilized to work in this mode of operation in accordance with the subject invention. The grayed boxes, which include an AC/DC converter **150**, switch-mode inverter **151**, primary coil **154**, secondary coil **156**, rectifier stage **158**, regulator stage **159**, and load **1500**, are components of a typical contactless power system, for example, as shown in Figure 1. In order to achieve the method of operation in accordance with the subject invention, this system uses four transformation networks, including receiver-side impedance transformation network **157**, coupling network **155**, transmitter-side impedance transformation network **153**, phase shift network **152**. Measuring the impedance at probe points looking into the rectifier stage **1503**, receiver-side impedance transformation network **1504**, primary coil **1505**, transmitter-side impedance transformation network **1506**, and phase shift network **1507**, facilitate a better understanding of the operation.

Figure 16 shows a simulated load resistance vs. time **160** measured looking into the rectifier stage from probe **1503**. The swing from 0-500 ohms is well outside usable operating

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range of an inverter **20** and **31**, shown in Figure 2 and Figure 3, respectively. It would be desirable to compress the resistance into a useable operating range **20**, **31**. At this stage there is no reactive component which is introduced by the impedance transformation network **157** in order to use the phase angle method of power control in accordance with embodiments of the invention.

Figure 17 shows the transformed load resistance **170** looking into the receiver-side impedance transformation stage from probe **1504**. The objective of this stage is to achieve the decoupling effect shown in Figure 14. This decoupling effect is automatic decoupling where the degradation of coupling efficiency between the contactless power transmitter and the load(s) effectively decouples the receiver from the transmitter. Figure 17 also shows the reactive component **171** introduced by the impedance transformation network **157**. The introduction of the reactive component **171** compresses the resistance looking into the receiver in order to stay within the useable operating range of the inverter identified in Figure 2. Additional reactive components will be further added on the transmitter side for implementing the phase-angle method of control in accordance with the invention. At this stage the reactive component **171** decreases with respect to load resistances, which means that phase angle is decreasing with respect to load resistance. From Figure 11, we can see that the working range **114** requires an increase in phase angle for inductive load, to reduce power output. Impedance transformation networks **153** on the transmitter side can compensate from the phase angle introduced by the impedance transformation network **157**.

Figure 18 shows the impedance transformation that is the result of the coupling network **155** and is measured looking into the primary coil **154** from probe **1505**. The objective is to maximize the real part **170** shown in Figure 17, which has been compressed to the point where parasitic losses would become less dominant. Increasing the resistance can improve the efficiency of the circuit. The real part **180** is much greater at this stage and has been increased to maximize power delivery through to the secondary coil **156** and minimize the losses from other parasitic upstream stages closer to the wall outlet, or AC/DC **150**. The negative aspect, however, is that magnitude change of the real component **180** is too large when compared to the working region of a switch-mode supply **20**and **31,** shown in Figure 2 and Figure 3, respectively. This can be corrected by the upstream transformation networks, such as impedance transformation network **153**. The reactive component **181** still trends downward with load resistance and can also be corrected by upstream transformation networks.

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Figure 19 shows the impedance transformation that is the result of impedance transformation network **153** and is measured looking into the impedance transformation network **153** from probe **1506**. The objective is to compress the real component **180** such that it falls within the operating range **20**and **31**, defined in Figure 2 and Figure 3, respectively. The second objective is to transform the reactive component **181** such that the increase in load resistance increases the reactive component and phase angle. The real part **190** is compressed back within the operating range of a switch-mode inverter **20** and **31**. The reactive part **191** has been corrected such that it trends upward with increasing load resistance. This corresponds to an increasing phase angle and decreased power delivery as load resistance increases. The reactive part **191** is negative at this stage and this would correspond to a negative phase angle. From Figure 11, it can be seen, for a class E inverter, that a negative phase angle corresponds with poor efficiency and high actual power losses. The same is true for class D and Phi inverters. The trend is undesirable at this stage because an increase in phase angle on the negative slope of **110** would increase power output. The reactive component can be shifted by phase shift network **152**, for example, so that is falls within the working region **114**.

Figure 20 shows the impedance transformation that is the result of the phase shift network **152** and is measured looking into the phase shift network **152** from probe **1507**. The objective is to keep the real part **190** in the operating range of the switch-mode inverter and shift the reactive part **191** into the operating range of the switch-mode inverter. The real part **200** is within the operating range of resistances of a switch-mode inverter **20** and **31**, from Figure 2 and Figure 3, respectively. The reactive part **201** now falls in the correct operating region **114** shown in Figure 11. Confirmation that the phase angle and trend are correct can be shown by converting **200** and **201** into a phase angle plot, as shown in Figure 21. The phase angle **210** is within the operating region **114** and increases with respect to load resistance. The phase angle **210** has a dip at very low impedances and in specific embodiments the initial dip in phase can be avoided.

Figure 22 shows actual experimental data taken from the system shown in Figure 15. After the 30 Ohm inflection point **220**, power output decreases with load impedance and the system achieves high operating efficiency. Because a typical portable electronic device will operate at impedances greater than 30 ohms when the supply voltage is sufficiently high, this is an example of a preferred power delivery vs. load resistance vs. efficiency plot.

Example 2:

A primary coil parallel capacitor value in a specific embodiment can meet two

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constraints.

Figure 24 offers a contrast to the preferred phase angle vs. load resistance trend shown in Figure 21. The reference phase angle is approximately 80 degrees and decreases with load resistance. The phase angle **240** decreases with load resistance.

Figure 25 shows the result of this mode of operation when there are no communication and control mechanisms in place. The power output increases with load resistance, which is exactly opposite the response of a fixed voltage DC supply **130** which is shown in Figure 13.

Figure 27 shows the real and reactive components of the impedance as seen looking into the receiver side impedance transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 28 shows the real and reactive components of the impedance as looking into the primary coil, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 29 shows the real and reactive components of the impedance as seen from the transmitter side load-transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 30 shows the real and reactive components of the impedance as seen from the transmitter-side, phase shift network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figures 31-40 show a variety of ways that the components of various embodiments of the subject invention can be located, for example proximate the transmitter coil, proximate the receiver coil, or separate from both.

Figure 31 shows the circuitry shown in Figure 68 with dotted lines, labeled A and B, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 32 shows the block diagram of Figure 15 with dotted lines, labeled A and B, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 31.

Figure 33 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

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Figure 34 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 33.

Figure 35 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 36 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 35.

Figure 37 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 38 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 37.

Figure 39 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 40 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 39.

Figure 41 shows a typical inductive coupling system.

Figures 42-83 show various components and systems or subsystems that can be utilized with various embodiments of the invention, and/or data corresponding to various embodiments of the invention.

Figure 42 shows some of the possible topologies for a single-element transformation network.

Figure 43 shows some of the possible topologies for a single-element transformation network.

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Figure 44 shows a typical Class E driver using parallel-parallel transformation network.

Figure 45 shows a dual channel class E driver that can be used in accordance with an embodiment of the invention.

Figure 46 shows an impedance response looking into receiver with different parallel capacitor value.

Figure 47 shows an optimum receiver capacitor value across a range of load resistances to achieve maximum R looking into the transmitter coil.

Figures 48A-48B show a coupling efficiency and transformed impedance looking into the primary coil.

Figure 49 shows a normalize primary coil voltage across a range of load resistances.

Figure 50 shows a load network reactance with different transmitter capacitor.

Figure 51 shows an amplitude and phase of impedance of unloaded transmitter load network with different C_{tx}.

Figure 52 shows an impedance looking into transmitter load network.

Figure 53 shows a phase looking into transmitter load network.

Figure 54 shows a power delivered into the transmitting load network if transmitter is an ideal sine voltage source.

Figure 55 shows a transistor drain voltage where $C_{shunt} = 19nF$.

Figure 56 shows a dual channel class E driver.

Figure 57 shows a primary coil – 10 turns (embedded into the table top) and secondary coil – 5 turns (taped up).

Figure 58 shows a power delivery and efficiency of 120V system with a peak power of 295W.

Figure 59 shows a temperature of transistor and inductor with natural convection cooling and forced cooling.

Figure 60 shows a dual channel class E with forced air cooling.

Figure 61 shows a waveform of the class E driver.

Figures 62A-62B show power delivered to load with respect to load resistance. Peak power occurs at approximately 50Ω load resistance for dual channel at 69W for dual channel and 75Ω for single channel at 10W for single channel.

Figure 63 shows system efficiency with respect to load resistance with both peak efficiency of 64.5% for single channel and 76% of dual channel at approximately 70Ω load resistance.

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Figure 64 shows transmitter efficiency with respect to load resistance. Peak transmitter efficiency occurs across the band of 60Ω to 100Ω load resistance at 90% for dual channel and 79% for single channel.

Figure 65 shows system efficiency with respect to load resistance with both cases achieving high efficiency at heavy load and also illustratin that a single channel mode is more efficient at low power delivery state.

Figure 66 shows primary coil RMS voltage having a unique load resistance for each value.

Figure 67 shows receiver DC voltage converging to approximately 70V for dual channel and 37V for single channel.

Figure 68 shows a generalized contactless power system with a single transistor power amplifer in a single ended configuration.

Figure 69 shows a generalized contactless power system with two, single transistor power amplifiers in a push-pull configuration.

Figure 70 shows a generalized contactless power with a two transistor power amplifier in a single ended configuration.

Figure 71 shows a generalized contactless power system with two, two transistor power ampliferrs in a push-pull configuration.

Figure 72 shows different supply network configurations that are used to connect a DC supply voltage to a terminal of the active device of a power amplifier.

Figure 73 shows the functions of a impedance transformation network for a single ended system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 74 shows the functions of a impedance transformation network for a push-pull system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 75 shows various circuit elements arranged to achieve the fuction of reactance shifting. These circuit elements, or variants thereof, can add or remove the mangitude of reactance looking into the impedance transformation network. Inductive elements increase reactance. Capacitive elements decrease reactance.

Figure 76 shows various circuit elements arranged to achieve the fuction of frequency filtering. Two notch filters are shown that can remove unwanted harmonics from the signal. A combination of other filter types can be used to achieve frequency filtering.

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Figure 77 shows various circuit elements arranged to adjust the correlation between the equivelent resistance and the phase of the load. Inductive elements will tend to result in a positive correlation between phase and load resistance. Capacitive elements will tend to result in a negative correlation between phase and load resistance. These elements can also serve the purpose of resistance compression.

Figure 78 shows primary to secondary coil configurations. The impedance transformation network may comprise a single primary and a single secondary. Alternatively, the impedance transformation network may comprise one or more primary coils coupled to one or more secondary coils. The inductance of the primary and/or secondary coil(s) can be used to compress resistance and change the phase vs. resistance relationship.

Figure 79 show various circuit elements arranged to compress the resistance seen looking into the impedance transformation network. Either capacitive or inductive elements can be used.

Figure 80 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 81 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 82 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 83 shows a typical configuration of an impedance tranformation network connected to an active device.

Specific embodiments pertain to a method and a circuit for inductive power transfer, incorporating an impedance transformation network, where the impedance transformation network has an input port for coupling to an active device for creating a signal at a selected operating frequency, an output port for coupling to a load having a variable impedance; and a reactive network coupled between the input port and the output port, where the reactive network includes a primary coil; and a secondary coil, where the primary coil is inductively coupled to the secondary coil, where when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is inductive and negatively correlated with the amount of power delivered to the load. A real part of the impedance looking into the impedance transformation network through the input port can be in a range between a minimum real part and a maximum real part. The maximum real part can be less than or

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equal to one order of magnitude greater than the minimum real part. Further embodiments can incorporate at least one additional input port, at least one additional output port, at least one additional primary coil, and/or at least one additional secondary coil. The output port can be adapted for coupling to at least two loads.

In an embodiment, the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with the resistance of the load. In another embodiment, the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load. In a specific embodiment, the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load, wherein when the impedance looking to the primary coil, Zin, is explained by:

$$Z_{in} = \{1_{1M}[\mathbb{Z}^{IV} - (\mathbb{Z}^{II})^T(\mathbb{Z}^{I})^{-1}\mathbb{Z}^{II}]^{-1}1_{M1}\}$$

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}^{III} & (\mathbb{Z}^{II})^T \\ \mathbb{Z}^{II} & \mathbb{Z}^{I} \end{bmatrix}$$

$$\mathbb{Z}_{ab} = \begin{cases} j\omega L_a + R_a & \text{for } a = b \\ j\omega M_{ab} & \text{otherwise} \end{cases}$$

$$\mathbb{Z}^{IV} = \mathbb{Z}^{III} + Z_{in}1_{MM}$$

Zin: Input impedance looking into the primary coil

1_{1M}: Vector of 1's of length M

1_{MM}: M X M matrix of 1's

Z: Impedance matrix

Z_{ab}: Element ab of the impedance matrix

Z^{I} : Sub-matrix of Z

Z^{II}: Sub-matrix of Z

Z^{III}: Sub-matrix of Z

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M_{ab}: Mutual inductance between the a^{th} and b^{th} coil

j: imaginary number

a: coil index

b: coil index

ω: radian frequency

R_a: Parasitic resistance of the a^{th} coil

L_a: Self inductance of the a^{th} coil

The reactive network can have at least one shunt network with a negative reactance that is connected between a first terminal of the secondary coil and a second terminal of the secondary coil. The at least one shunt network with a negative reactance can have a capacitor. The active device can have a transistor. In a specific embodiment, active device includes a switching component that operates substantially as a switch; and a capacitance in parallel with the switching component. The input port can be coupled to a voltage source or input port can be coupled to a current source. A supply network can be connected between the input port and a voltage source, where the supply network includes at least one inductor. The supply network connected between the input port and a voltage source can be configured to reject harmonics not intended to reach the load. In specific embodiments, the supply network connected between the input port and a voltage source can include elements of the supply network, load network, and the active device so as to represent at least one class D inverter or variant, at least one class DE inverter or variant, at least one class E inverter or variant, at least one class E^{-1} inverter or variant at least one class F inverter or variant, at least one class F^{-1} inverter or variant, at least one class EF^{-1} inverter or variant, or at least one class Phi inverter or variant.

The signal from the active device can be an AC signal and/or a periodic signal. When the active device is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero voltage-switching of the active device occurs. Regarding this range, in specific embodiments switching of the active device can occur when the voltage is within a range of 10% of a peak voltage and zero voltage, switching of the active device can occur when the voltage is within a range of 5% of a peak voltage and zero voltage, and/or switching

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of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage.

In another embodiment, when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs. Regarding this range, in specific embodiments, switching of the active device occurs when the slope of the voltage is within a range of -1 and +1, switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1. In a further specific embodiment, when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching and substantially zero voltage derivation switching of the active device occurs. Such switching of the active device can occur when the voltage is within a range of 10% of a peak voltage and zero and when the slope of the voltage is within a range of -1 and +1, when the voltage is within a range of 5% of a peak voltage and zero and when the slope of the voltage is within a range of -0.5 and +0.5, and/or when the voltage is within a range of 1% of a peak voltage and zero and when the slope of the voltage is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero voltage-switching of the active device occurs. Switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero voltage, switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero voltage, and/or switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage. When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range

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such that substantially zero voltage derivative switching of the active device occurs. Switching of the active device occurs when the slope of the voltage is within a range of -1 and +1, switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current-switching of the active device occurs. Switching of the active device occurs when the current is within a range of 10% of a peak current and zero current, switching of the active device occurs when the current is within a range of 5% of a peak current and zero current, and/or switching of the active device occurs when the current is within a range of 1% of a peak current and zero current. When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current derivative switching of the active device occurs. Switching of the active device occurs when the slope of the current is within a range of -1 and +1, switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current-switching of the active device occurs. Switching of the active device occurs when the current is within a range of 10% of a peak current and zero current, switching of the active device occurs when the current is within a range of 5% of a peak current and zero current, and/or switching of the active device occurs when the current is within a range of 1% of a peak current and zero current. When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that

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substantially zero current derivative switching of the active device occurs. Switching of the active device occurs when the slope of the current is within a range of -1 and +1, switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage is coupled to the input port, and the load is coupled to the output port, the real part of the impedance looking into the impedance transformation network through the input port can be within a range such that the maximum real part of the impedance looking into the impedance transformation network through the input port is no more than two orders of magnitude greater than the minimum real part of the impedance looking into the impedance transformation network through the input port. A supply network can be connected between the input port and a voltage source, where the supply network is configured to reject harmonics not intended to reach the load. At least one load having a time-dependent impedance connected to the output port. In another embodiment, the system can be adapted least one load having a time dependent non-negative real resistance can be connected to the output port. In a specific embodiment where the phase angle of the impedance looking into the impedance transformation network through the input port is inductive, the phase angle of the impedance looking into the impedance transformation network through the input port is between 40 and 85 degrees.

In an embodiment with a shunt network connected between the first terminal of the secondary coil and the second terminal of the secondary coil, where the shunt network has a negative reactance, the shunt network can be configured such that the resistance looking from the secondary coil towards the load is between an upper bound and a lower bound, wherein the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and minimum resistance. In specific embodiments, the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, or the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms. In a further specific embodiment, the at least one shunt network has a

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negative reactive value such that the phase angle looking into the primary coil is positively correlated with the load resistance. In a further specific embodiment, the at least one shunt network is configured to have a negative reactive value such that the phase angle looking into the primary coil is negatively correlated with the load resistance, where the reactive network further utilizes at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil, the at least one additional shunt network having a positive reactive value such that the phase angle looking into the impedance transformation network through the input port is positively correlated with the load resistance.

The reactive network can further include at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil.

The reactive network can include at least one reactive component connected to the primary coil, where the at least one reactive component has a reactance that shifts the phase angle looking into the impedance transformation network through the input port can be within a range such that substantially zero-voltage switching of the active device occurs. In specific embodiments, the impedance transformation network is configured such that the range of resistances looking into the impedance transformation network through the input port is between an upper bound and a lower bound, where the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and the minimum load resistance. In various embodiments, the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, and the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms.

The at least one filter network having a positive reactance can be connected in series with the primary coil, where a reactance of the at least one filter network divided by a resistance looking from the filter network towards the load has a value between 1.5 and 10.

The impedance transformation network can be configured to couple to two active devices via a single input port. The input port can have at least two input ports for coupling to at least two active devices.

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A rectifier can be positioned between the impedance transformation network and the load.

The primary coil can be connected in series with at least one reactive component and the secondary coil can be connected in series with at least one additional reactive component. In another embodiment, the primary coil is connected in series with at least one reactive component and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil. In yet another embodiment, at least one other reactive component is connected between a first terminal of the primary and a second terminal of the primary coil and the secondary coil is connected in series with at least one additional reactive component. In further embodiments, at least one other reactive component is connected between a first terminal of the primary coil and a second terminal of the primary coil and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

The primary coil can be a single primary coil inductively coupled to at least two secondary coils. In another embodiment, at least two primary coils are inductively coupled to the secondary coils. In various other embodiments, m primary coils are inductively coupled to n secondary coils, where $m>1$ and $n>1$.

A specific embodiment relates to a circuit for inductive power transfer having an impedance transformation network, incorporating an input port for coupling to an active device for creating a signal at a selected operating frequency, an output port for coupling to a load having a variable impedance; and a reactive network coupled between the input port and the output port, wherein the reactive network has a primary coil; and a secondary coil, where the primary coil is inductively coupled to the secondary coil, such that when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is capacitive and positively correlated with the amount of power delivered to the load.

Another embodiment pertains to a circuit for inductive power transfer, having a primary impedance transformation network, where the primary impedance transformation network has an input port for coupling to a active device that creates a signal at a selected operating frequency, a primary coil for coupling to a secondary coil, and a reactive network coupled to the input port and coupled to the primary coil, where the reactive network incorporates at least one capacitor, and at least one inductor, such that when the primary coil

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is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is inductive and negatively correlated with the amount of power inductively transferred from the primary coil.

Another embodiment relates to a circuit for inductive power transfer, having a primary impedance transformation network, where the primary impedance transformation network includes an input port for coupling to an one active device that creates a signal at a selected operating frequency, a primary coil for coupling to a secondary coil, a reactive network coupled to the input port and coupled to the primary coil, where the reactive network incorporates at least one capacitor, at least one inductor, such that when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is capacitive and positively correlated with the amount of power inductively transferred from the primary coil.

A further embodiment pertains to a circuit for inductive power transfer, having a secondary side impedance transformation network, where the secondary side impedance transformation network incorporates at least one secondary coil for coupling to at least one primary coil, at least one output port for coupling to at least one load having a variable impedance; and a secondary side reactive network coupled to the output port and coupled to the secondary coil, where the reactive network incorporates at least one capacitor, such that when the secondary coil is coupled to the primary coil, where the primary coil is coupled to a primary side reactive network, where the primary side reactive network has an input port for connection to at least one active device that creates a signal at a selected operating frequency, the a phase angle of an impedance looking into the primary side reactive network through the input port is inductive and positively correlated with the amount of power inductively transferred from the primary coil.

A further embodiment is directed to a circuit for inductive power transfer, having a secondary side impedance transformation network, wherein the secondary side impedance transformation network has at least one secondary coil for coupling to at least one primary coil, at least one output port for coupling to at least one load having a variable impedance; and a secondary side reactive network coupled to the at least one output port and coupled to the at least one secondary coil, wherein the reactive network includes at least one capacitor, such that when the secondary coil is coupled to the primary coil, where the primary coil is coupled to a primary side reactive network, where the primary side reactive network has an

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input port for connection to at least one active device that creates a signal at a selected operating frequency, the a phase angle of an impedance looking into the primary side reactive network through the input port is capacitive and negatively correlated with the amount of power inductively transferred from the primary coil.

An embodiment of the invention is directed to an apparatus for wireless power transfer, having a rectifier stage, where the rectifier stage is adapted to interconnect with a load; a first impedance transformation network (FITN), where the first impedance transformation network interconnects with the rectifier stage and transforms the impedance looking into the rectifier stage such that the impedance looking into the FITN is such that the load decouples from the primary coil; a secondary coil, where the secondary coil is interconnected with the FITN such that the power coupled from the primary coil to the secondary coil is received by the FITN; a primary coil, where the primary coil is positioned with respect to the secondary coil such that the primary coil is coupled to the secondary coil, wherein the interaction between the primary coil and secondary coil is such that the impedance looking into the primary coil has a resistance large enough to maximize power delivery through to the secondary coil; a second impedance transformation network (SITN), where the SITN interconnects with the primary coil and transforms the impedance looking into the primary coil such that the resistance looking into the SITN toward the load is within a usable operating range of the tuned switch-mode inverter, large enough to maximize power delivery through to the secondary coil; a phase shifting network, where the phase shifting network interconnects with the SITN and transforms the impedance looking into the SITN such that the impedance looking into the phase shifting network has a resistance in the operating range of the tuned switch-mode inverter and a reactive part in the operating range of the tuned switch-mode inverter; a tuned switch-mode inverter, where the tuned switch-mode inverter is interconnected with the phase shifting network; and a power source, where the power source is interconnected with the tuned switch-mode inverter. In this embodiment, the load can have a load resistance that can range from 0 to 500 ohms.

An embodiment is an apparatus for wireless power transfer, having a rectifier stage, where the rectifier stage is adapted to interconnect with a load; a secondary coil, where the secondary coil is interconnected with the rectifier stage; a primary coil, where the primary coil is coupled to the secondary coil; a tuned switch-mode supply, wherein the tuned switch-mode supply is interconnected to the primary coil; a power supply, where the power supply supplies power to the tuned switch-mode supply; a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and a second circuitry interconnected

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between the secondary coil and the rectifier stage, such that power output to the load decreases as the impedance of the load increases.

Another embodiment is an apparatus for wireless power transfer, having a rectifier stage, where the rectifier stage is adapted to interconnect with a load; a secondary coil, where the secondary coil is interconnected with the rectifier stage; a primary coil, where the primary coil is coupled to the secondary coil; a tuned switch-mode supply, where the tuned switch-mode supply is interconnected to the primary coil; a power supply, where the power supply supplies power to the tuned switch-mode supply; a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and a second circuitry interconnected between the secondary coil and the rectifier stage, such that power output to the load is adjusted as the phase angle of the load changes.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

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CLAIMS

1. A circuit for inductive power transfer, comprising:

an impedance transformation network, wherein the impedance transformation network comprises:

an input port for coupling to an active device for creating a signal at a selected operating frequency,

an output port for coupling to a load having a variable impedance; and

a reactive network coupled between the input port and the output port, wherein the reactive network comprises:

a primary coil;

a secondary coil, wherein the primary coil is inductively coupled to the secondary coil, wherein when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is inductive and negatively correlated with the amount of power delivered to the load.

2. The circuit according to claim 1, wherein a real part of the impedance looking into the impedance transformation network through the input port is in a range between a minimum real part and a maximum real part.

3. The circuit according to claim 2, wherein the maximum real part is less than or equal to one order of magnitude greater than the minimum real part.

4. The circuit according to claim 1, further comprising at least one additional input port.

5. The circuit according to claim 1, further comprising at least one additional output port.

6. The circuit according to claim 1, further comprising at least one additional primary coil.

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7. The circuit according to claim 1, further comprising at least one additional secondary coil.

8. The circuit according to claim 1, wherein the output port is for coupling to at least two loads.

9. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with the resistance of the load.

10. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load.

11. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load, wherein when the impedance looking to the primary coil, Zin, is explained by:

$$Z_{in} = \{1_{1M}[\mathbb{Z}^{IV} - (\mathbb{Z}^{II})^T(\mathbb{Z}^{I})^{-1}\mathbb{Z}^{II}]^{-1}1_{M1}\}$$

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}^{III} & (\mathbb{Z}^{II})^T \\ \mathbb{Z}^{II} & \mathbb{Z}^{I} \end{bmatrix}$$

$$\mathbb{Z}_{ab} = \begin{cases} j\omega L_a + R_a & \text{for } a = b \\ j\omega M_{ab} & \text{otherwise} \end{cases}$$

$$\mathbb{Z}^{IV} = \mathbb{Z}^{III} + Z_{in}1_{MM}$$

Zin: Input impedance looking into the primary coil

1_{1M}: Vector of 1's of length M

1_{MM}: M X M matrix of 1's

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Z: Impedance matrix

Z_{ab}: Element ab of the impedance matrix

Z^{I} : Sub-matrix of Z

Z^{II}: Sub-matrix of Z

Z^{III}: Sub-matrix of Z

M_{ab}: Mutual inductance between the a^{th} and b^{th} coil

j: imaginary number

a: coil index

b: coil index

ω: radian frequency

R_a: Parasitic resistance of the a^{th} coil

L_a: Self inductance of the a^{th} coil

12. The circuit according to claim 1, wherein the reactive network further comprises at least one shunt network with a negative reactance that is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

13. The circuit according to claim 12, wherein the at least one shunt network with a negative reactance comprises a capacitor.

14. The circuit according to claim 1, wherein the active device comprises a transistor.

15. The circuit according to claim 1 wherein the active device comprises:

a switching component that operates substantially as a switch; and

a capacitance in parallel with the switching component.

16. The circuit according to claim 1 wherein the input port is coupled to a voltage source.

17. The circuit according to claim 1, wherein the input port is coupled to a current source.

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18. The circuit according to claim 1 comprising a supply network connected between the input port and a voltage source, wherein the supply network comprises at least one inductor.

19. The circuit according to claim 1 comprising a supply network connected between the input port and a voltage source, wherein the supply network is configured to reject harmonics not intended to reach the load.

20. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class D inverter or variant.

21. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class DE inverter or variant.

22. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class E inverter or variant.

23. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class E^{-1} inverter or variant.

24. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class F inverter or variant.

25. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class F^{-1} inverter or variant.

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26. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class EF^{-1} inverter or variant.

27. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class Phi inverter or variant.

28. The circuit according to claim 1, wherein the signal is an AC signal.

29. The circuit according to claim 1, wherein the signal is a periodic signal.

30. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching of the active device occurs.

31. The circuit according to claim 30, wherein switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero voltage.

32. The circuit according to claim 30, wherein switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero voltage.

33. The circuit according to claim 30, wherein switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage.

34. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs.

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35. The circuit according to claim 34, wherein switching of the active device occurs when the slope of the voltage is within a range of -1 and +1.

36. The circuit according to claim 34, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5.

37. The circuit according to claim 34, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1.

38. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching and substantially zero voltage derivation switching of the active device occurs.

39. The circuit according to claim 38, wherein switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero and when the slope of the voltage is within a range of -1 and +1.

40. The circuit according to claim 38, wherein switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero and when the slope of the voltage is within a range of -0.5 and +0.5.

41. The circuit according to claim 38, wherein switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero and when the slope of the voltage is within a range of -0.1 and +0.1.

42. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching of the active device occurs.

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43. The circuit according to claim 42, wherein switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero voltage.

44. The circuit according to claim 42, wherein switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero voltage.

45. The circuit according to claim 42, wherein switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage.

46. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs.

47. The circuit according to claim 46, wherein switching of the active device occurs when the slope of the voltage is within a range of -1 and +1.

48. The circuit according to claim 46, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5.

49. The circuit according to claim 46, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1.

50. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current-switching of the active device occurs.

51. The circuit according to claim 50, wherein switching of the active device occurs when the current is within a range of 10% of a peak current and zero current.

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52. The circuit according to claim 50, wherein switching of the active device occurs when the current is within a range of 5% of a peak current and zero current.

53. The circuit according to claim 50, wherein switching of the active device occurs when the current is within a range of 1% of a peak current and zero current.

54. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current derivative switching of the active device occurs.

55. The circuit according to claim 54, wherein switching of the active device occurs when the slope of the current is within a range of -1 and +1.

56. The circuit according to claim 54, wherein switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5.

57. The circuit according to claim 54, wherein switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

58. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current-switching of the active device occurs.

59. The circuit according to claim 58, wherein switching of the active device occurs when the current is within a range of 10% of a peak current and zero current.

60. The circuit according to claim 58, wherein switching of the active device occurs when the current is within a range of 5% of a peak current and zero current.

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61. The circuit according to claim 58, wherein switching of the active device occurs when the current is within a range of 1% of a peak current and zero current.

62. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current derivative switching of the active device occurs.

63. The circuit according to claim 62, wherein switching of the active device occurs when the slope of the current is within a range of -1 and +1.

64. The circuit according to claim 62, wherein switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5.

65. The circuit according to claim 62, wherein switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

66. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage is coupled to the input port, and the load is coupled to the output port, the real part of the impedance looking into the impedance transformation network through the input port is within a range such that the maximum real part of the impedance looking into the impedance transformation network through the input port is no more than two orders of magnitude greater than the minimum real part of the impedance looking into the impedance transformation network through the input port.

67. The circuit according to any of claims 27 – 31, comprising a supply network connected between the input port and a voltage source, wherein the supply network is configured to reject harmonics not intended to reach the load.

68. The circuit according to claim 1, comprising at least one load connected to the output port, the load having a time-dependent impedance.

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69. The circuit according to claim 1, comprising at least one load connected to the output port, the load having a time dependent non-negative real resistance.

70. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is inductive.

71. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is between 40 and 85 degrees.

72. The circuit according to claim 12, wherein the shunt network is configured such that the resistance looking from the secondary coil towards the load is between an upper bound and a lower bound, wherein the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and minimum resistance.

73. The circuit according to claim 72, wherein the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

74. The circuit according to claim 72, wherein the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

75. The circuit according to claim 72, wherein the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

76. The circuit according to claim 72, wherein the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms.

77. The circuit according to claim 12, wherein the at least one shunt network has a negative reactive value such that the phase angle looking into the primary coil is positively correlated with the load resistance.

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78. The circuit according to claim 12, wherein the at least one shunt network is configured to have a negative reactive value such that the phase angle looking into the primary coil is negatively correlated with the load resistance, wherein the reactive network further comprises at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil, wherein the at least one additional shunt network has a positive reactive value such that the phase angle looking into the impedance transformation network through the input port is positively correlated with the load resistance.

79. The circuit according to claim 1, wherein the reactive network further comprises at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil.

80. The circuit according to claim 78, wherein the at least one additional shunt network has a positive reactive value such that the phase angle looking into the impedance transformation network through the input port is positively correlated with the load resistance.

81. The circuit according to claim 1, wherein the reactive network comprises at least one reactive component connected to the primary coil, wherein the at least one reactive component has a reactance that shifts the phase angle looking into the impedance transformation network through the input port is within a range such that substantially zero-voltage switching of the active device occurs.

82. The circuit according to claim 1, wherein impedance transformation network is configured such that the range of resistances looking into the impedance transformation network through the input port is between an upper bound and a lower bound, wherein the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and the minimum load resistance.

83. The circuit according to claim 82, wherein the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

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84. The circuit according to claim 82, wherein the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

85. The circuit according to claim 82, wherein the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

86. The circuit according to claim 82, wherein the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms.

87. The circuit according to claim 1, wherein at least one filter network having a positive reactance is connected in series with the primary coil, wherein a reactance of the at least one filter network divided by a resistance looking from the filter network towards the load has a value between 1.5 and 10.

88. The circuit according to claim 1, wherein the impedance transformation network is configured to couple to two active devices via a single input port.

89. The circuit according to claim 1, wherein the input port comprises at least two input ports for coupling to at least two active devices.

90. The circuit according to claim 1, wherein the load is resistive.

91. The circuit according to claim 1, wherein the load is reactive.

92. The circuit according to claim 1, wherein the load comprises resistive and reactive components.

93. The circuit according to claim 1, wherein a rectifier is positioned between the impedance transformation network and the load.

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94. The circuit according to claim 93, wherein the load comprises a portable electronic device.

95. The circuit according to claim 94, wherein the load comprises:
a voltage regulator;
a power management system; and
a battery.

96. The circuit according to claim 1, wherein the primary coil is connected in series with at least one reactive component and the secondary coil is connected in series with at least one additional reactive component.

97. The circuit according to claim 1, wherein the primary coil is connected in series with at least one reactive component and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

98. The circuit according to claim 1, wherein at least one other reactive component is connected between a first terminal of the primary and a second terminal of the primary coil and the secondary coil is connected in series with at least one additional reactive component.

99. The circuit according to claim 1, wherein at least one other reactive component is connected between a first terminal of the primary coil and a second terminal of the primary coil and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

100. The circuit according to claim 1, wherein the primary coil is a single primary coil inductively coupled to at least two secondary coils.

101. The circuit according to claim 1, wherein the at least two primary coils are inductively coupled to the secondary coils.

102. The circuit according to claim 1, wherein m primary coils are inductively coupled to n secondary coils, where $m>1$ and $n>1$.

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103. A circuit for inductive power transfer, comprising:

an impedance transformation network, wherein the impedance transformation network comprises:

an input port for coupling to an active device for creating a signal at a selected operating frequency,

an output port for coupling to a load having a variable impedance; and

a reactive network coupled between the input port and the output port, wherein the reactive network comprises:

a primary coil;

a secondary coil, wherein the primary coil is inductively coupled to the secondary coil, wherein when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is capacitive and positively correlated with the amount of power delivered to the load.

104. A circuit for inductive power transfer, comprising:

a primary impedance transformation network, wherein the primary impedance transformation network comprises:

an input port for coupling to a active device that creates a signal at a selected operating frequency,

a primary coil for coupling to a secondary coil

a reactive network coupled to the input port and coupled to the primary coil, wherein the reactive network comprises:

at least one capacitor

at least one inductor

wherein when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is inductive and negatively correlated with the amount of power inductively transferred from the primary coil.

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105. A circuit for inductive power transfer, comprising:

a primary impedance transformation network, wherein the primary impedance transformation network comprises:

an input port for coupling to an one active device that creates a signal at a selected operating frequency,

a primary coil for coupling to a secondary coil

a reactive network coupled to the input port and coupled to the primary coil, wherein the reactive network comprises:

at least one capacitor

at least one inductor

wherein when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is capacitive and positively correlated with the amount of power inductively transferred from the primary coil.

106. A circuit for inductive power transfer, comprising:

a secondary side impedance transformation network, wherein the secondary side impedance transformation network comprises:

at least one secondary coil for coupling to at least one primary coil

at least one output port for coupling to at least one load having a variable impedance; and

a secondary side reactive network coupled to the output port and coupled to the secondary coil, wherein the reactive network comprises:

at least one capacitor

wherein when the secondary coil is coupled to the primary coil wherein the primary coil is coupled to a primary side reactive network

wherein the primary side reactive network comprises an input port for connection to at least one active device that creates a signal at a selected operating frequency

the a phase angle of an impedance looking into the primary side reactive network through the input port is inductive and positively correlated with the amount of power inductively transferred from the primary coil.

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107. A circuit for inductive power transfer, comprising:

a secondary side impedance transformation network, wherein the secondary side impedance transformation network comprises:

at least one secondary coil for coupling to at least one primary coil

at least one output port for coupling to at least one load having a variable impedance; and

a secondary side reactive network coupled to the at least one output port and coupled to the at least one secondary coil, wherein the reactive network comprises:

at least one capacitor

wherein when the secondary coil is coupled to the primary coil wherein the primary coil is coupled to a primary side reactive network

wherein the primary side reactive network comprises an input port for connection to at least one active device that creates a signal at a selected operating frequency

the a phase angle of an impedance looking into the primary side reactive network through the input port is capacitive and negatively correlated with the amount of power inductively transferred from the primary coil.

108. An apparatus for wireless power transfer, comprising:

a rectifier stage, wherein the rectifier stage is adapted to interconnect with a load;

a first impedance transformation network (FITN), wherein the first impedance transformation network interconnects with the rectifier stage and transforms the impedance looking into the rectifier stage such that the impedance looking into the FITN is such that the load decouples from the primary coil;

a secondary coil, wherein the secondary coil is interconnected with the FITN such that the power coupled from the primary coil to the secondary coil is received by the FITN;

a primary coil, wherein the primary coil is positioned with respect to the secondary coil such that the primary coil is coupled to the secondary coil, wherein the interaction between the primary coil and secondary coil is such that the impedance looking into the primary coil has a resistance large enough to maximize power delivery through to the secondary coil;

a second impedance transformation network (SITN), wherein the SITN interconnects with the primary coil and transforms the impedance looking into the primary coil such that the resistance looking into the SITN toward the load is within a usable operating range of the

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tuned switch-mode inverter, large enough to maximize power delivery through to the secondary coil;

a phase shifting network, wherein the phase shifting network interconnects with the SITN and transforms the impedance looking into the SITN such that the impedance looking into the phase shifting network has a resistance in the operating range of the tuned switch-mode inverter and a reactive part in the operating range of the tuned switch-mode inverter;

a tuned switch-mode inverter, wherein the tuned switch-mode inverter is interconnected with the phase shifting network; and

a power source, wherein the power source is interconnected with the tuned switch-mode inverter.

109. The apparatus according to claim 108, wherein the load has a load resistance that can range from 0 to 500 ohms.

110. An apparatus for wireless power transfer, comprising:

a rectifier stage, wherein the rectifier stage is adapted to interconnect with a load;

a secondary coil, wherein the secondary coil is interconnected with the rectifier stage;

a primary coil, wherein the primary coil is coupled to the secondary coil;

a tuned switch-mode supply, wherein the tuned switch-mode supply is interconnected to the primary coil;

a power supply, wherein the power supply supplies power to the tuned switch-mode supply;

a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and

a second circuitry interconnected between the secondary coil and the rectifier stage, wherein power output to the load decreases as the impedance of the load increases.

111. An apparatus for wireless power transfer, comprising:

a rectifier stage, wherein the rectifier stage is adapted to interconnect with a load;

a secondary coil, wherein the secondary coil is interconnected with the rectifier stage;

a primary coil, wherein the primary coil is coupled to the secondary coil;

a tuned switch-mode supply, wherein the tuned switch-mode supply is interconnected to the primary coil;

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a power supply, wherein the power supply supplies power to the tuned switch-mode supply;

a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and

a second circuitry interconnected between the secondary coil and the rectifier stage, wherein power output to the load is adjusted as the phase angle of the load changes.

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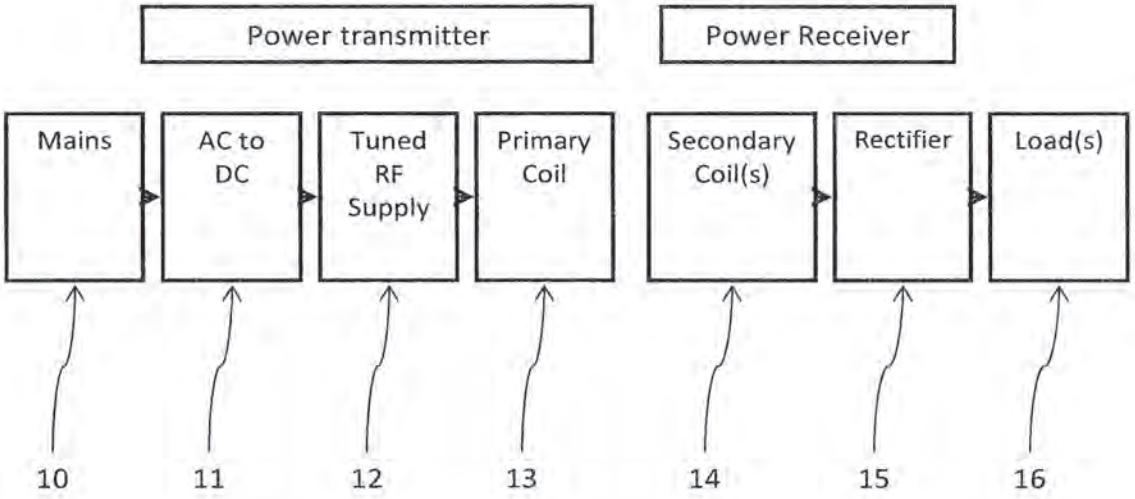

Power transmitter
Power Receiver
Mains
AC to DC
Tuned RF Supply
Primary Coil
Secondary Coil(s)
Rectifier
Load(s)
10
11
12
13
14
15
16

FIG. 1

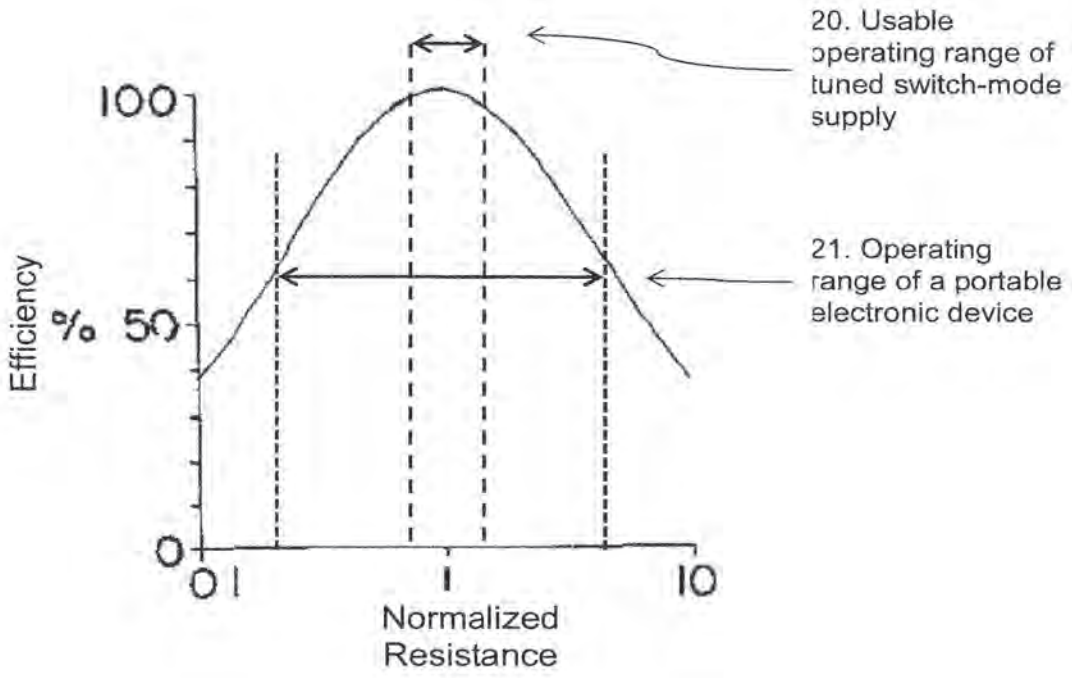

20. Usable operating range of tuned switch-mode supply
21. Operating range of a portable electronic device
100
Efficiency
% 50
0
0.1
1
10
Normalized Resistance

FIG. 2

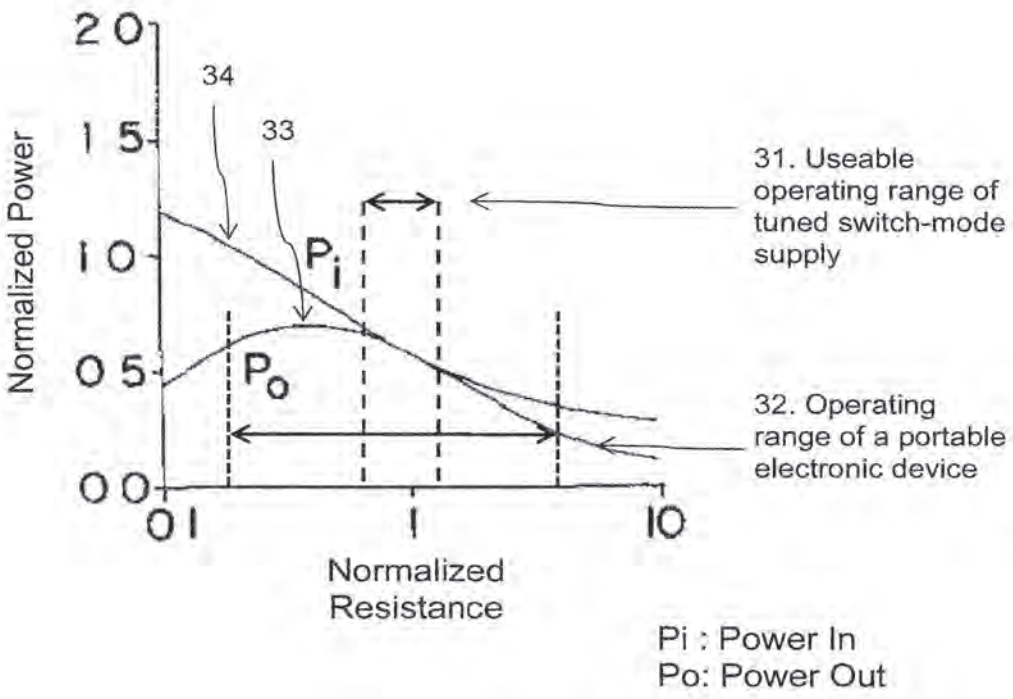

20
15
10
05
00
Normalized Power
34
33
Pi
Po
31. Useable operating range of tuned switch-mode supply
32. Operating range of a portable electronic device
01
1
10
Normalized Resistance
Pi : Power In
Po: Power Out

FIG. 3

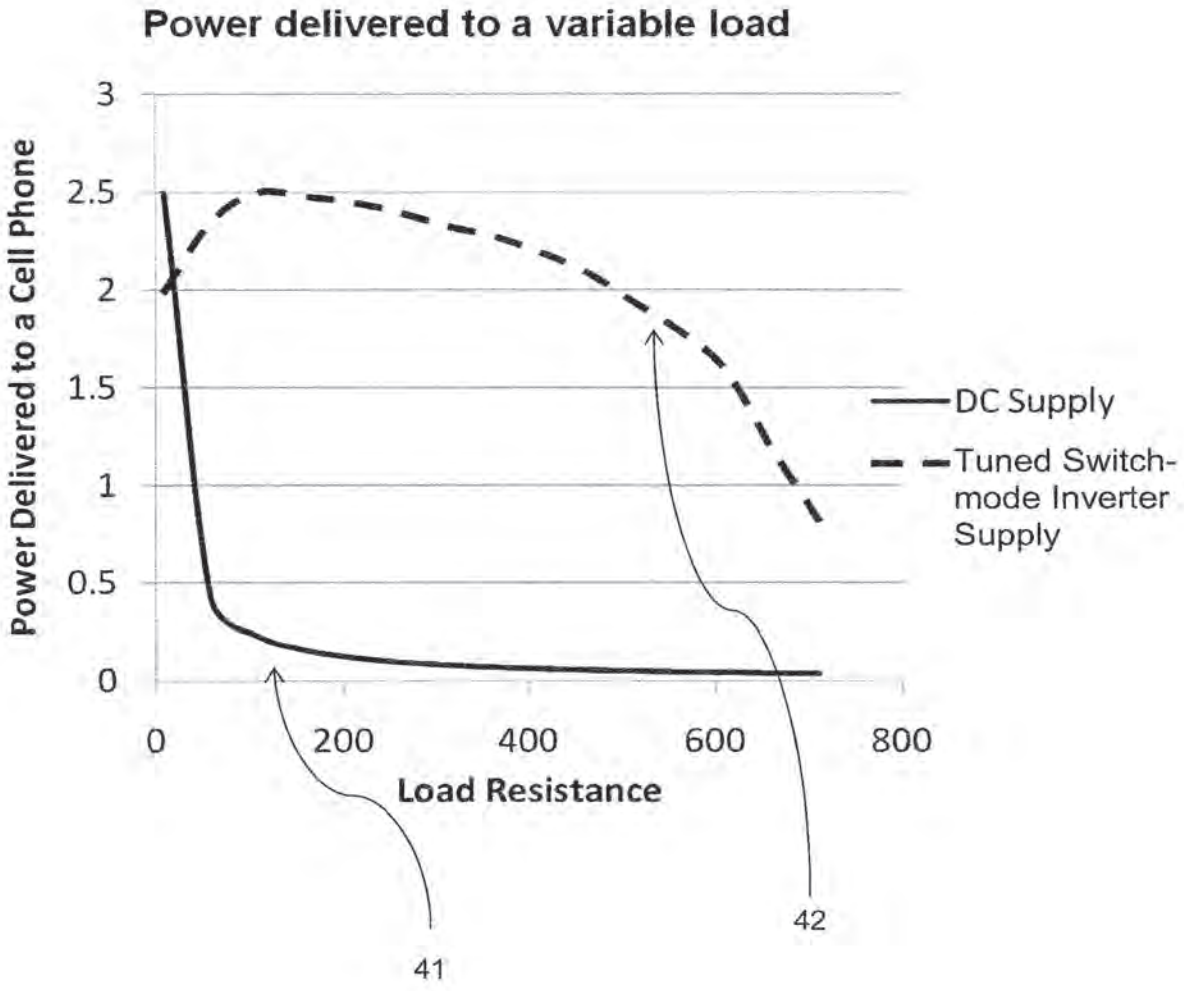

Power delivered to a variable load
Power Delivered to a Cell Phone
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
Load Resistance
DC Supply
Tuned Switch-mode Inverter Supply
41
42

FIG. 4

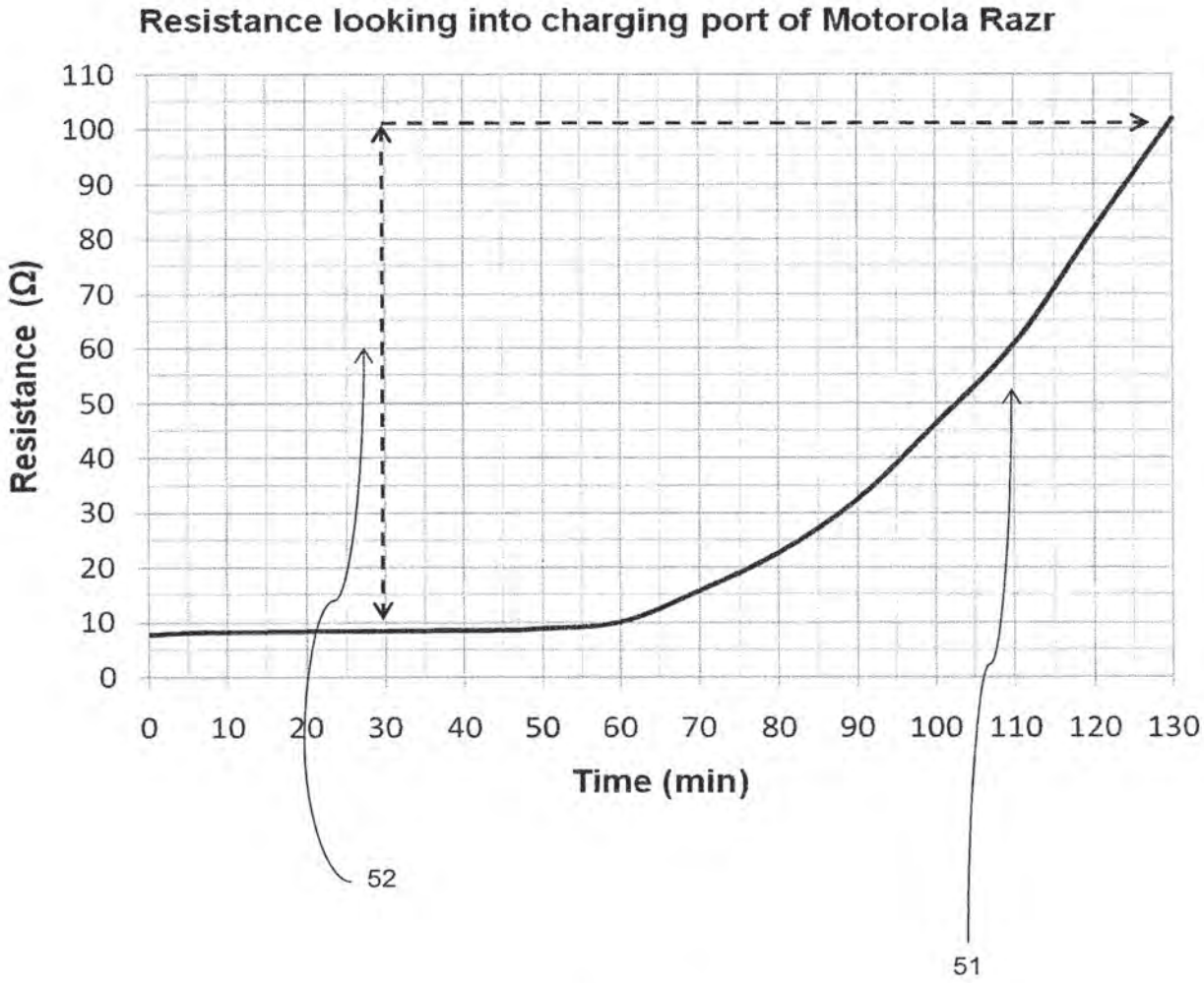

Resistance looking into charging port of Motorola Razr
Resistance (Ω)
110
100
90
80
70
60
50
40
30
20
10
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130
Time (min)
52
51

FIG. 5

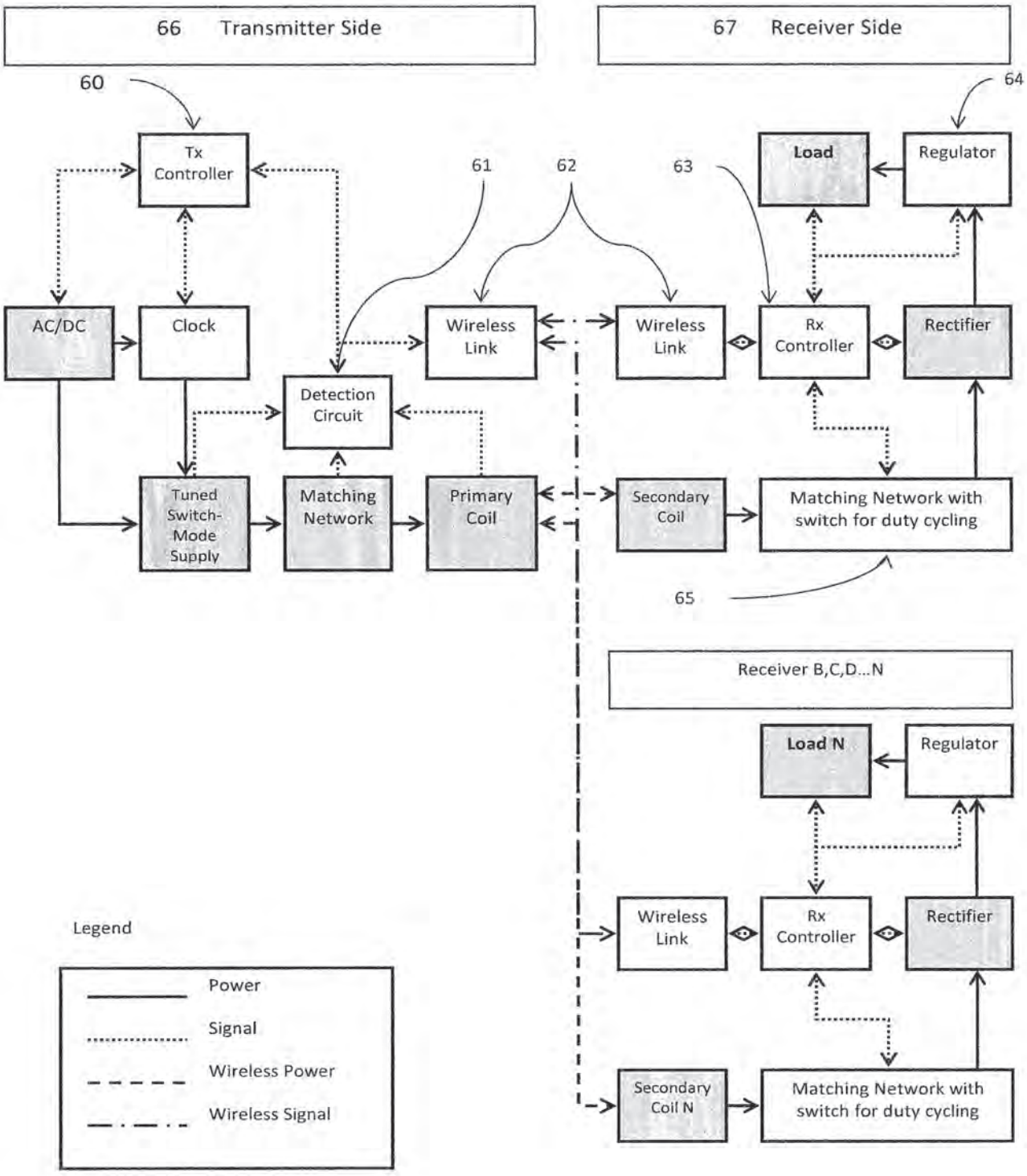
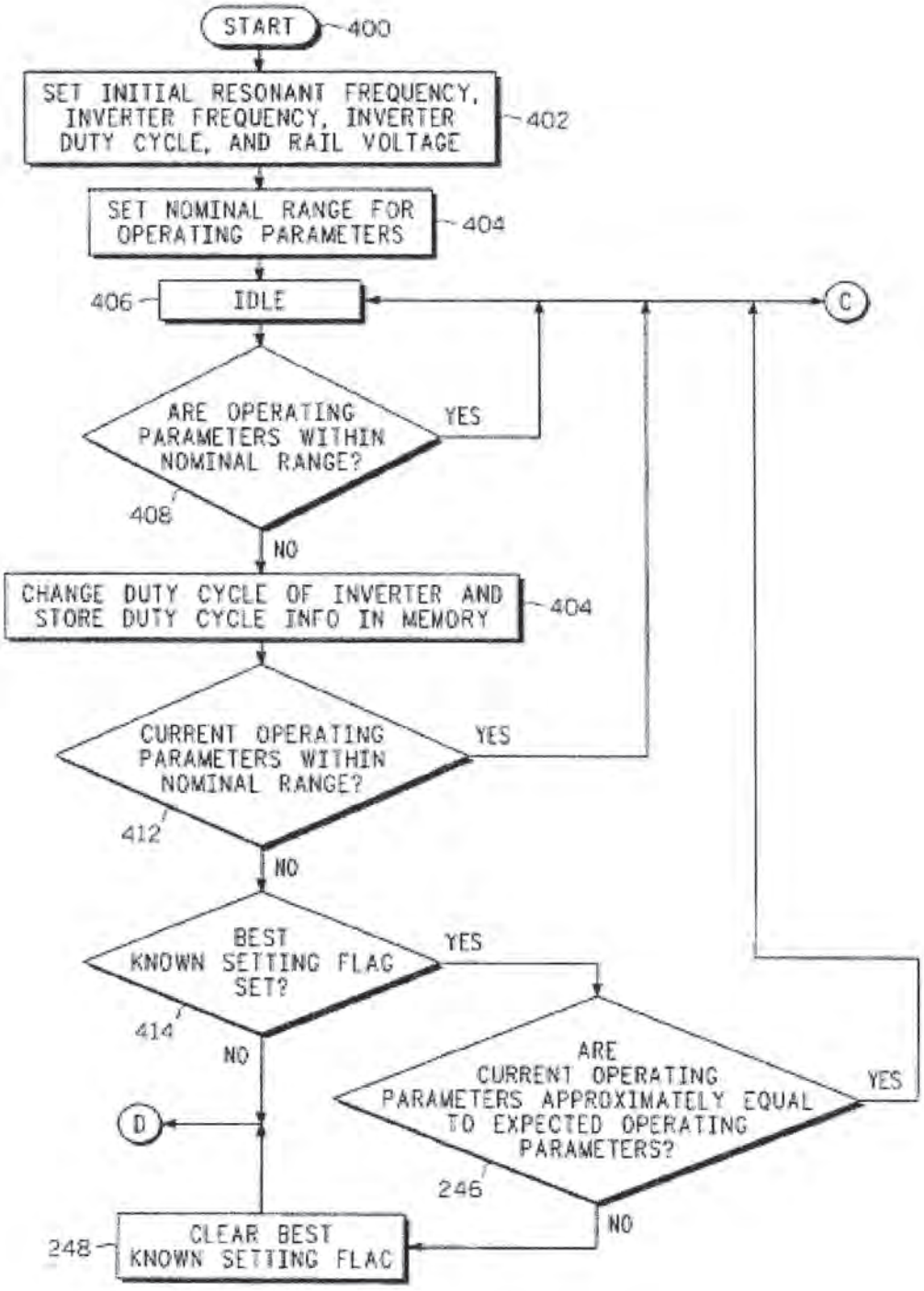
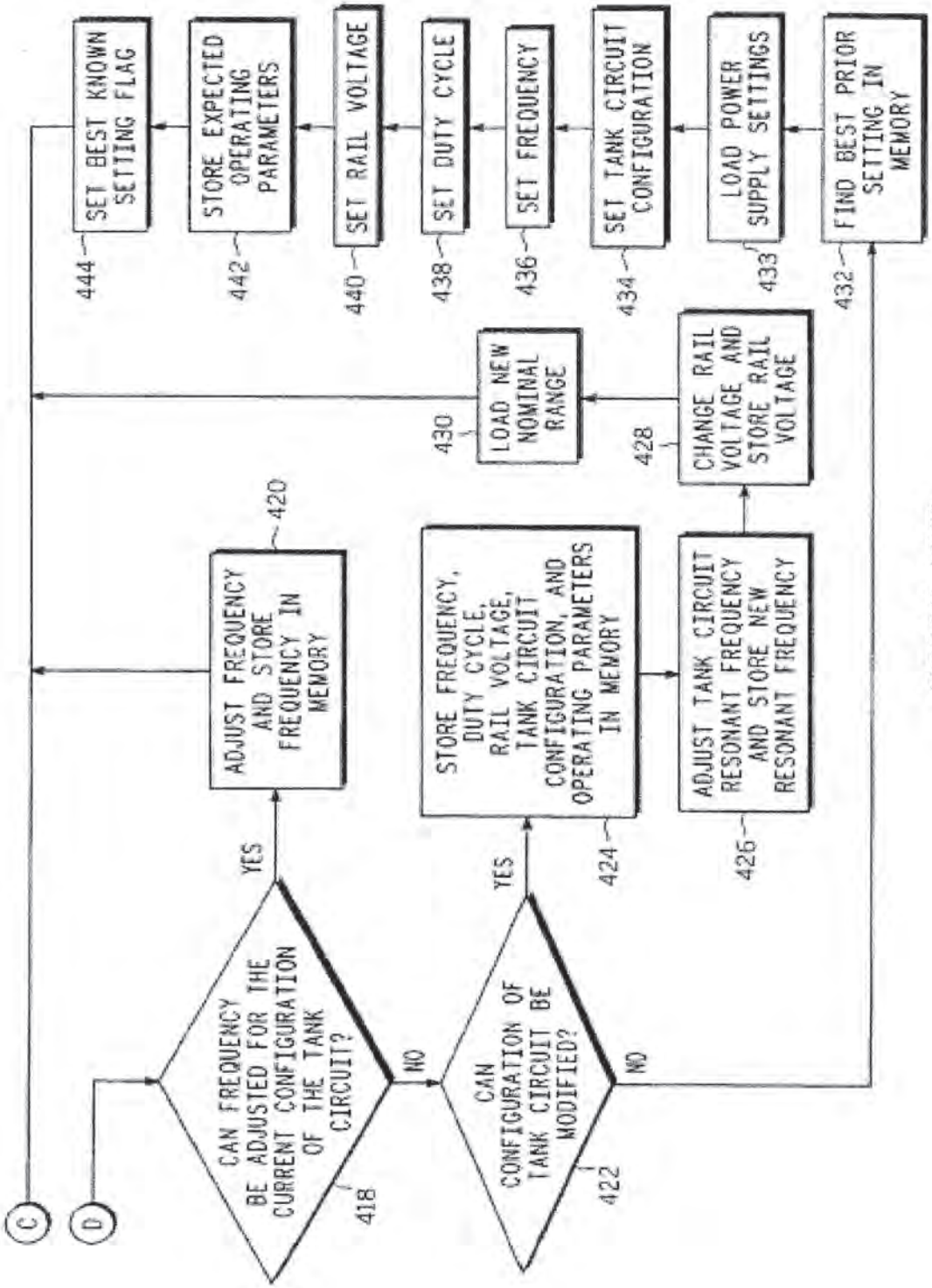

66 Transmitter Side
67 Receiver Side
60
64
Tx Controller
61
62
63
Load
Regulator
AC/DC
Clock
Wireless Link
Wireless Link
Rx Controller
Rectifier
Detection Circuit
Tuned Switch-Mode Supply
Matching Network
Primary Coil
Secondary Coil
Matching Network with switch for duty cycling
65
Receiver B,C,D...N
Load N
Regulator
Wireless Link
Rx Controller
Rectifier
Secondary Coil N
Matching Network with switch for duty cycling
Legend
Power
Signal
Wireless Power
Wireless Signal

FIG. 6



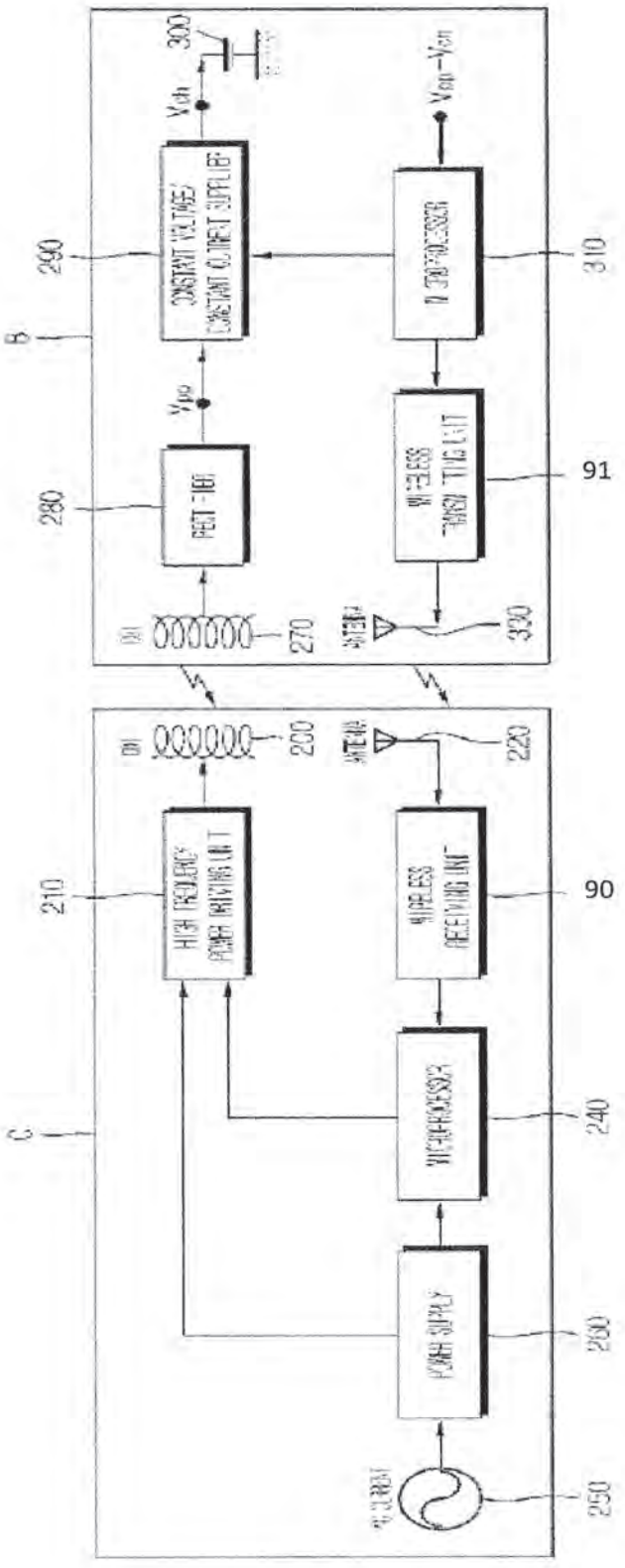
(PRIOR ART)

FIG. 7



(PRIOR ART)

FIG. 8



(PRIOR ART)

FIG. 9

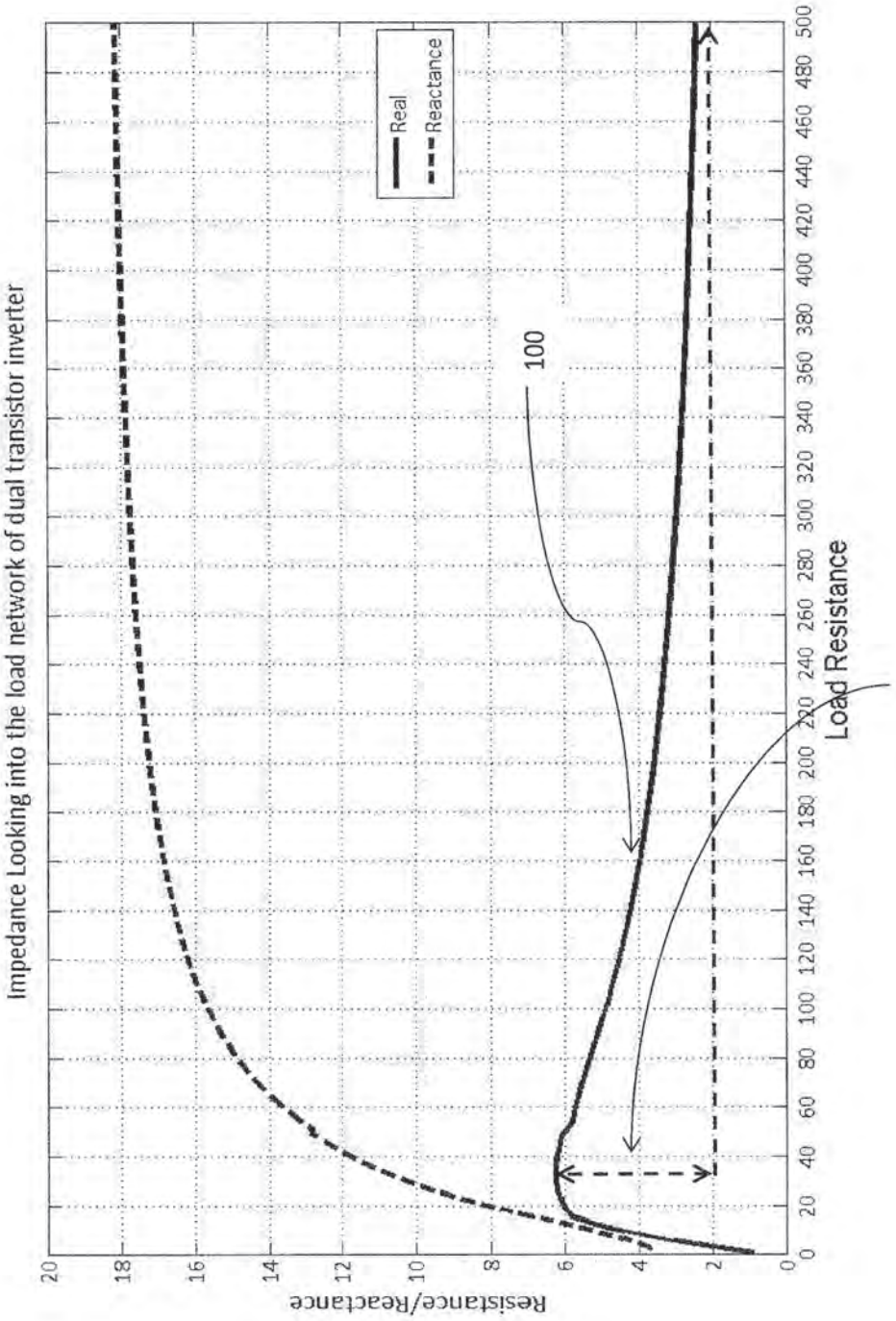

Impedance Looking into the load network of dual transistor inverter
Real
Reactance
100
Load Resistance
Resistance/Reactance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
2
4
6
8
10
12
14
16
18
20

FIG. 10

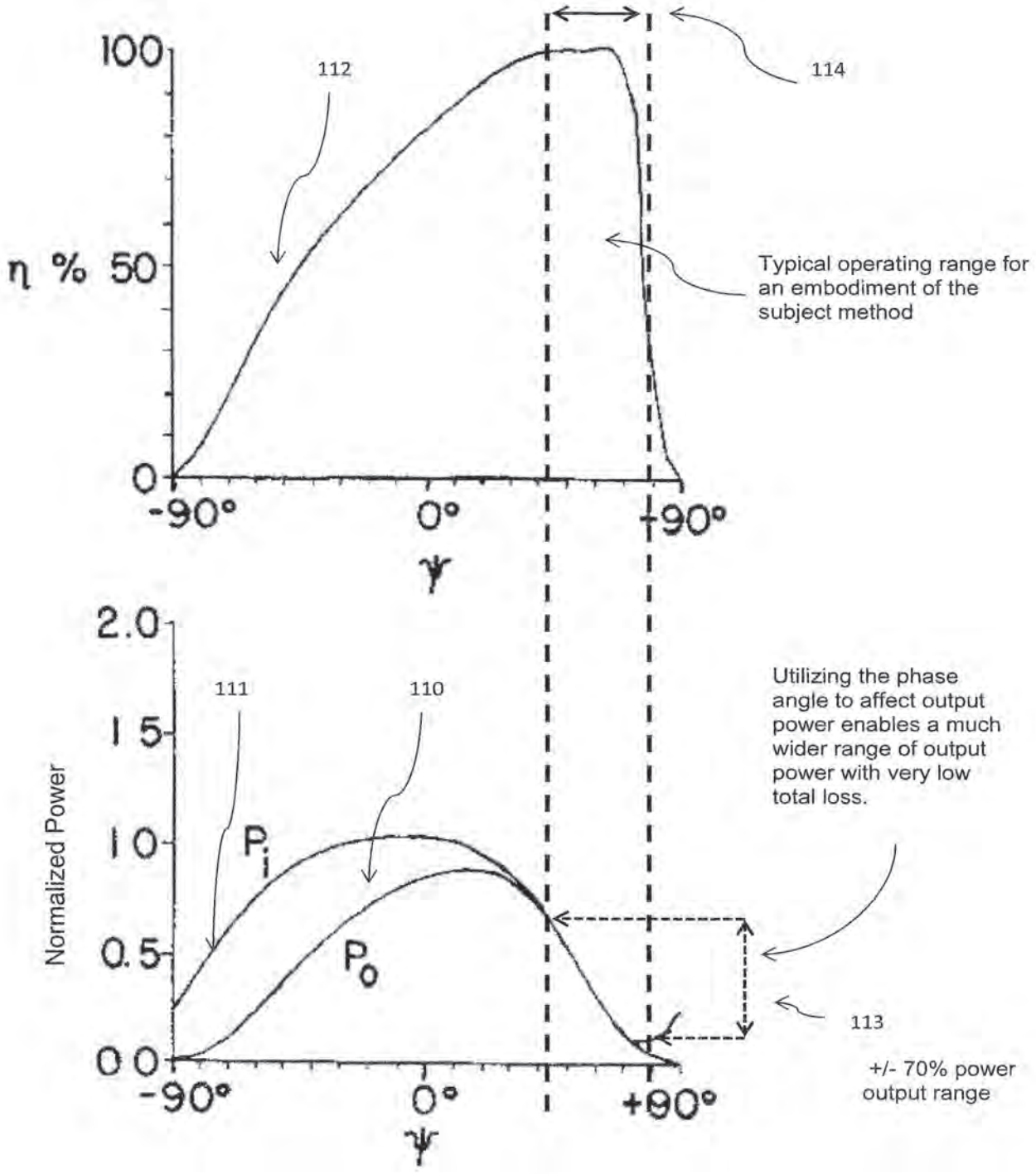

100
η % 50
0
112
114
-90°
0°
+90°
ψ
Typical operating range for an embodiment of the subject method
2.0
1.5
1.0
0.5
0.0
Normalized Power
111
110
P_i
P_o
Utilizing the phase angle to affect output power enables a much wider range of output power with very low total loss.
113
+/- 70% power output range
-90°
0°
+90°
ψ

FIG. 11

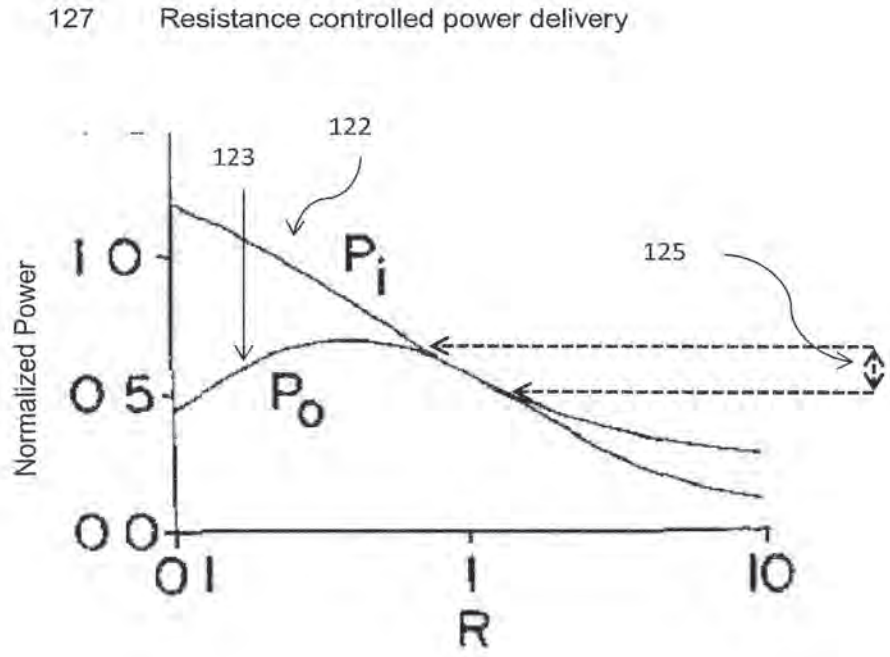


FIG. 12A

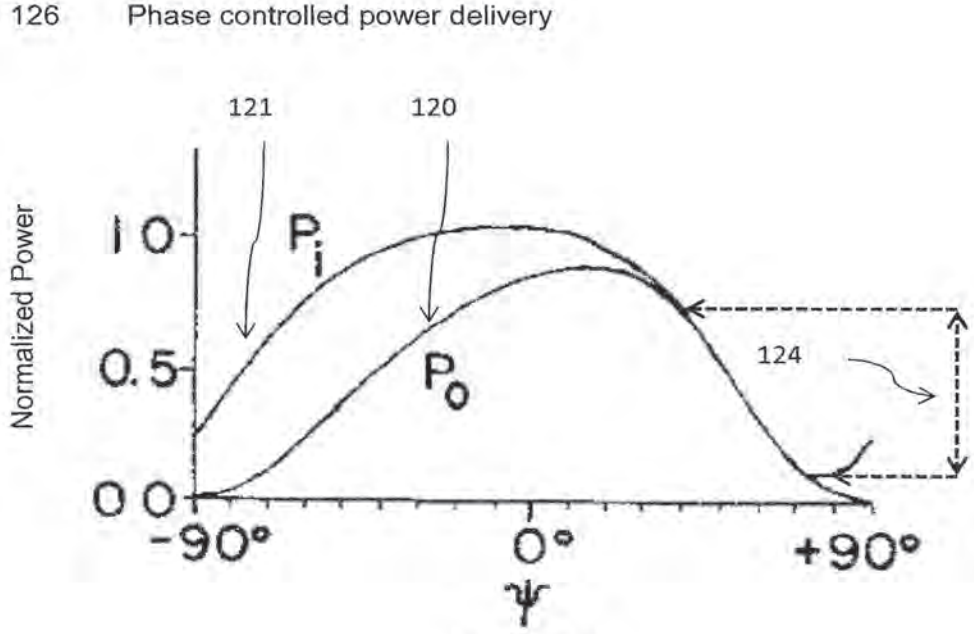


FIG. 12B

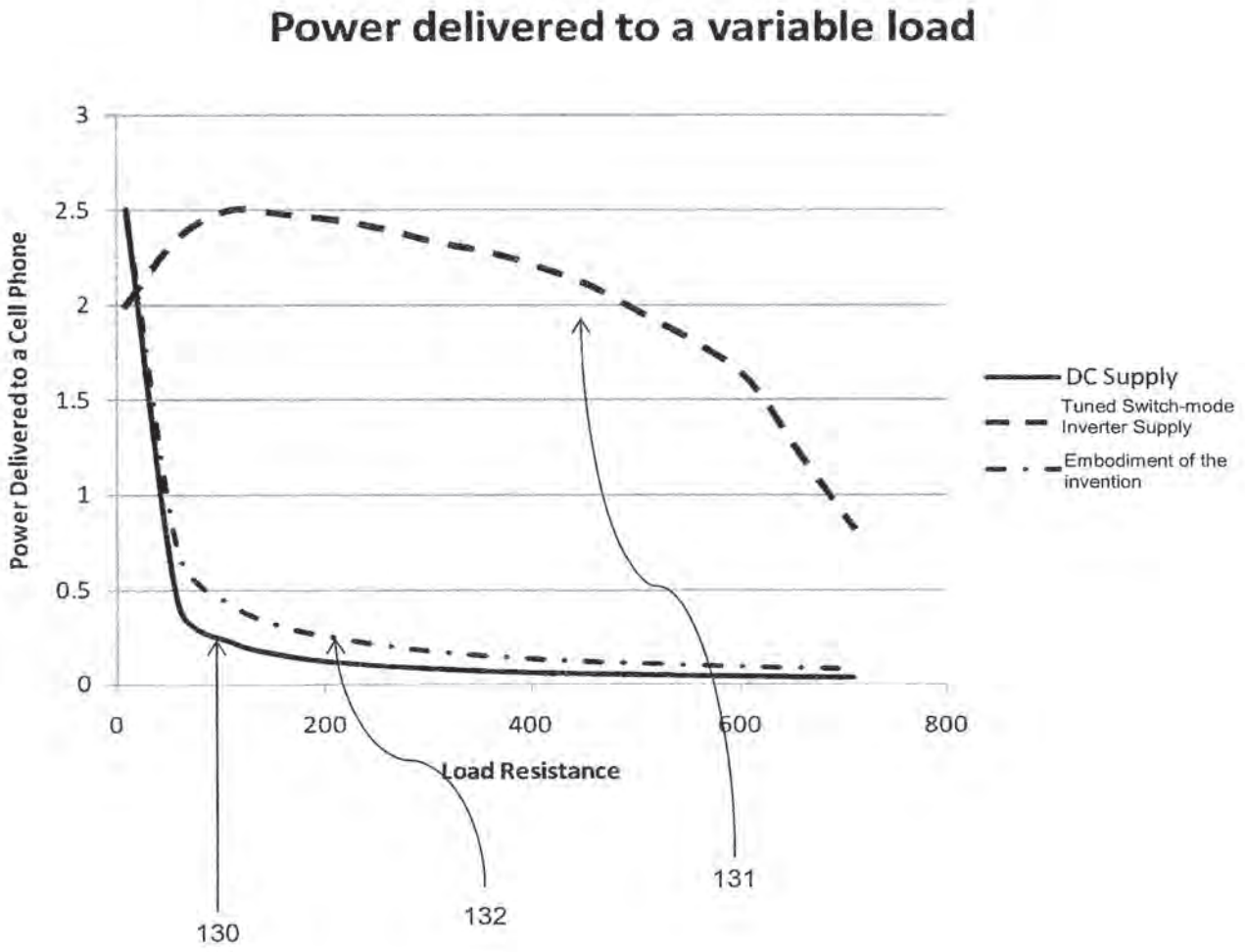

Power delivered to a variable load
Power Delivered to a Cell Phone
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
Load Resistance
DC Supply
Tuned Switch-mode Inverter Supply
Embodiment of the invention
130
132
131

FIG. 13

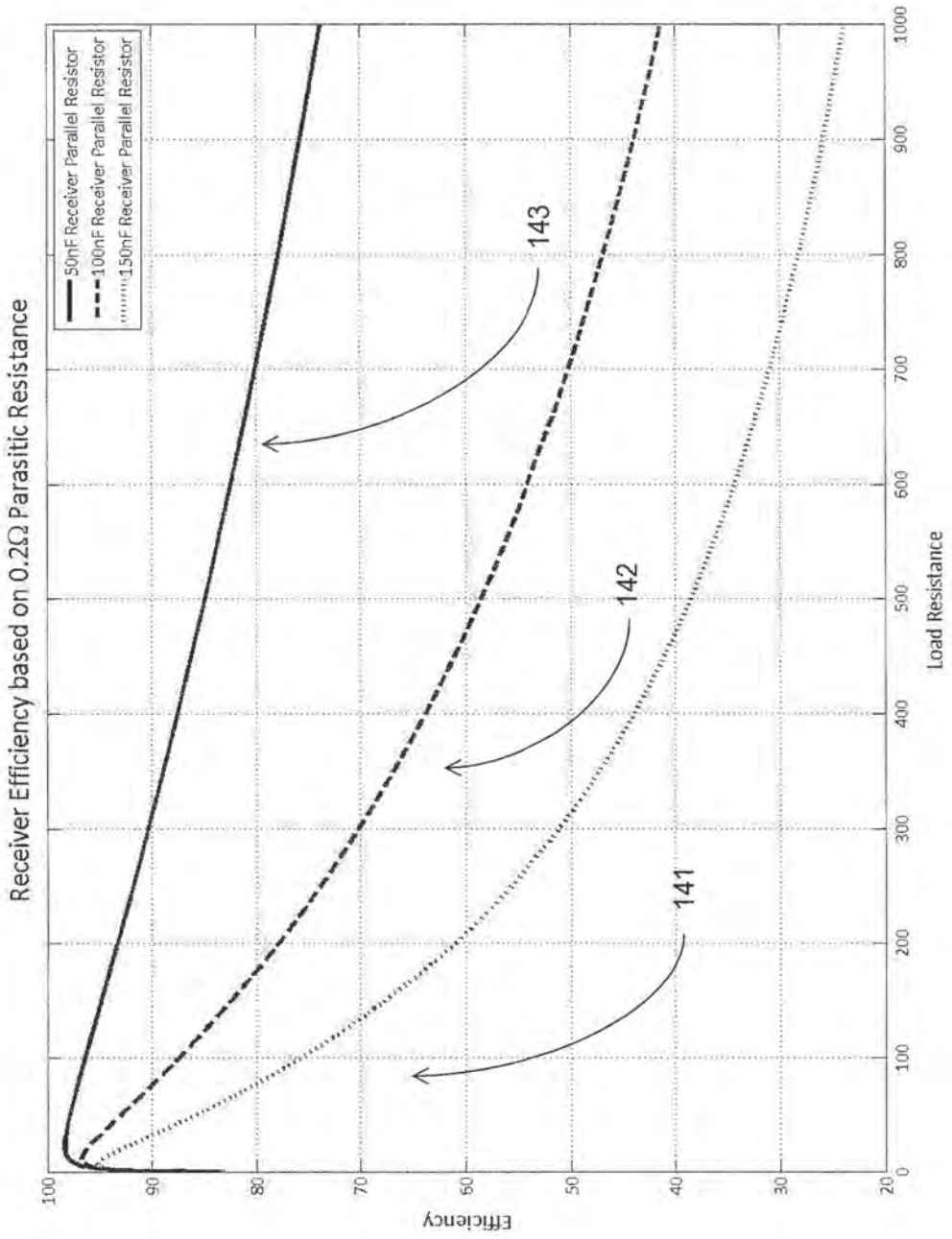

Receiver Efficiency based on 0.2Ω Parasitic Resistance
50nF Receiver Parallel Resistor
100nF Receiver Parallel Resistor
150nF Receiver Parallel Resistor
143
142
141
Efficiency
Load Resistance
100
90
80
70
60
50
40
30
20
0
100
200
300
400
500
600
700
800
900
1000

FIG. 14

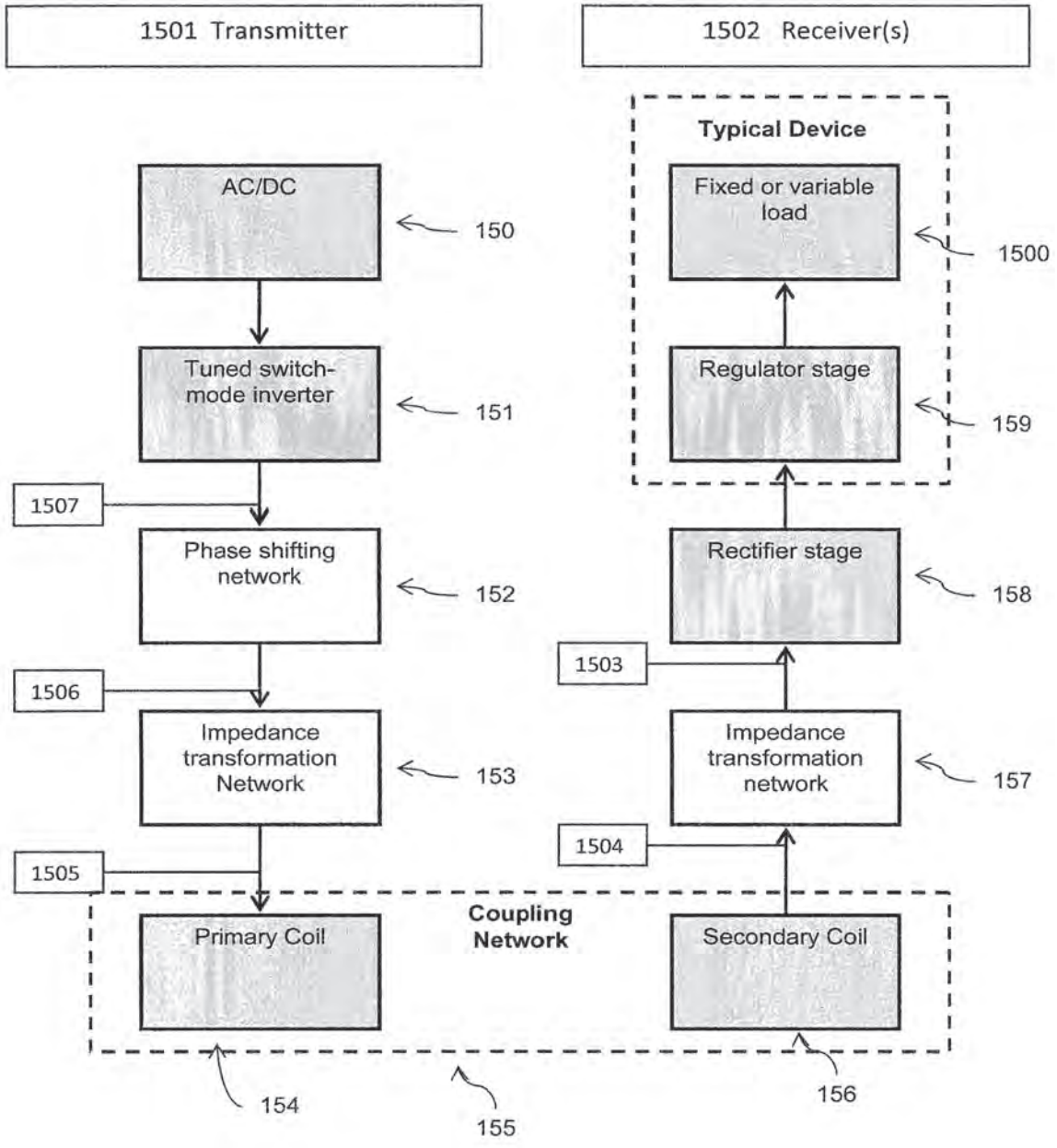

1501 Transmitter
1502 Receiver(s)
Typical Device
AC/DC
150
Fixed or variable load
1500
Tuned switch-mode inverter
151
Regulator stage
159
1507
Phase shifting network
152
Rectifier stage
158
1503
1506
Impedance transformation Network
153
Impedance transformation network
157
1504
1505
Coupling Network
Primary Coil
Secondary Coil
154
155
156

FIG. 15

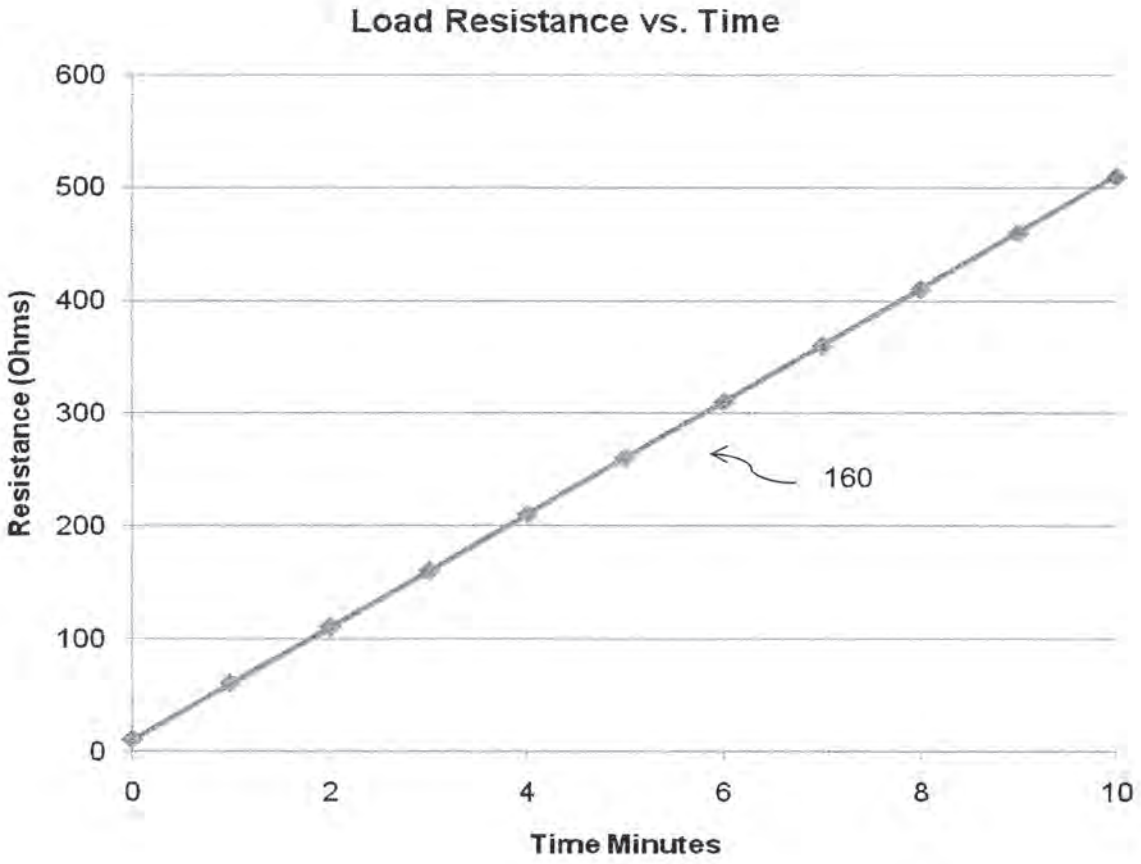

Load Resistance vs. Time
600
500
400
300
200
100
0
Resistance (Ohms)
0
2
4
6
8
10
Time Minutes
160

FIG. 16

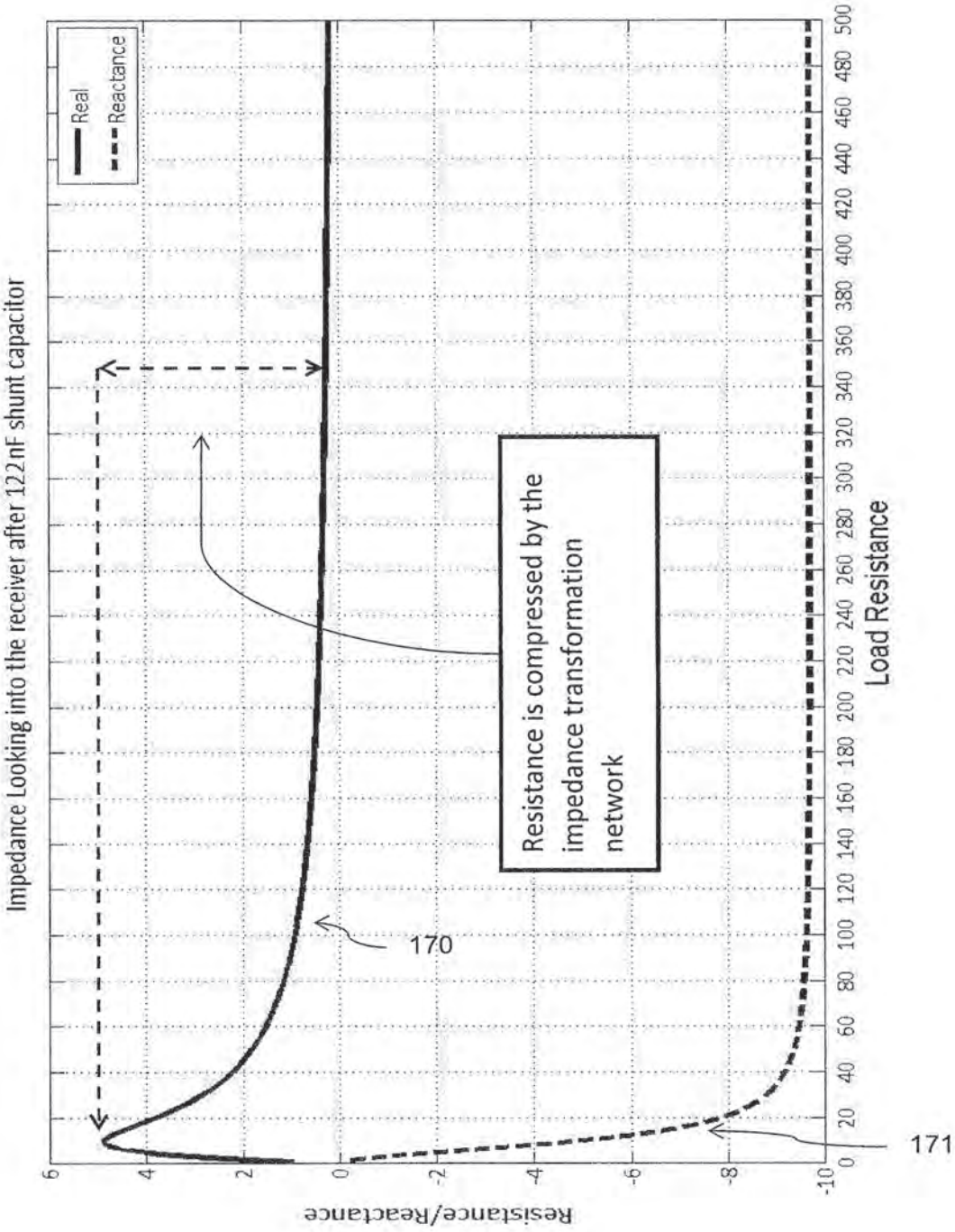

Impedance Looking into the receiver after 122nF shunt capacitor
Real
Reactance
Resistance is compressed by the impedance transformation network
170
171
Resistance/Reactance
Load Resistance
6
4
2
0
-2
-4
-6
-8
-10
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 17

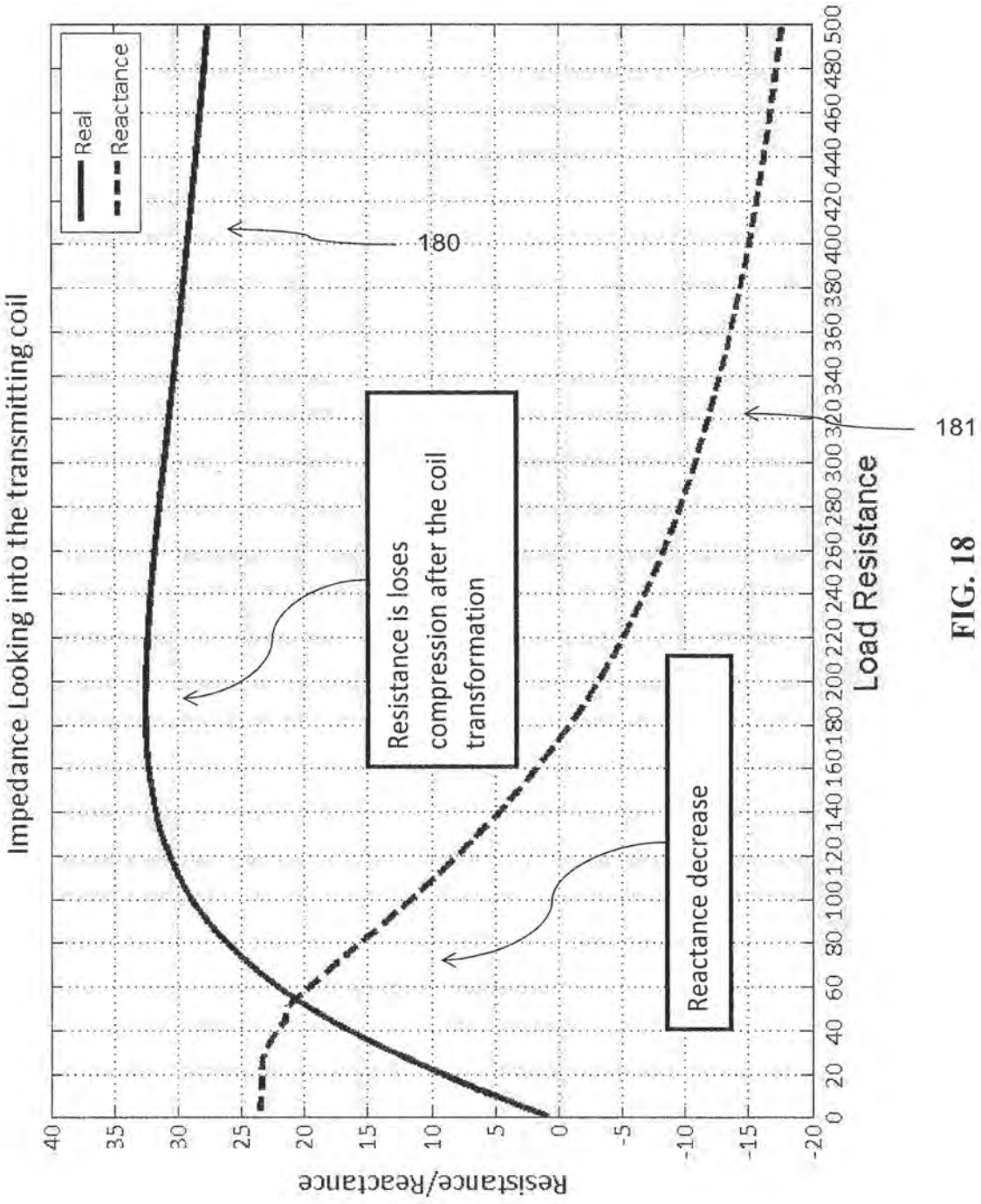

Impedance Looking into the transmitting coil
Real
Reactance
180
181
Resistance is loses compression after the coil transformation
Reactance decrease
Resistance/Reactance
Load Resistance
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500

FIG. 18

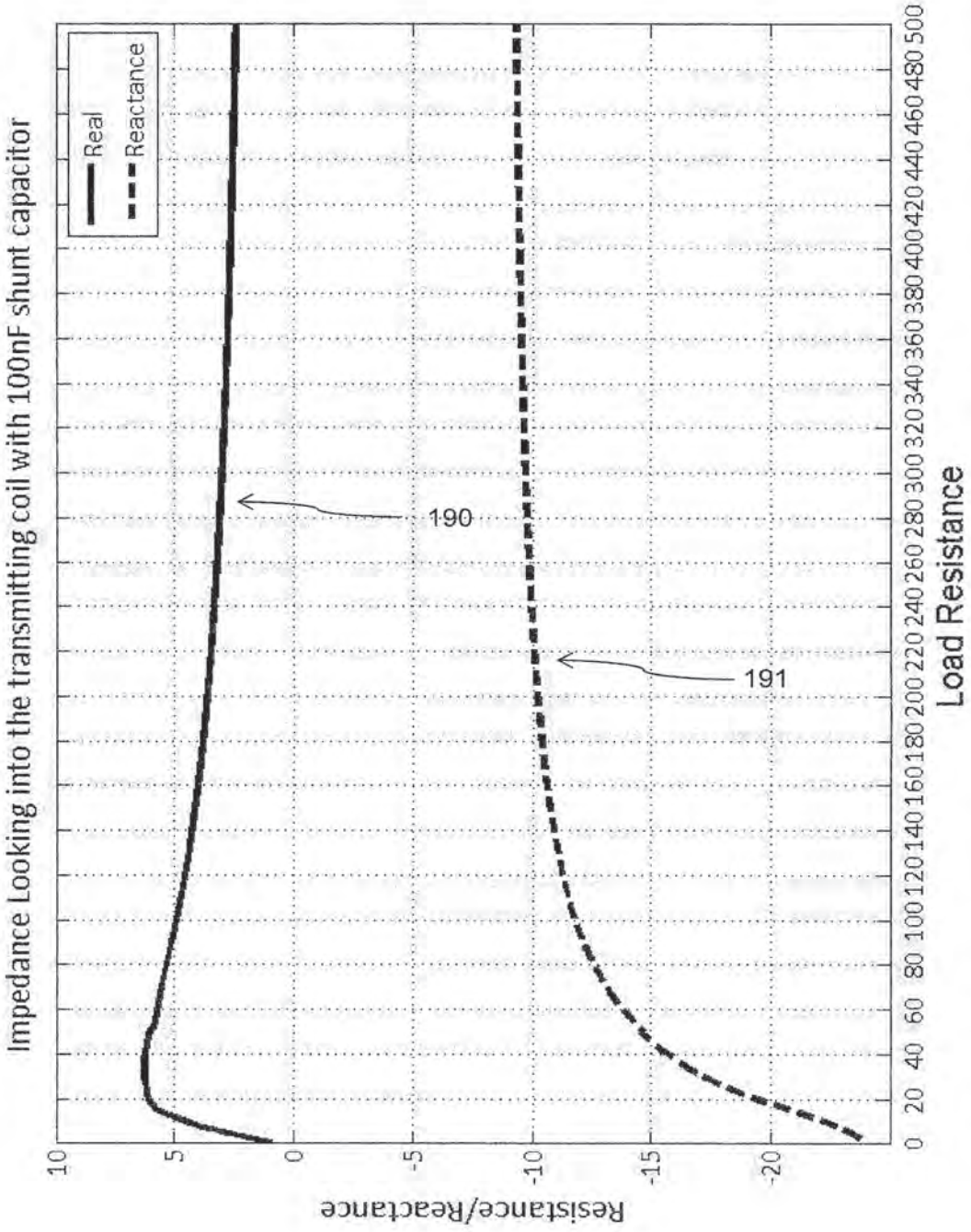

Impedance Looking into the transmitting coil with 100nF shunt capacitor
Real
Reactance
190
191
Resistance/Reactance
Load Resistance
10
5
0
-5
-10
-15
-20
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500

FIG. 19

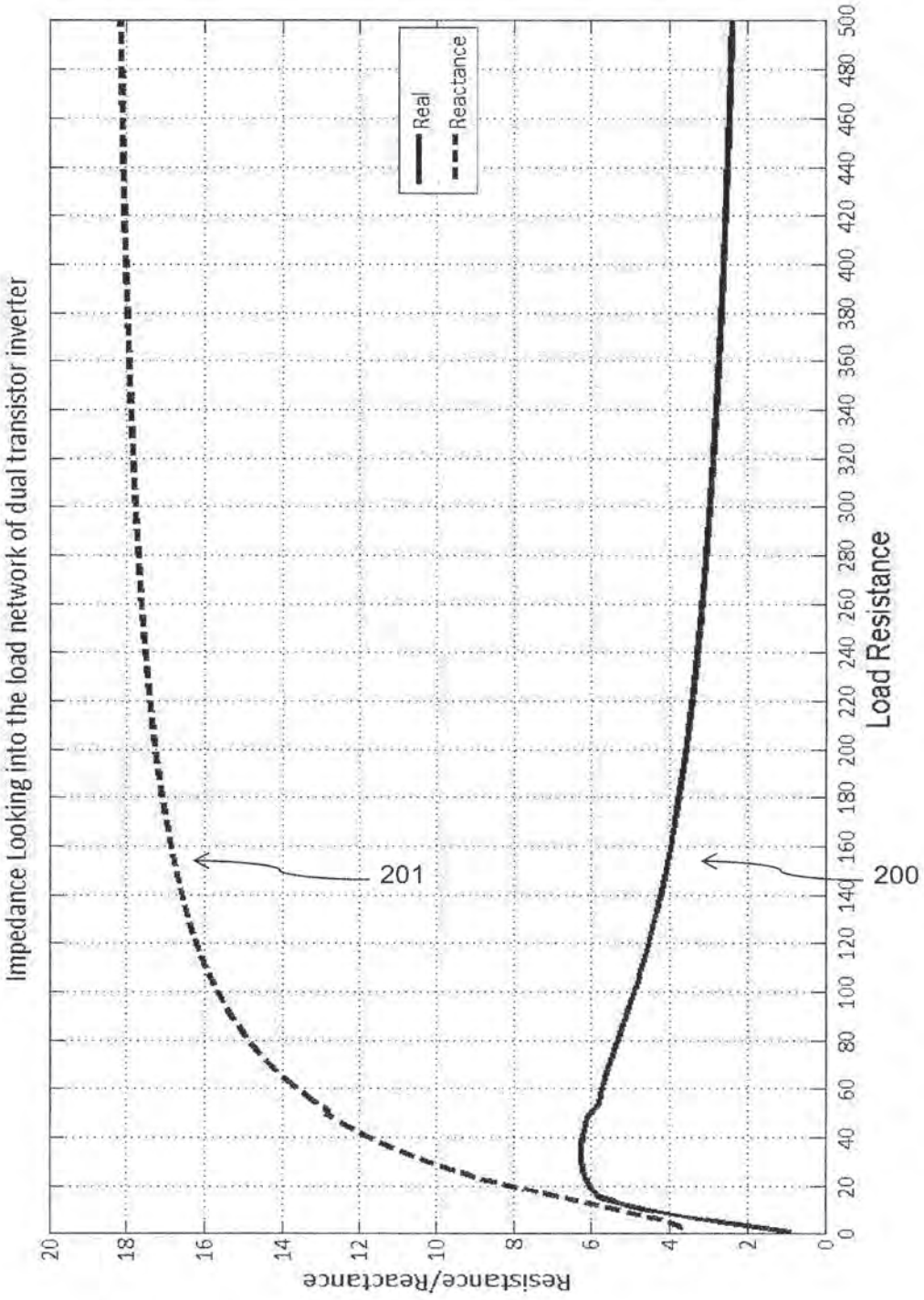

Impedance Looking into the load network of dual transistor inverter
Real
Reactance
201
200
Resistance/Reactance
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
2
4
6
8
10
12
14
16
18
20

FIG. 20

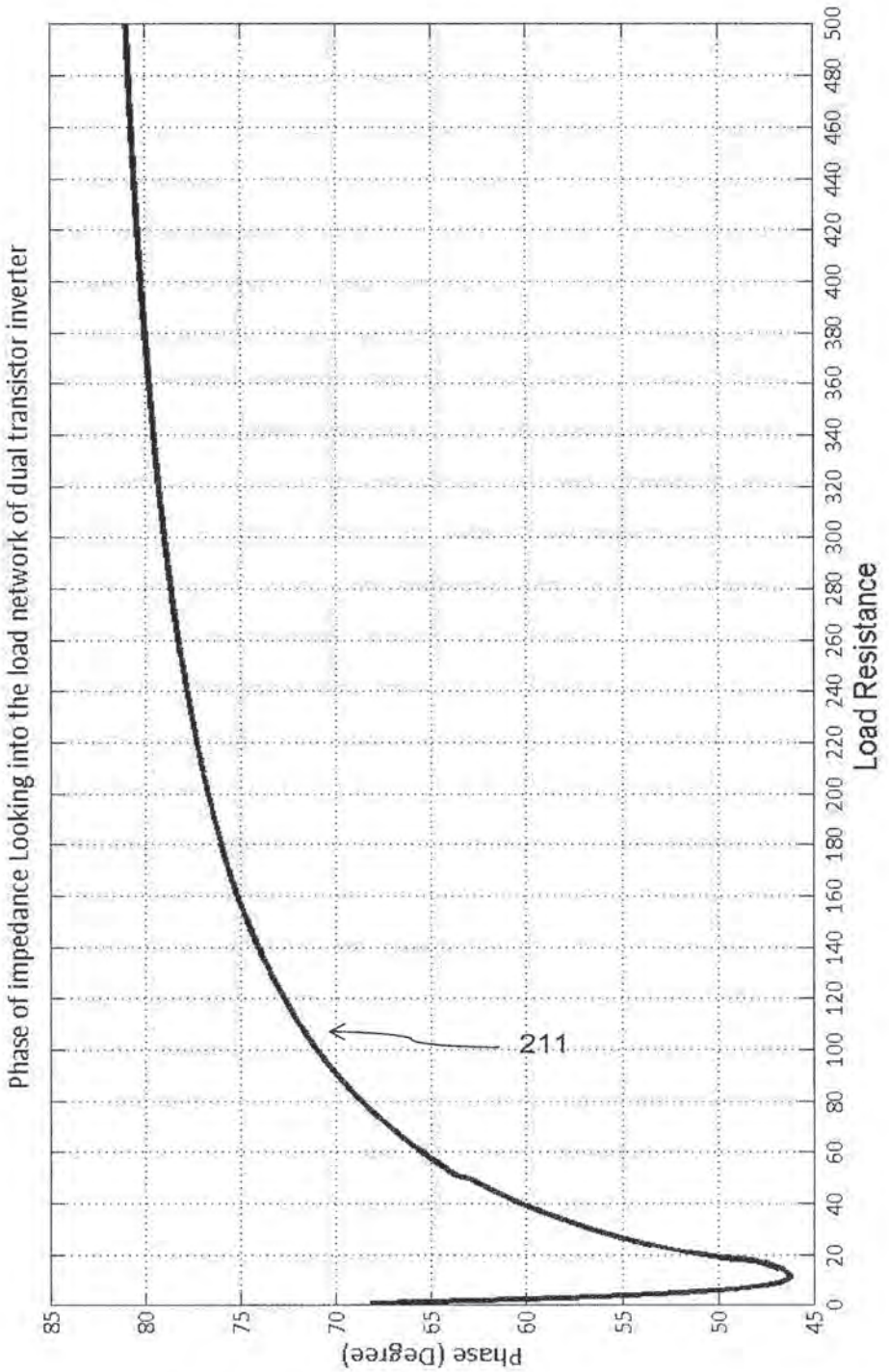

Phase of impedance Looking into the load network of dual transistor inverter
Phase (Degree)
Load Resistance
211
85
80
75
70
65
60
55
50
45
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 21

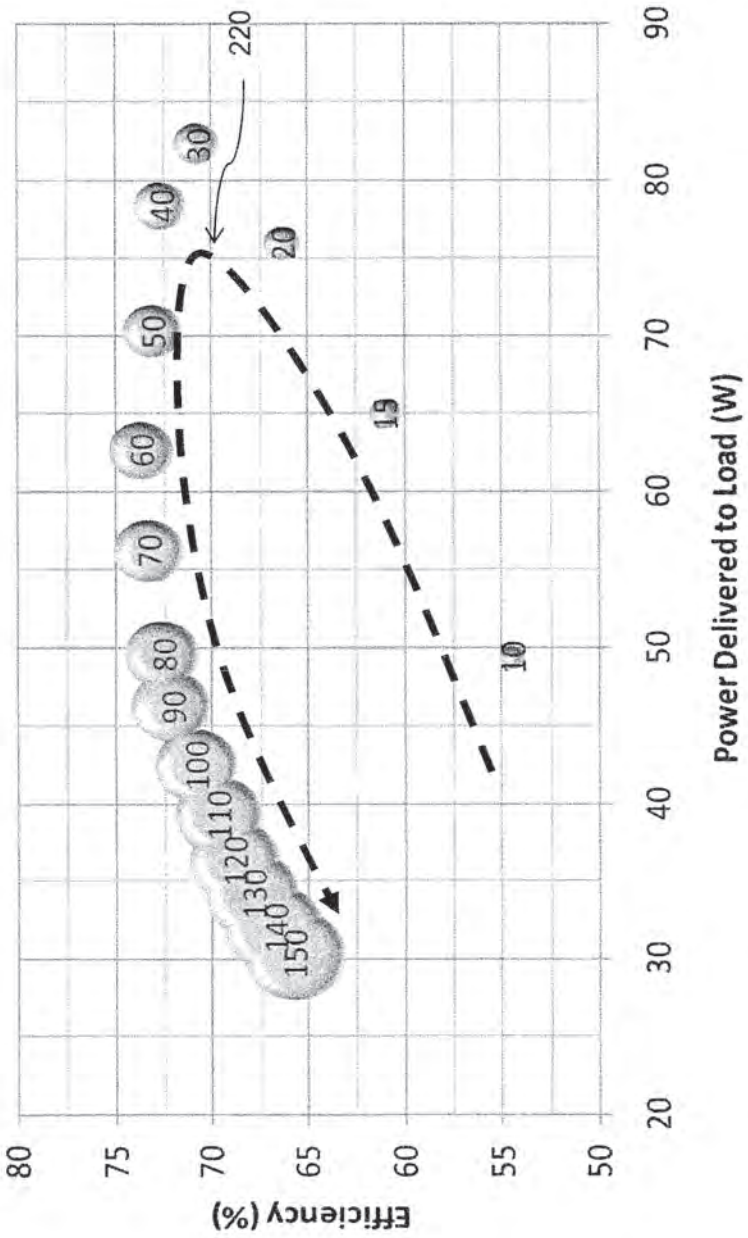

Efficiency (%)
80
75
70
65
60
55
50
Power Delivered to Load (W)
20
30
40
50
60
70
80
90
10
15
20
30
40
50
60
70
80
90
100
110
120
130
140
150
220

FIG. 22

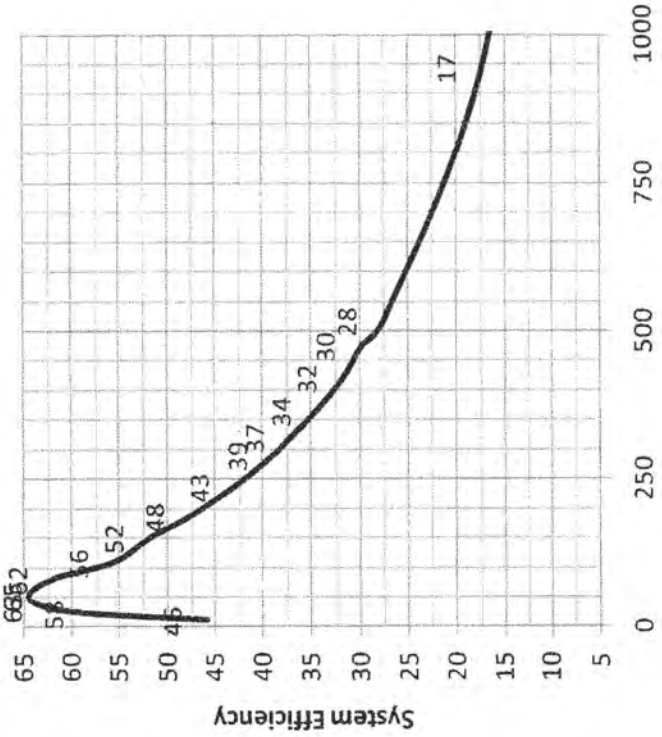


FIG. 23B

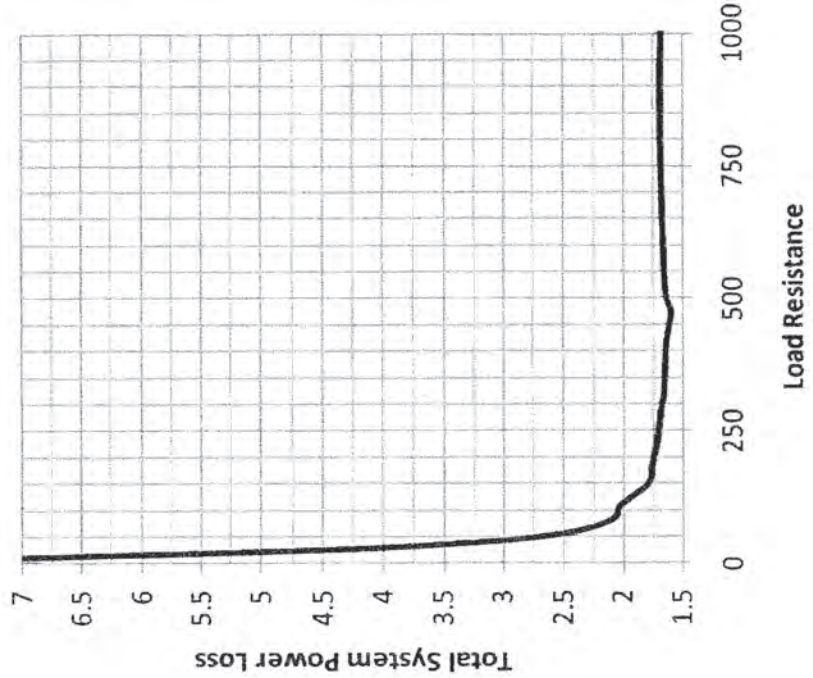


FIG. 23A

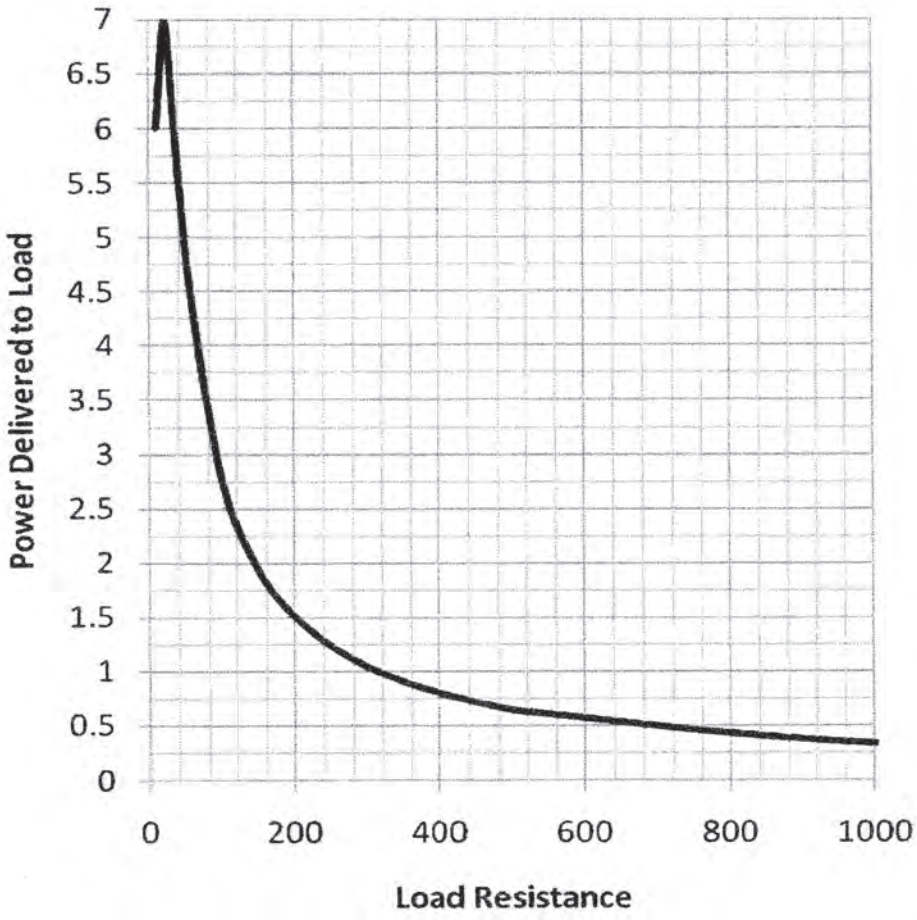

Power Delivered to Load
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
1000
Load Resistance

FIG. 23C

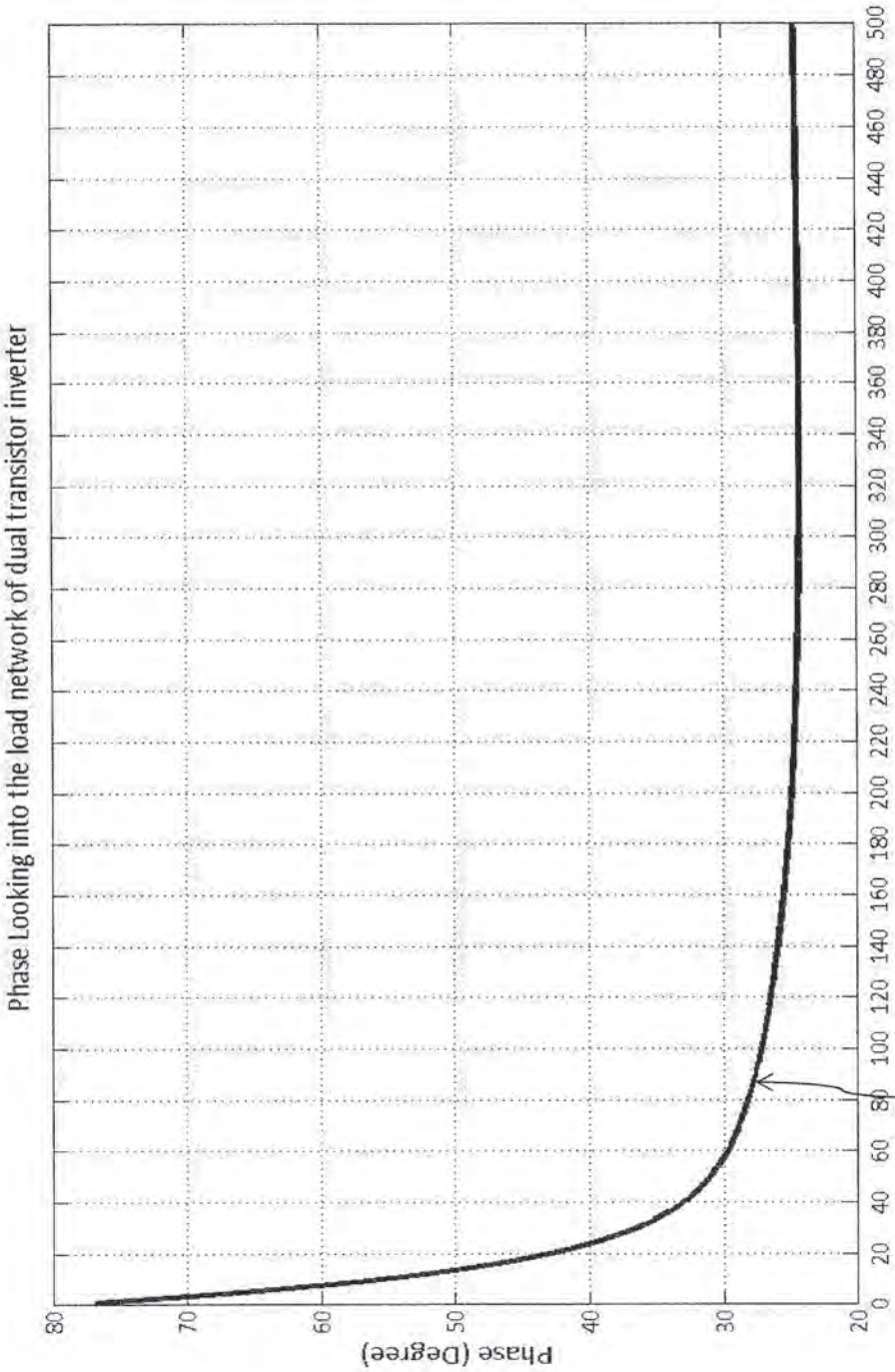

Phase Looking into the load network of dual transistor inverter
Phase (Degree)
Load Resistance
240
80
70
60
50
40
30
20
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 24

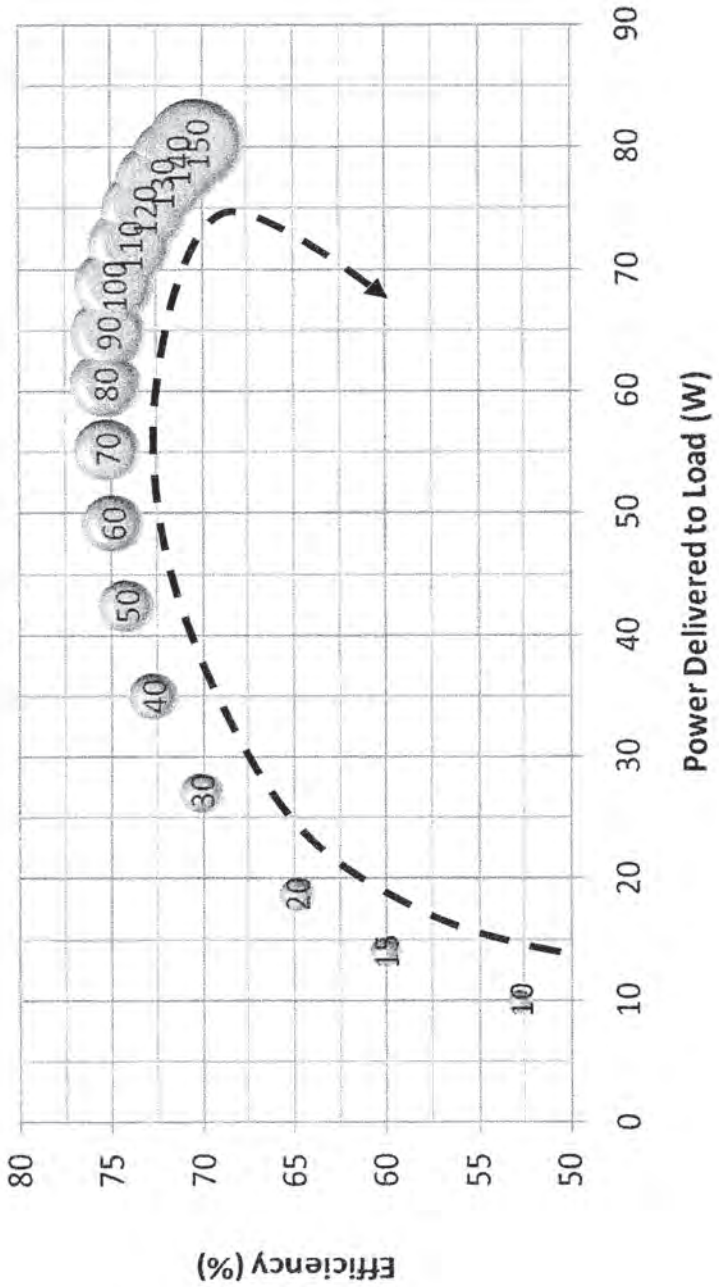

Efficiency (%)
80
75
70
65
60
55
50
Power Delivered to Load (W)
0
10
20
30
40
50
60
70
80
90
10
15
20
30
40
50
60
70
80
90
100
110
120
130
140
150

FIG. 25

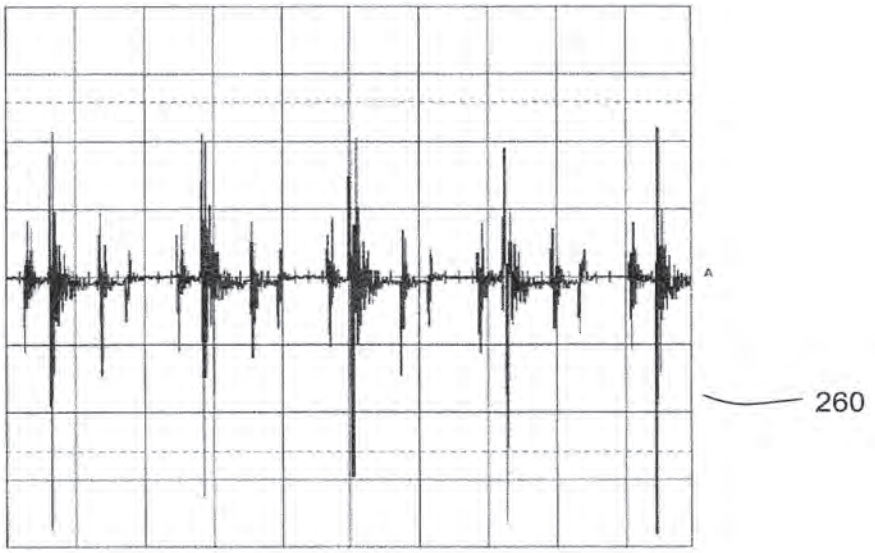


FIG. 26A

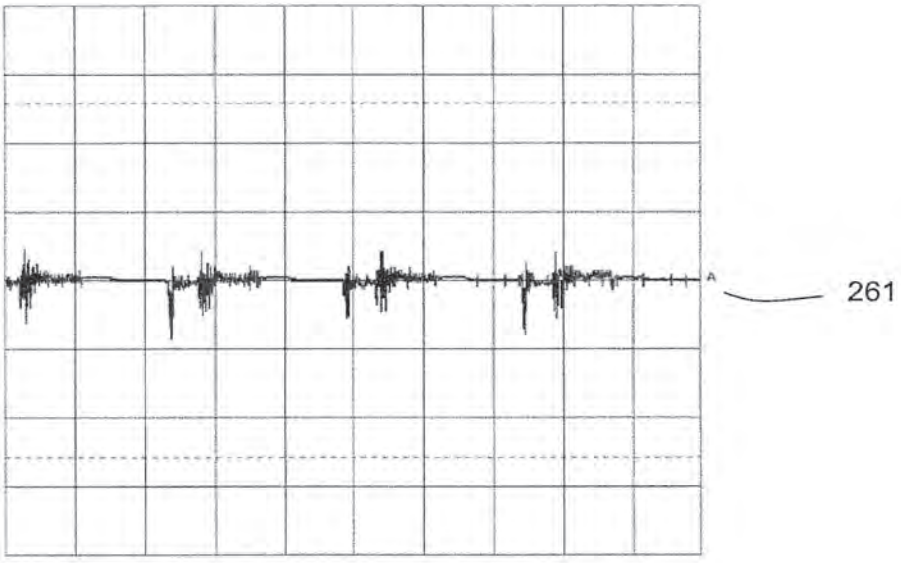


FIG. 26B

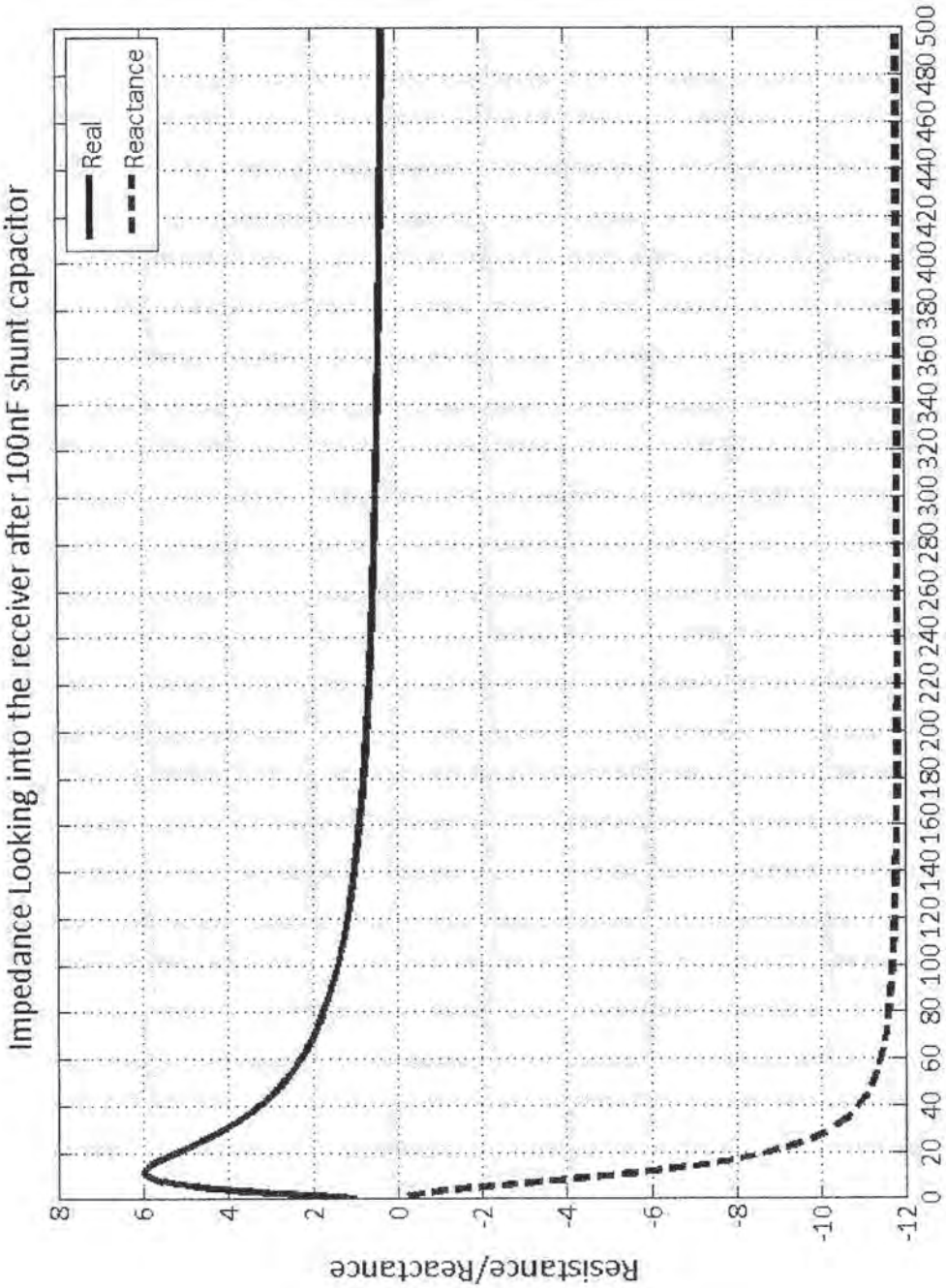

Impedance Looking into the receiver after 100nF shunt capacitor
Real
Reactance
Resistance/Reactance
Load Resistance
8
6
4
2
0
-2
-4
-6
-8
-10
-12
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500

FIG. 27

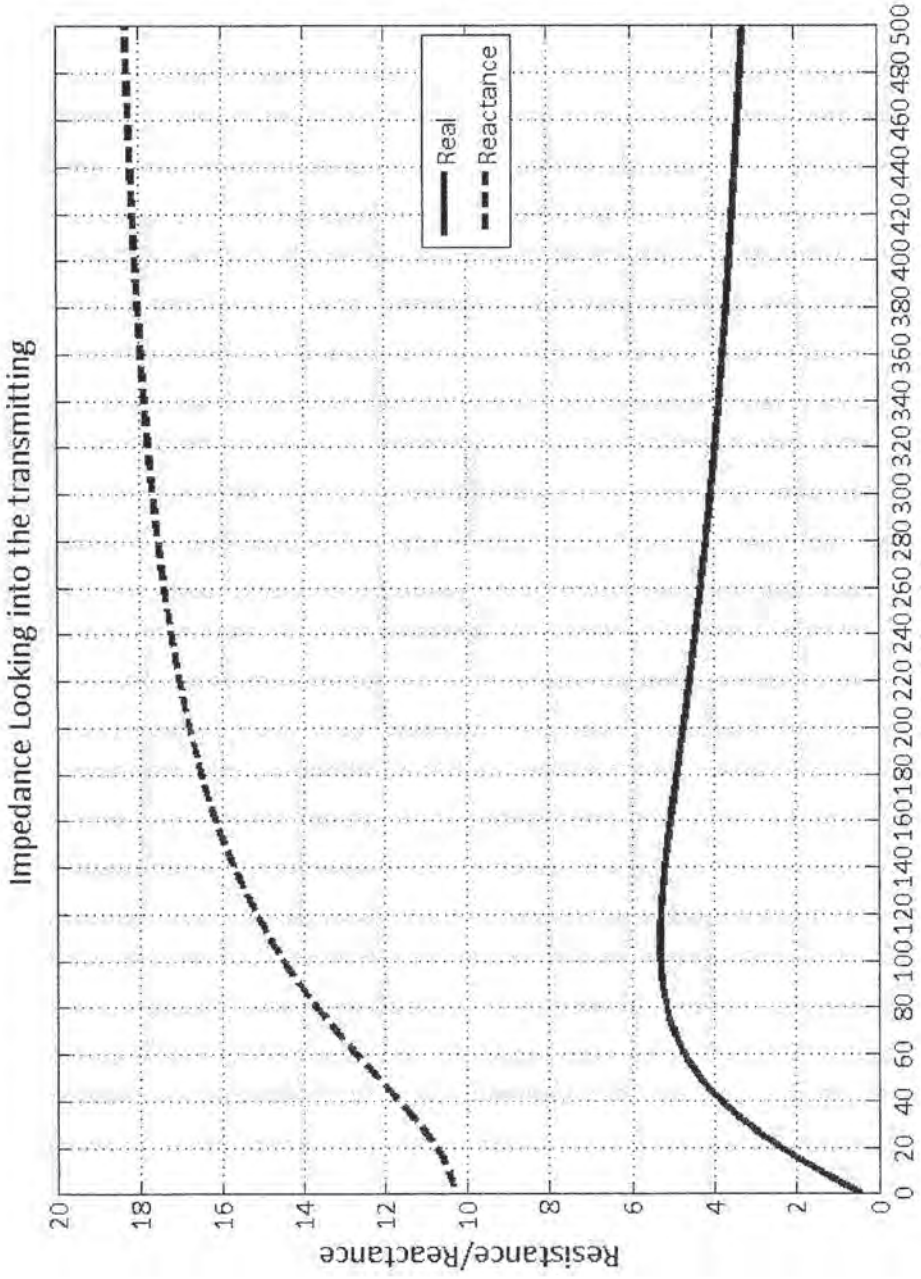

Impedance Looking into the transmitting
Resistance/Reactance
Load Resistance
Real
Reactance
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500
0 2 4 6 8 10 12 14 16 18 20

FIG. 28

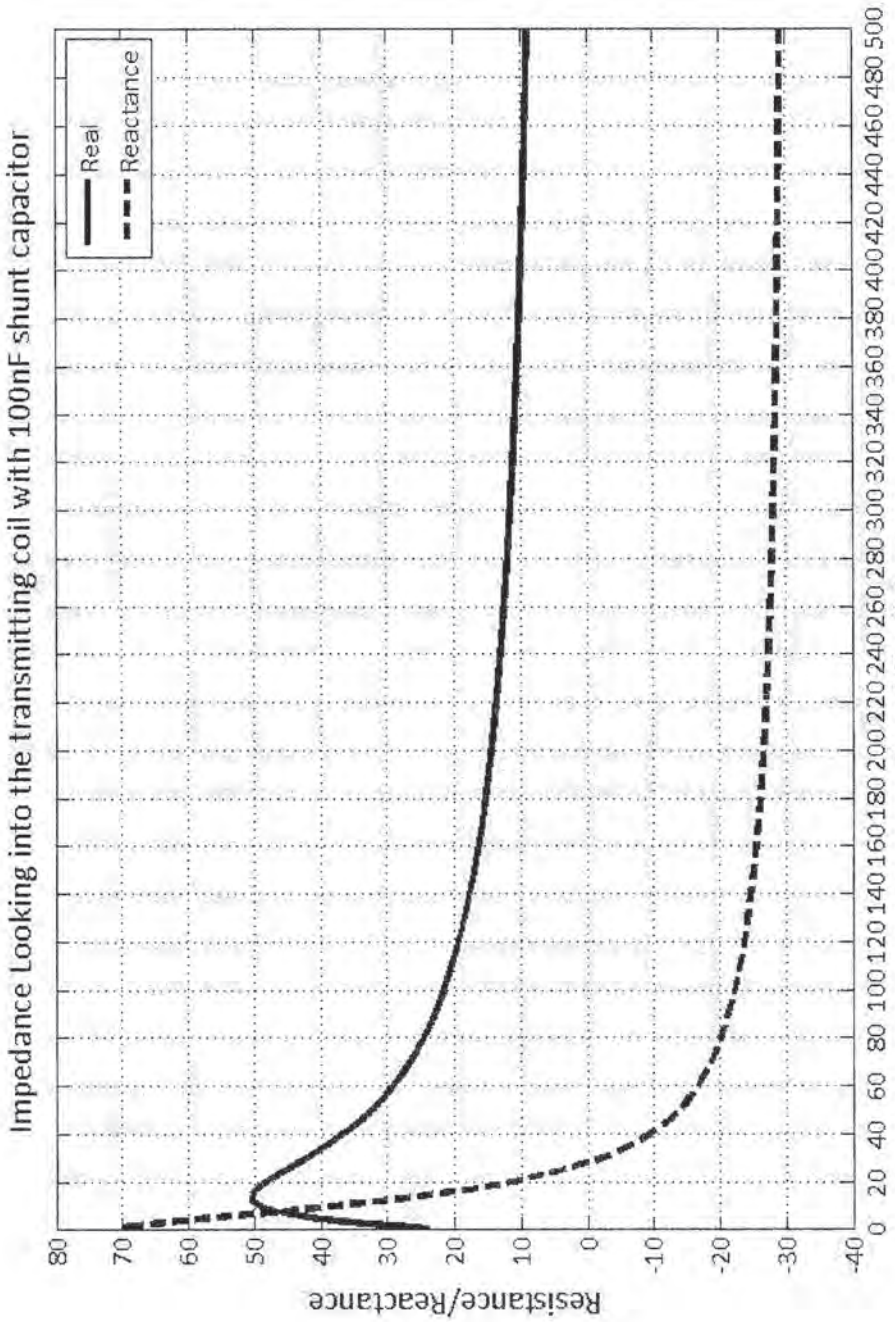

Impedance Looking into the transmitting coil with 100nF shunt capacitor
Real
Reactance
Resistance/Reactance
Load Resistance
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500

FIG. 29

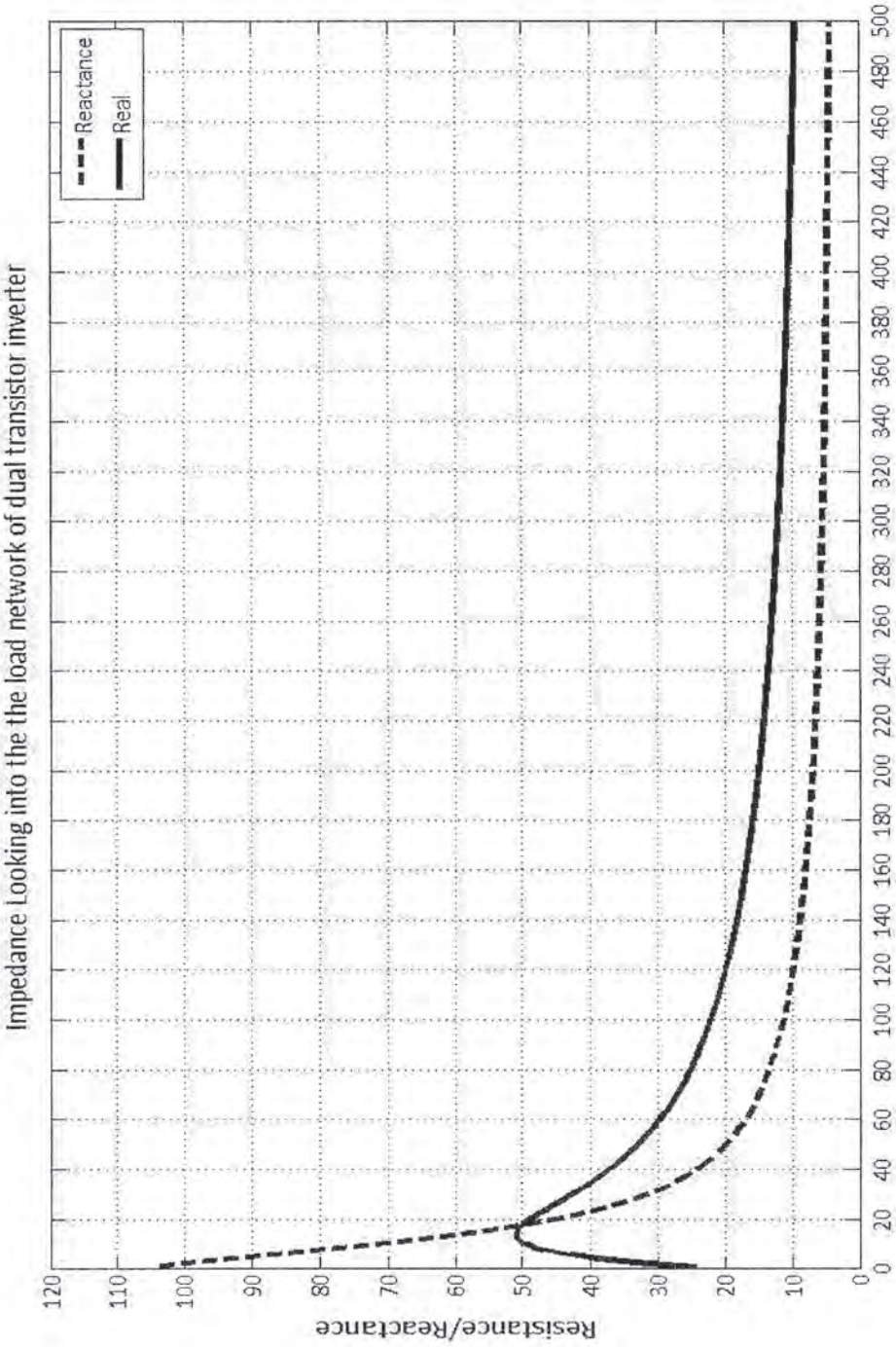

Impedance Looking into the the load network of dual transistor inverter
Reactance
Real
Resistance/Reactance
Load Resistance
0
10
20
30
40
50
60
70
80
90
100
110
120
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 30

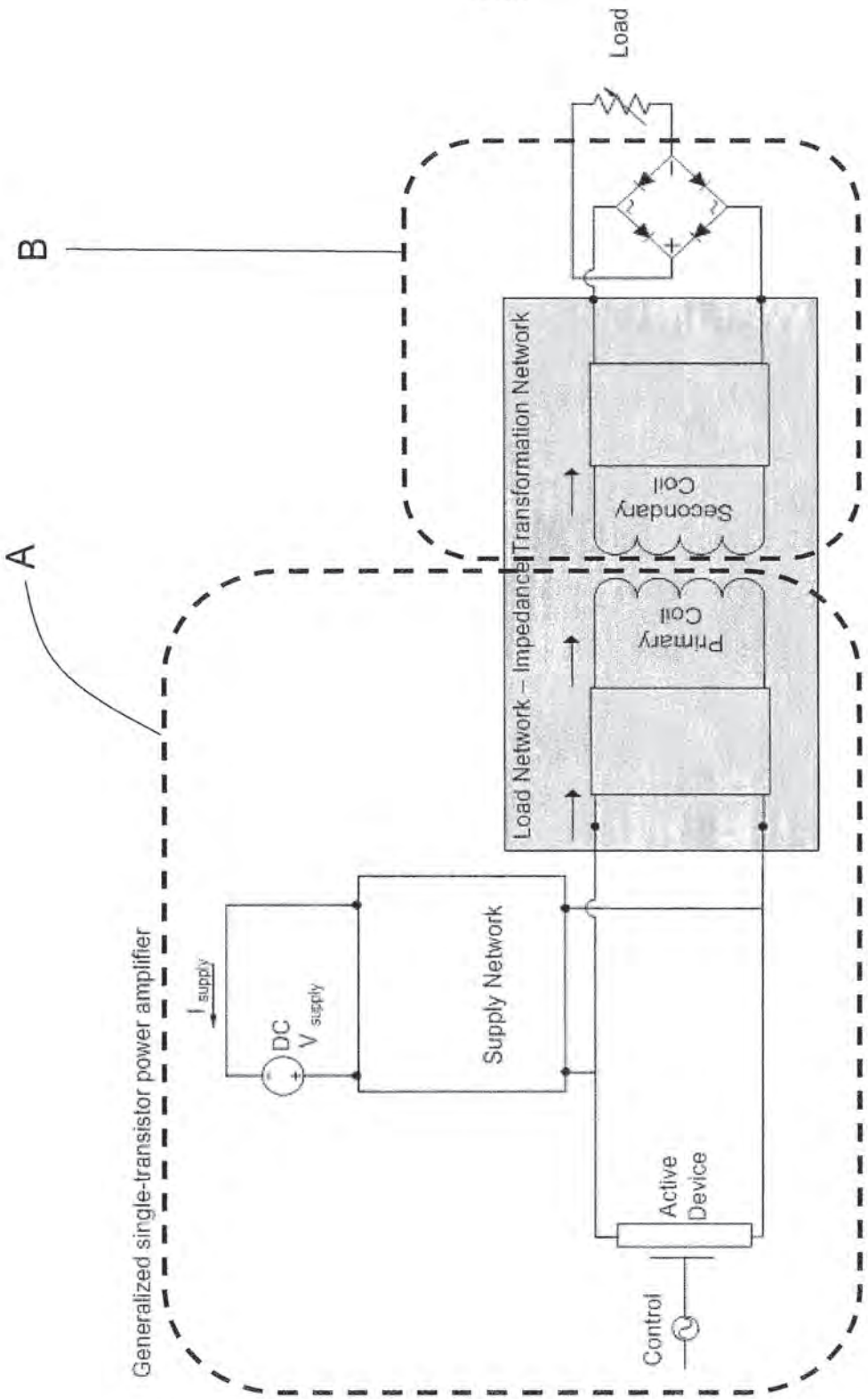

Load
B
A
Secondary Coil
Primary Coil
Load Network – Impedance Transformation Network
Generalized single-transistor power amplifier
I supply
DC
V supply
Supply Network
Active Device
Control

FIG. 31

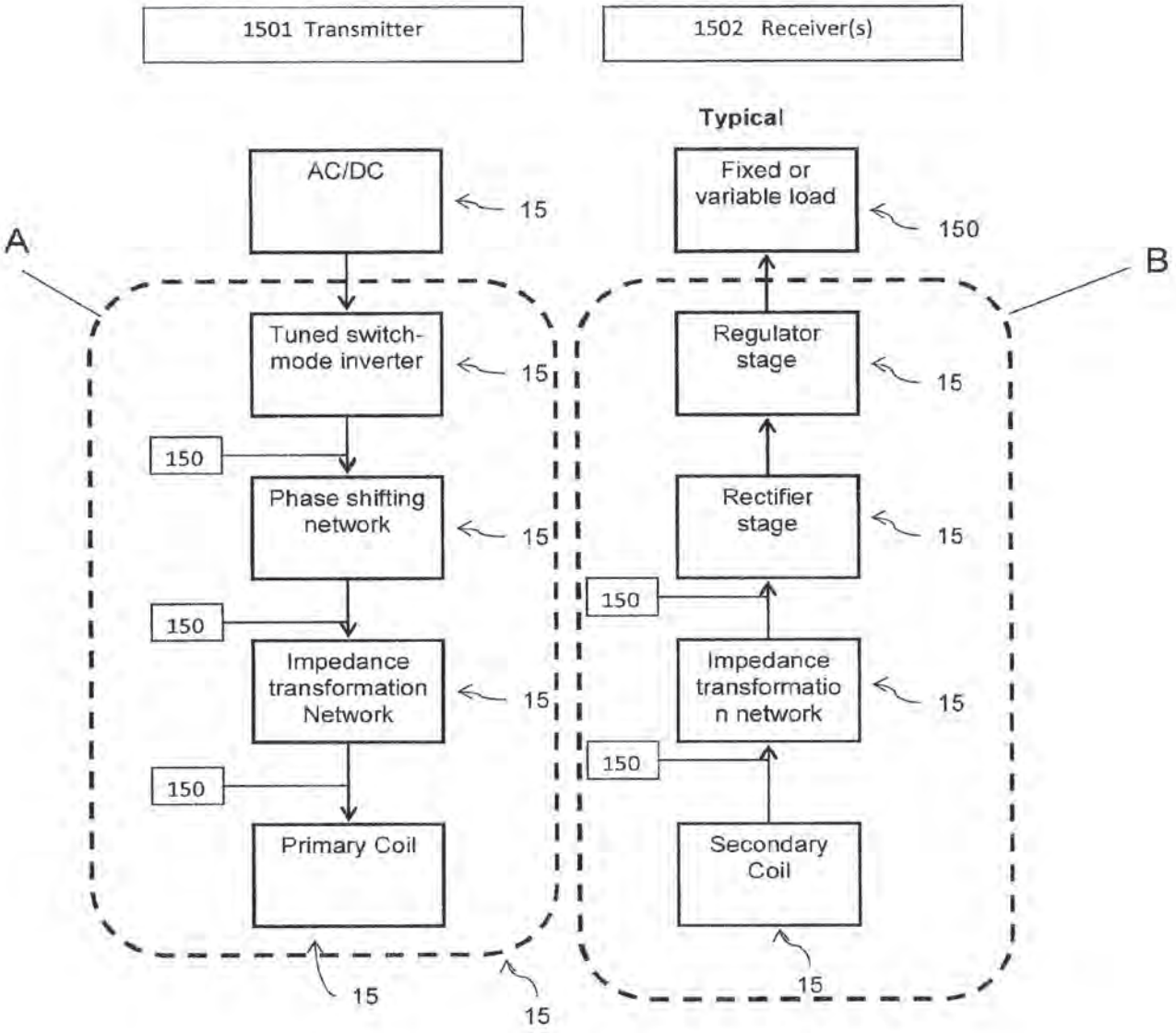

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
15
Fixed or variable load
150
A
B
Tuned switch-mode inverter
15
Regulator stage
15
150
Phase shifting network
15
Rectifier stage
15
150
150
Impedance transformation Network
15
Impedance transformatio n network
15
150
150
Primary Coil
Secondary Coil
15
15
15

FIG. 32

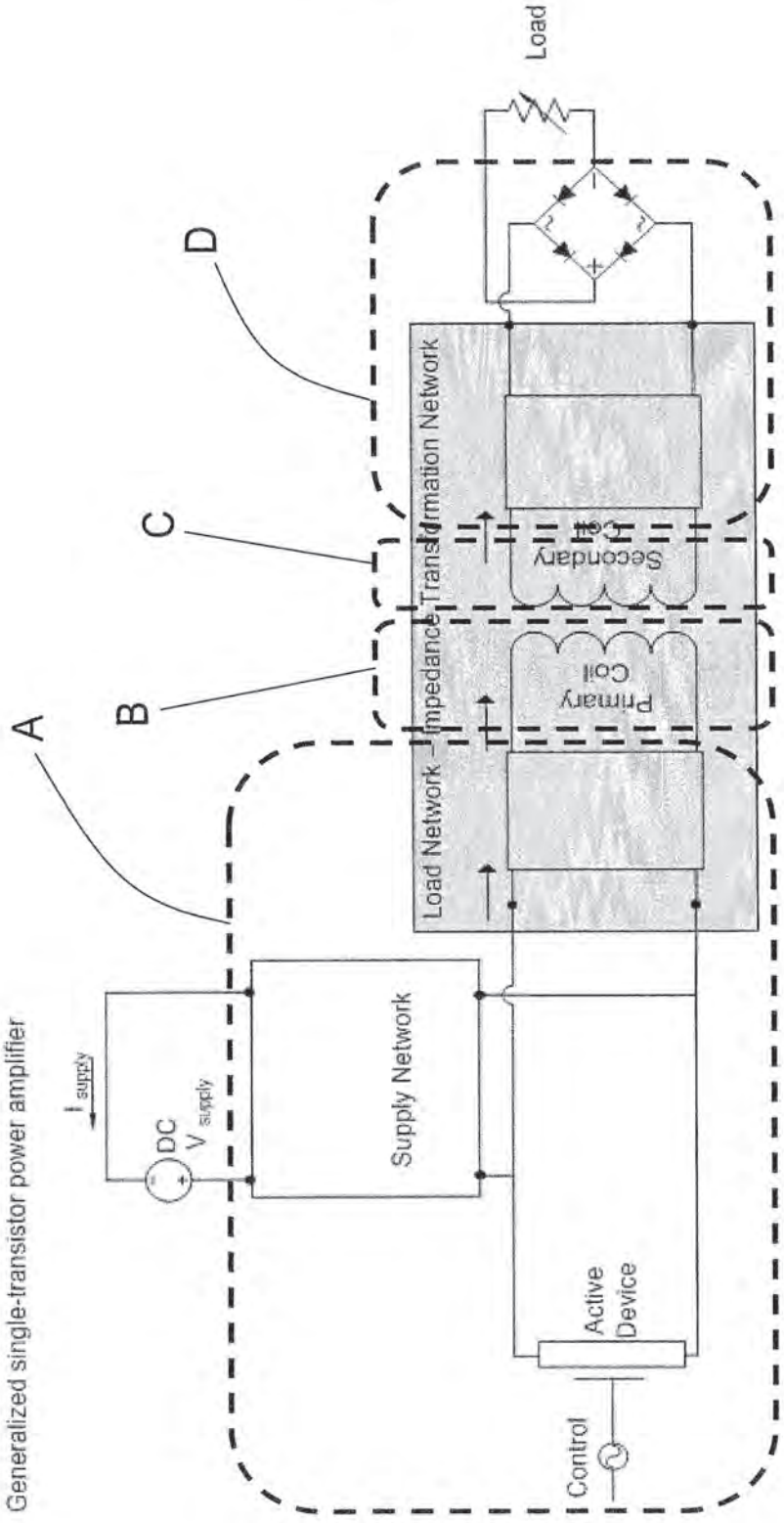

Load
D
C
B
A
Secondary Coil
Impedance Transformation Network
Primary Coil
Load Network
Supply Network
DC
V supply
I supply
Active Device
Control
Generalized single-transistor power amplifier

FIG. 33

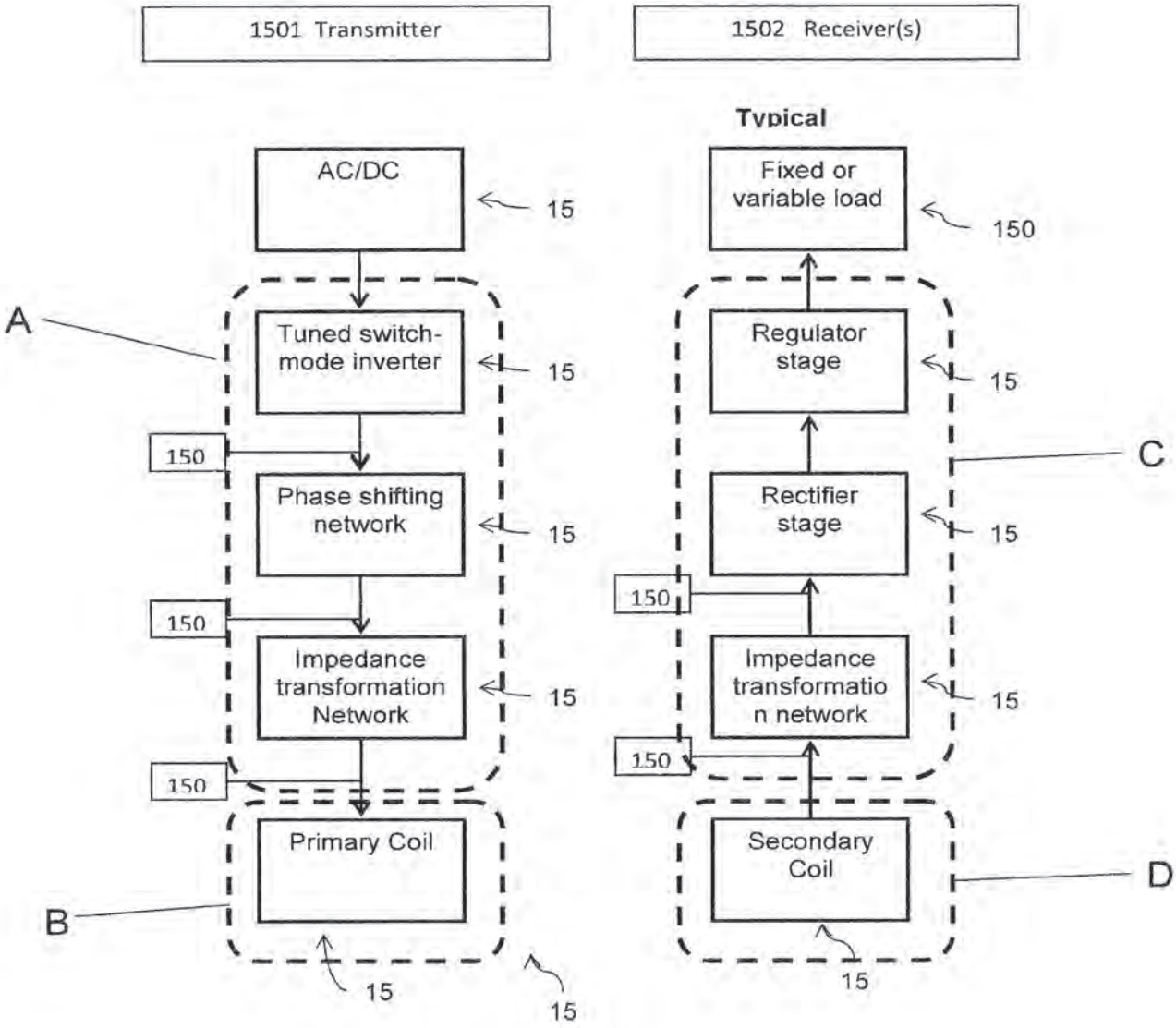

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
15
Tuned switch-mode inverter
15
150
Phase shifting network
15
150
Impedance transformation Network
15
150
Primary Coil
A
B
15
15
Fixed or variable load
150
Regulator stage
15
C
Rectifier stage
15
150
Impedance transformatio n network
15
150
Secondary Coil
D
15

FIG. 34

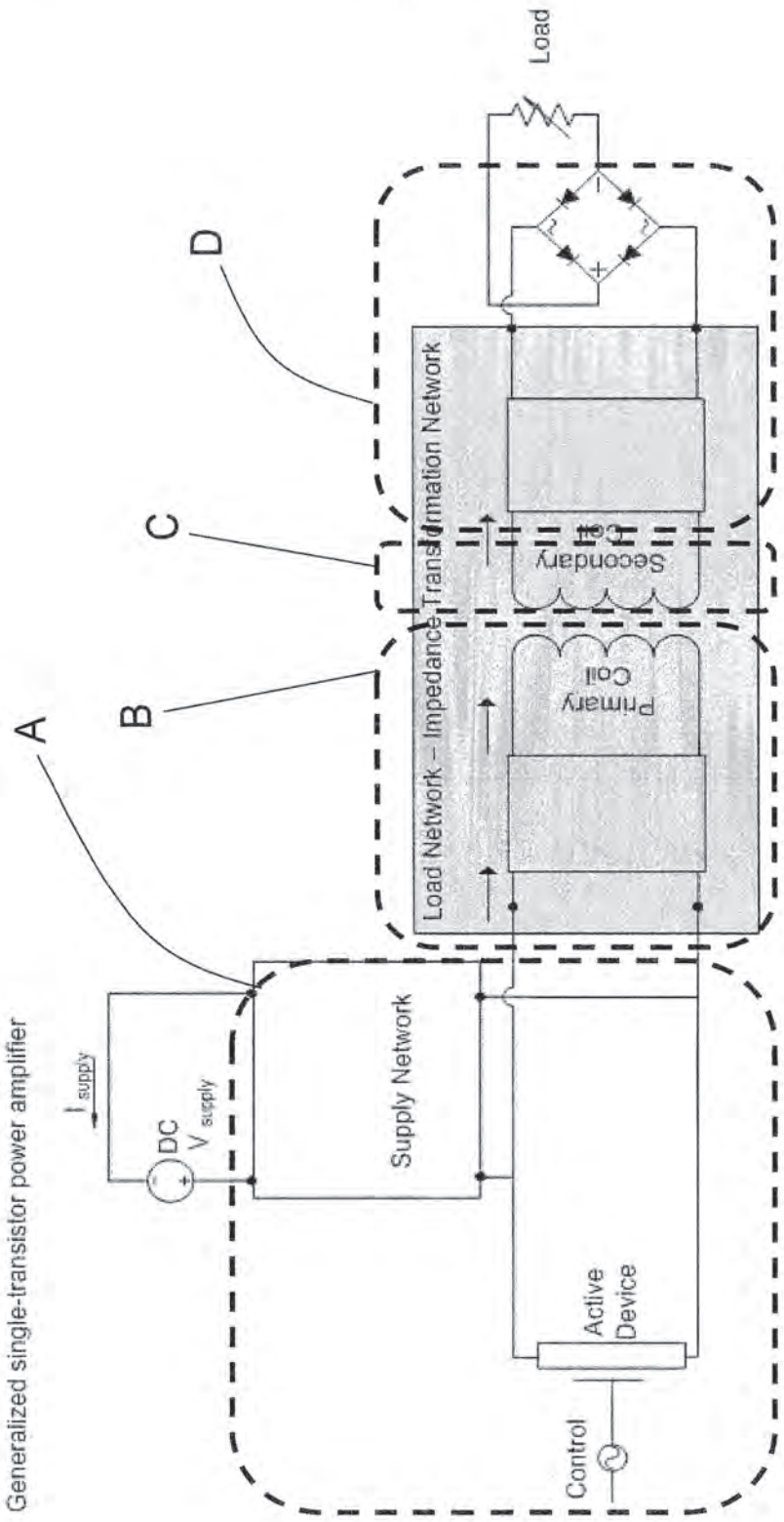

Load
D
C
B
A
Load Network – Impedance Transformation Network
Secondary Coil
Primary Coil
Generalized single-transistor power amplifier
I supply
DC
V supply
Supply Network
Active Device
Control

FIG. 35

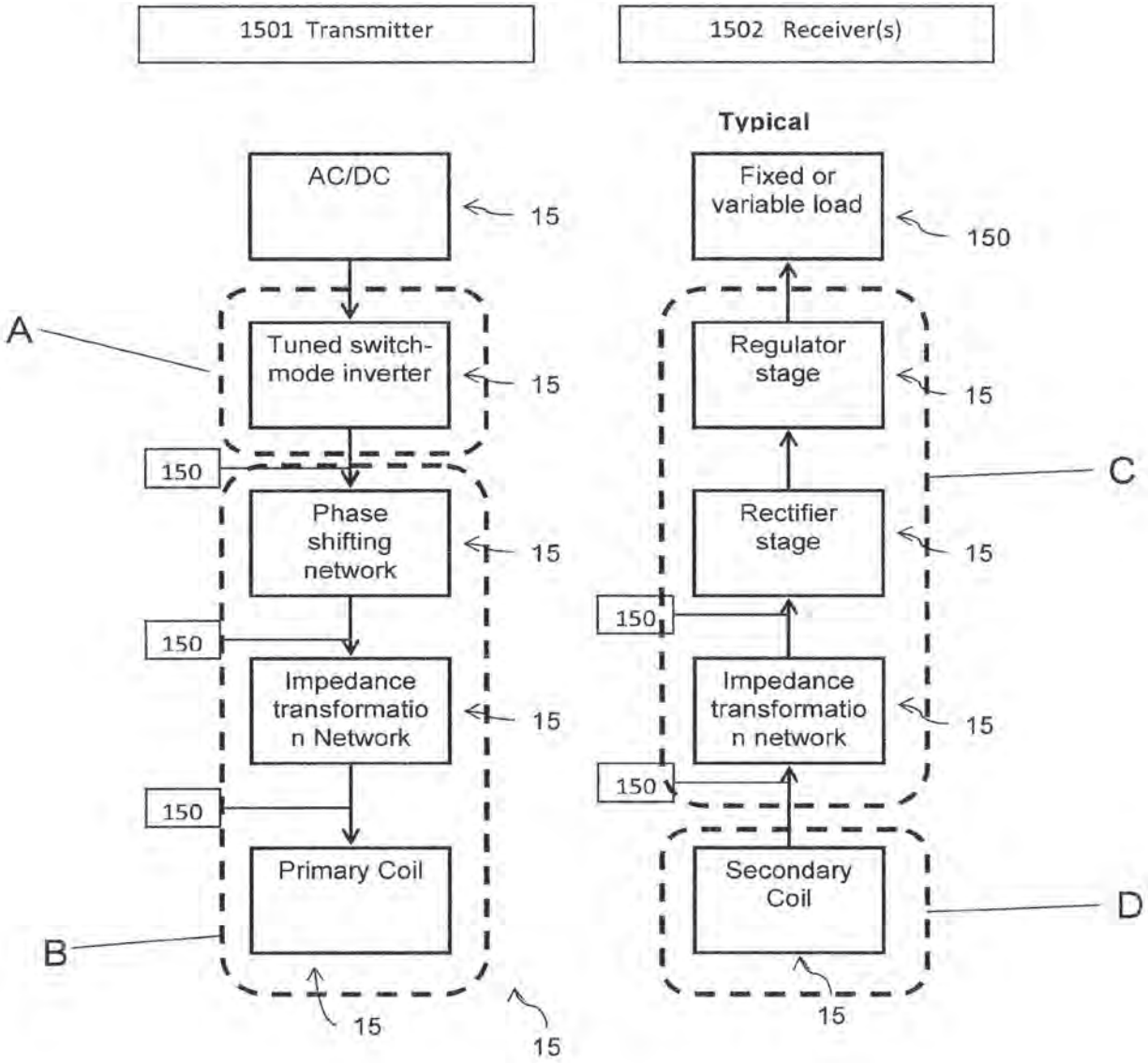

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
15
Tuned switch-mode inverter
15
150
Phase shifting network
15
150
Impedance transformatio n Network
15
150
Primary Coil
A
B
15
15
Fixed or variable load
150
Regulator stage
15
C
Rectifier stage
15
150
Impedance transformatio n network
15
150
Secondary Coil
D
15

FIG. 36

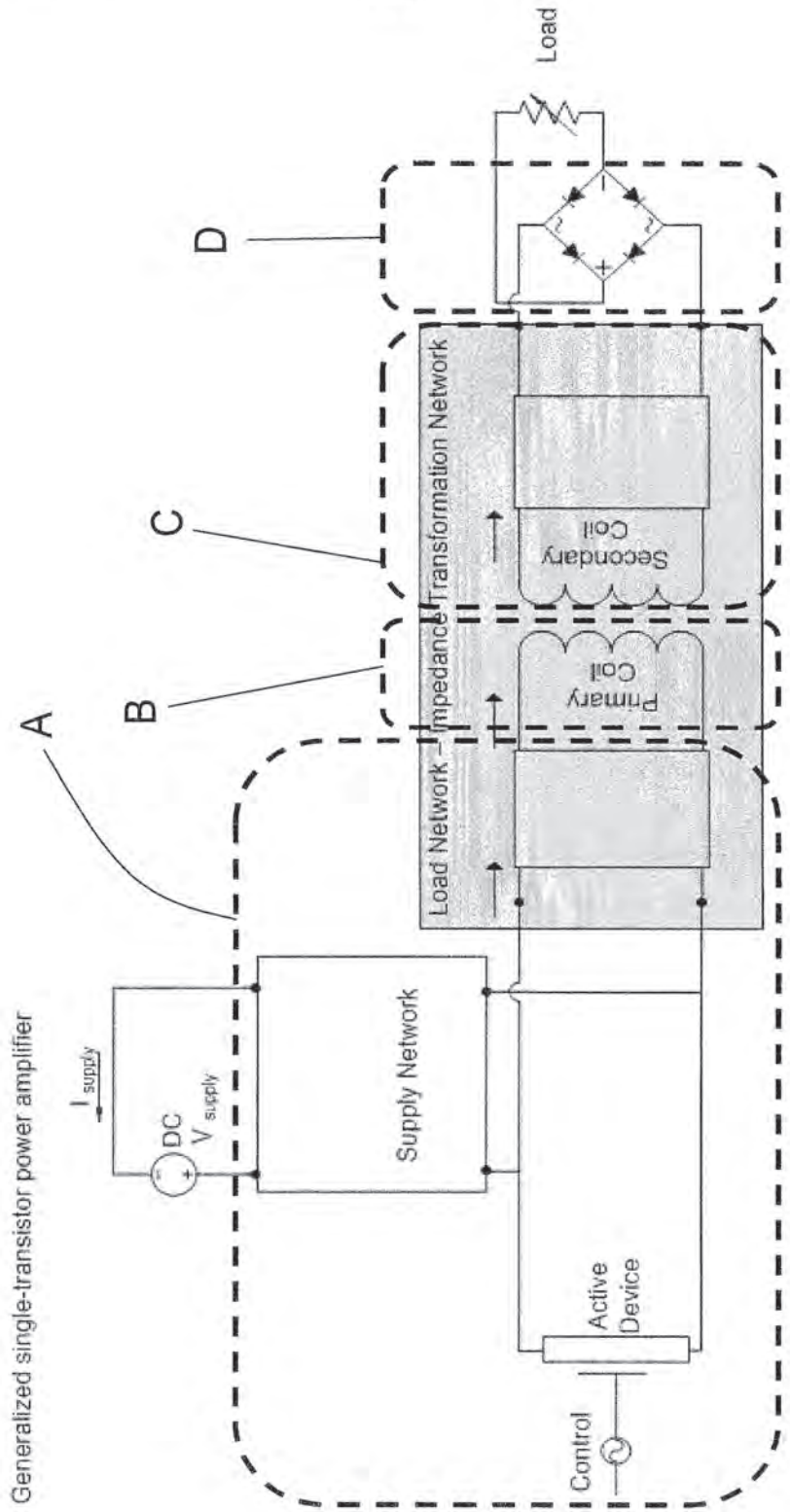

Load
D
C
B
A
Load Network – Impedance Transformation Network
Secondary Coil
Primary Coil
Generalized single-transistor power amplifier
DC
V_{supply}
I_{supply}
Supply Network
Active Device
Control

FIG. 37

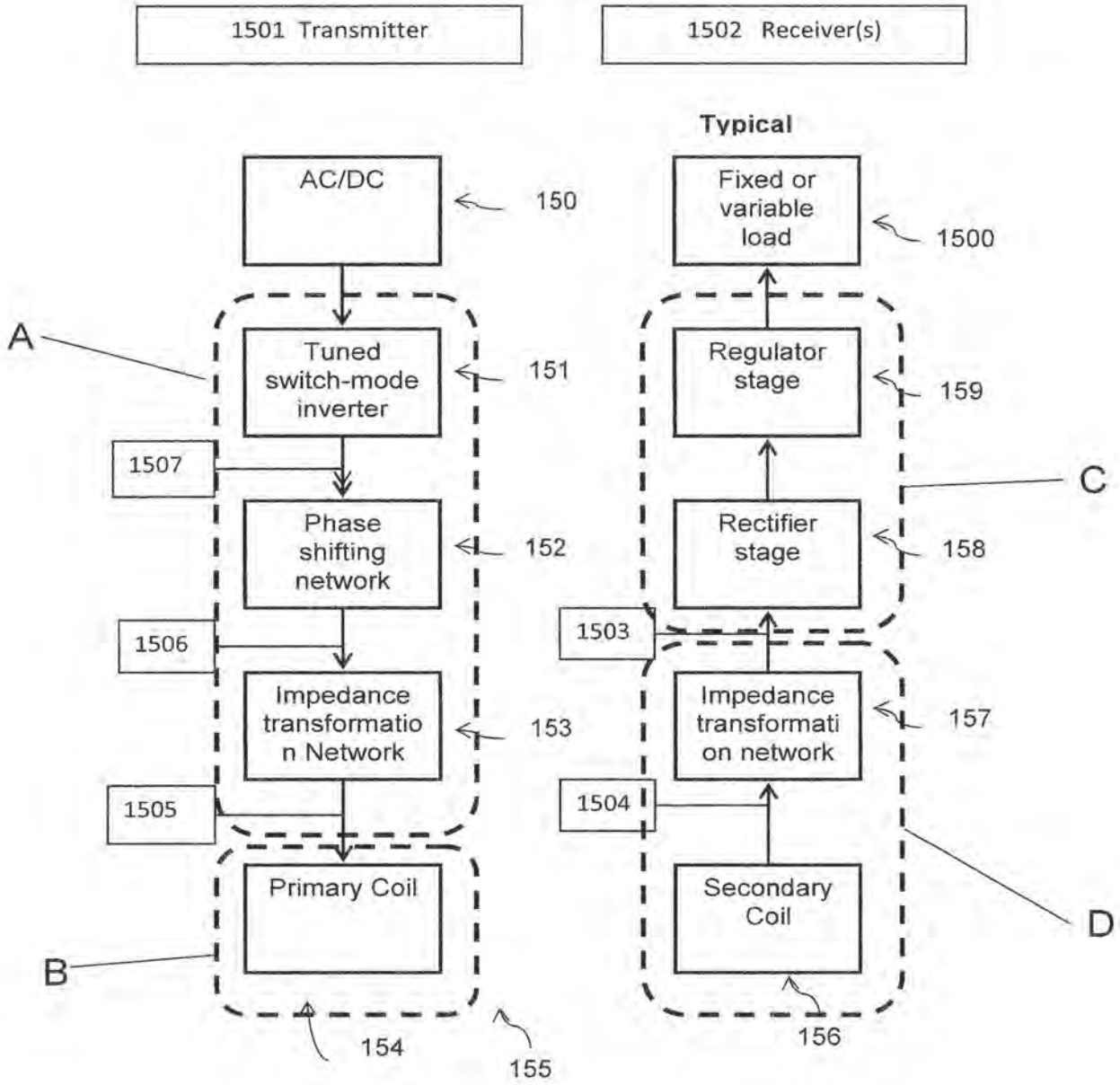

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
150
Fixed or variable load
1500
A
Tuned switch-mode inverter
151
Regulator stage
159
1507
C
Phase shifting network
152
Rectifier stage
158
1506
1503
Impedance transformatio n Network
153
Impedance transformati on network
157
1505
1504
Primary Coil
Secondary Coil
B
D
154
155
156

FIG. 38

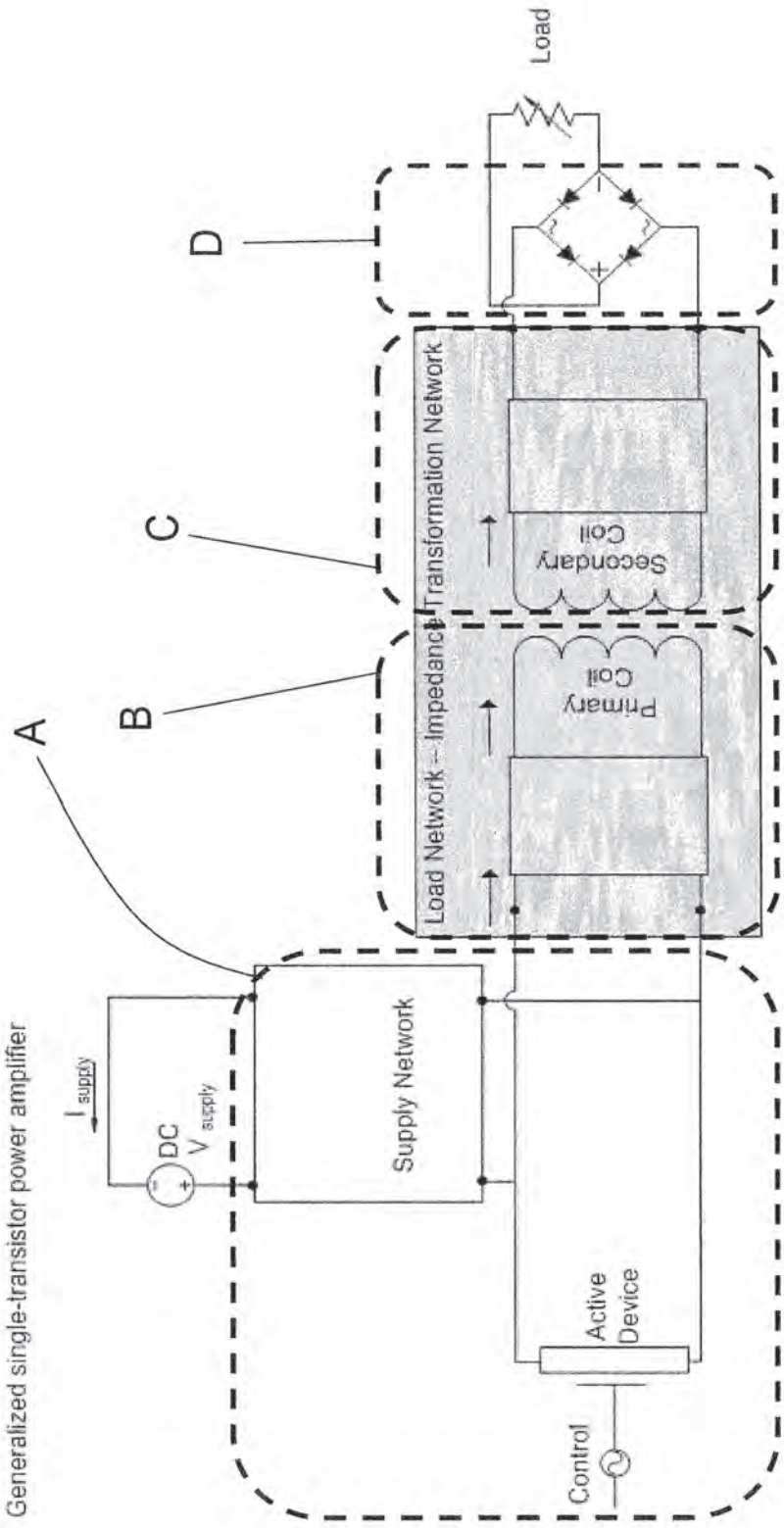

Load
D
C
Secondary Coil
Load Network – Impedance Transformation Network
B
Primary Coil
A
Generalized single-transistor power amplifier
I supply
DC
V supply
Supply Network
Active Device
Control

FIG. 39

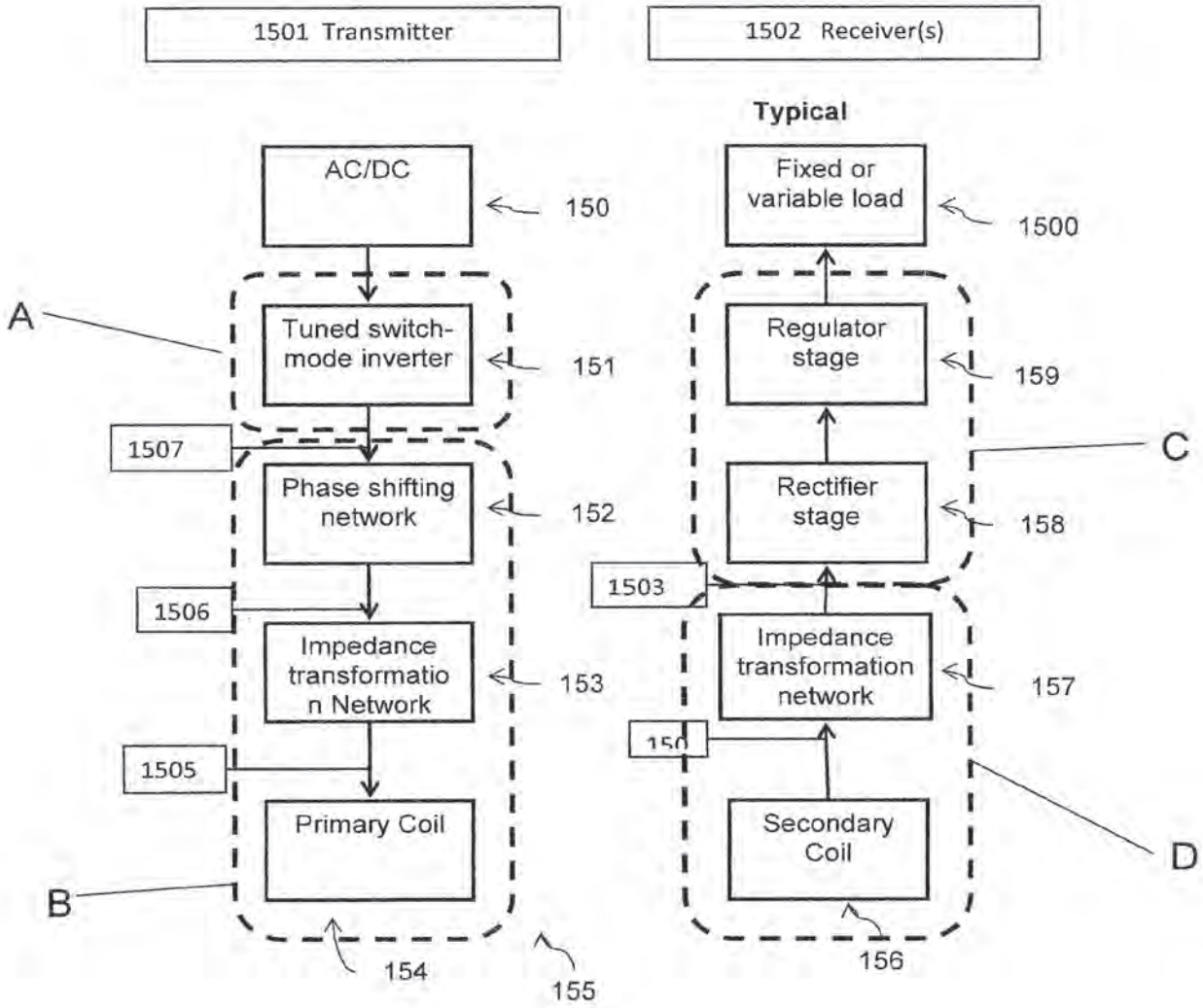

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
150
Fixed or variable load
1500
A
Tuned switch-mode inverter
151
Regulator stage
159
1507
C
Phase shifting network
152
Rectifier stage
158
1506
1503
Impedance transformatio n Network
153
Impedance transformation network
157
1505
Primary Coil
Secondary Coil
B
D
154
155
156

FIG. 40

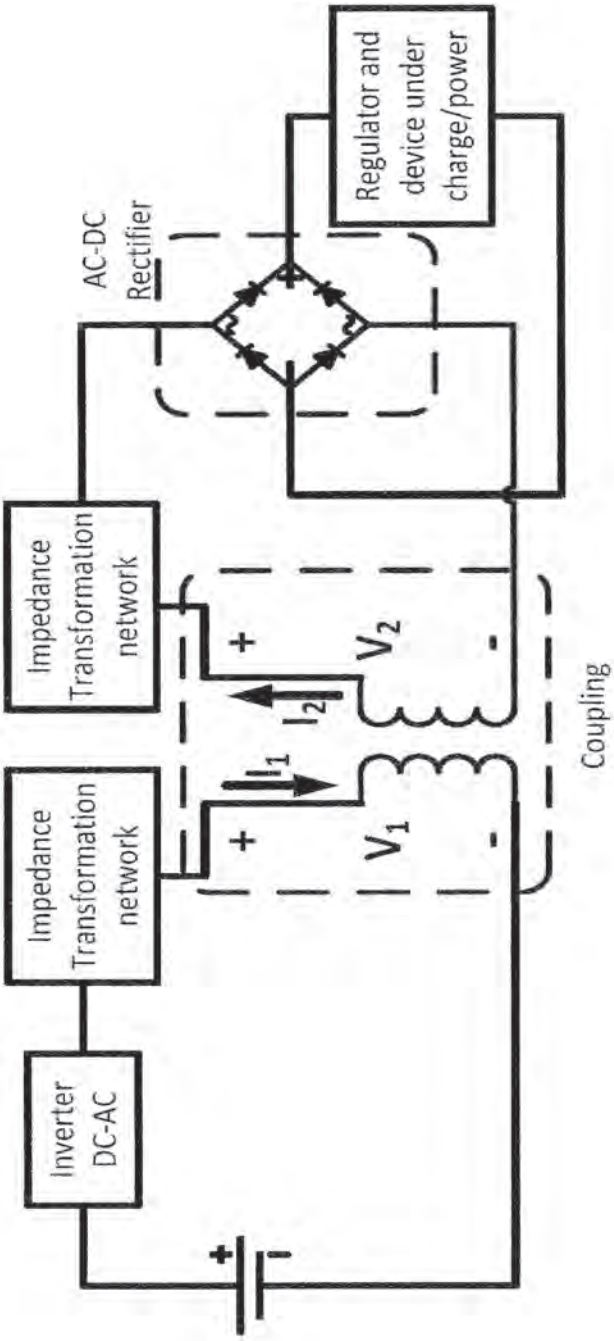

Regulator and device under charge/power
AC-DC Rectifier
Impedance Transformation network
Impedance Transformation network
Inverter DC-AC
+
-
V_2
I_2
I_1
V_1
Coupling

FIG. 41

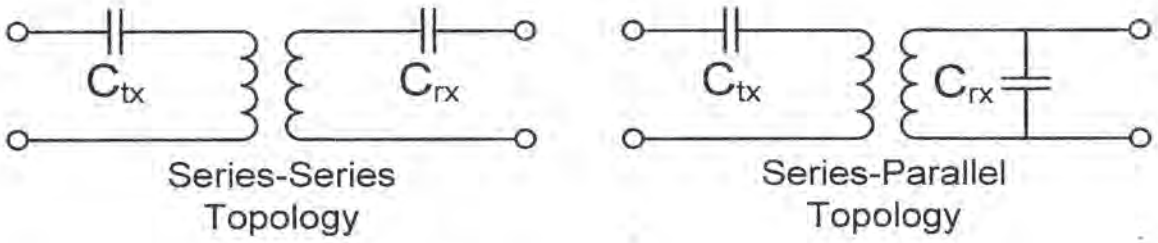

Ctx
Crx
Series-Series
Topology
Ctx
Crx
Series-Parallel
Topology

FIG. 42

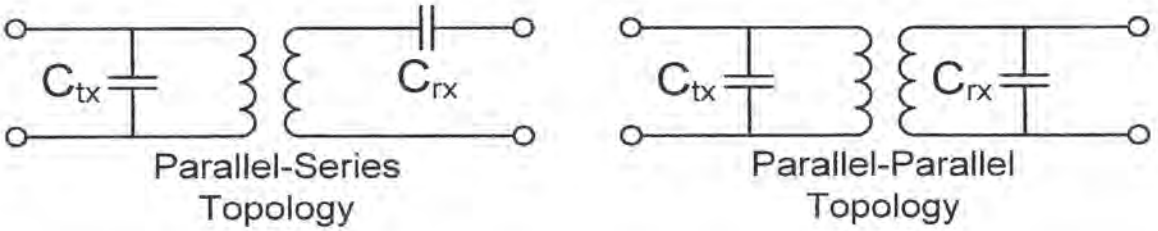

Ctx
Crx
Parallel-Series
Topology
Ctx
Crx
Parallel-Parallel
Topology

FIG. 43

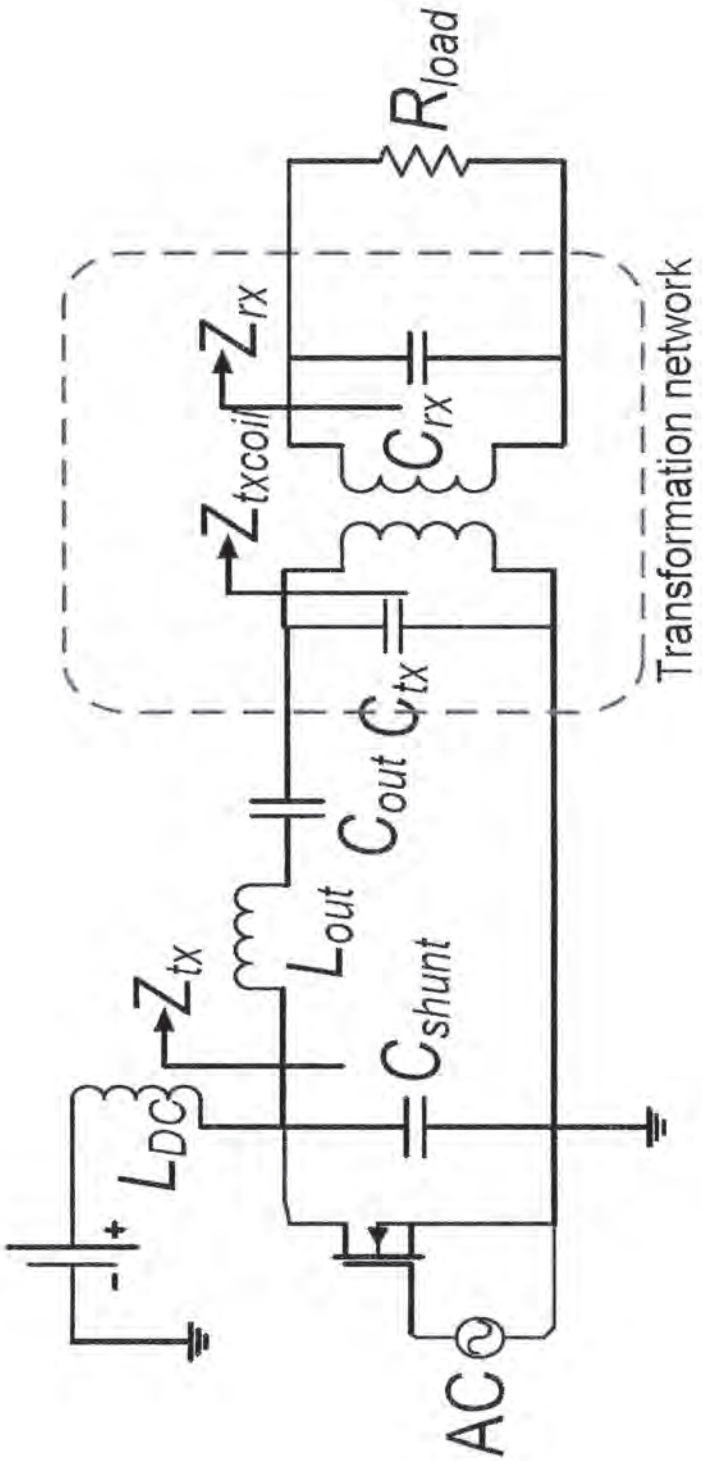

R_{load}
Z_{rx}
Z_{txcoil}
C_{rx}
Transformation network
C_{out} C_{tx}
L_{out}
Z_{tx}
C_{shunt}
L_{DC}
+
-
AC

FIG. 44

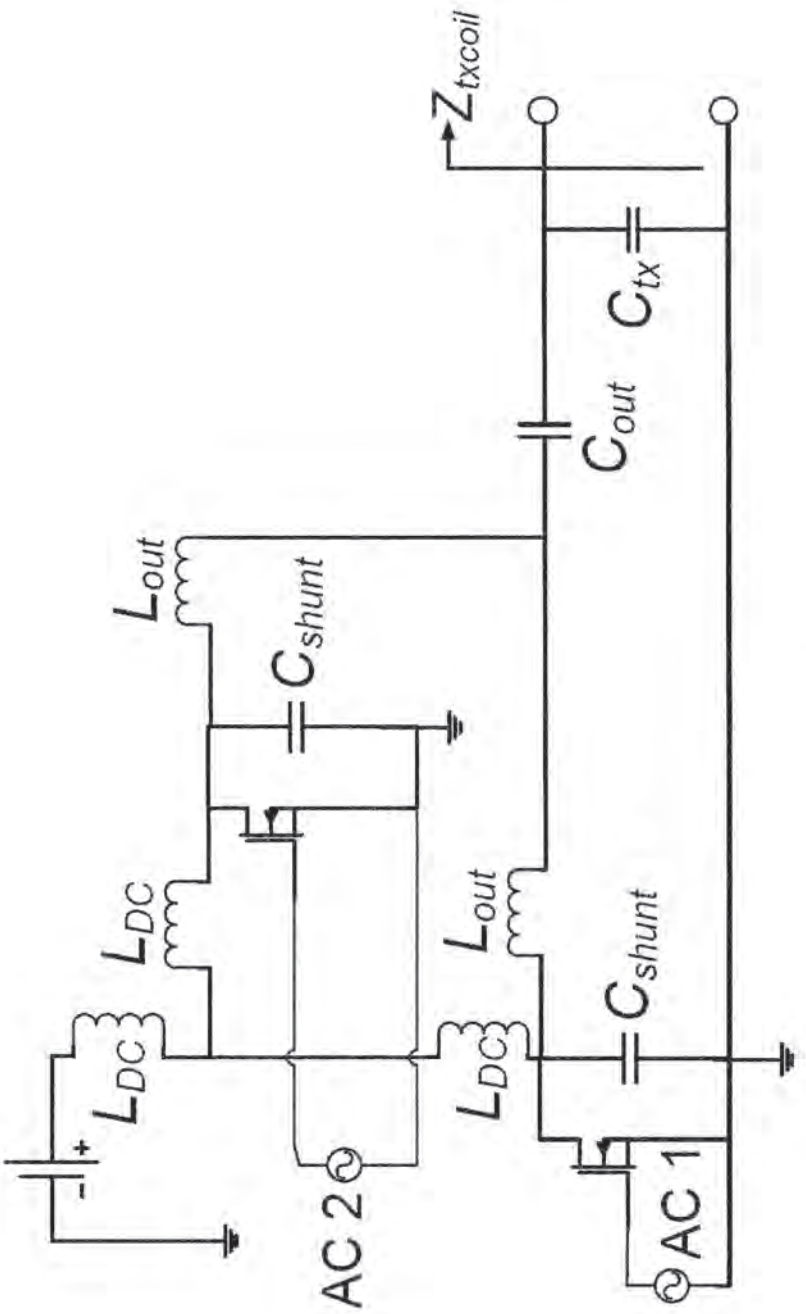


FIG. 45

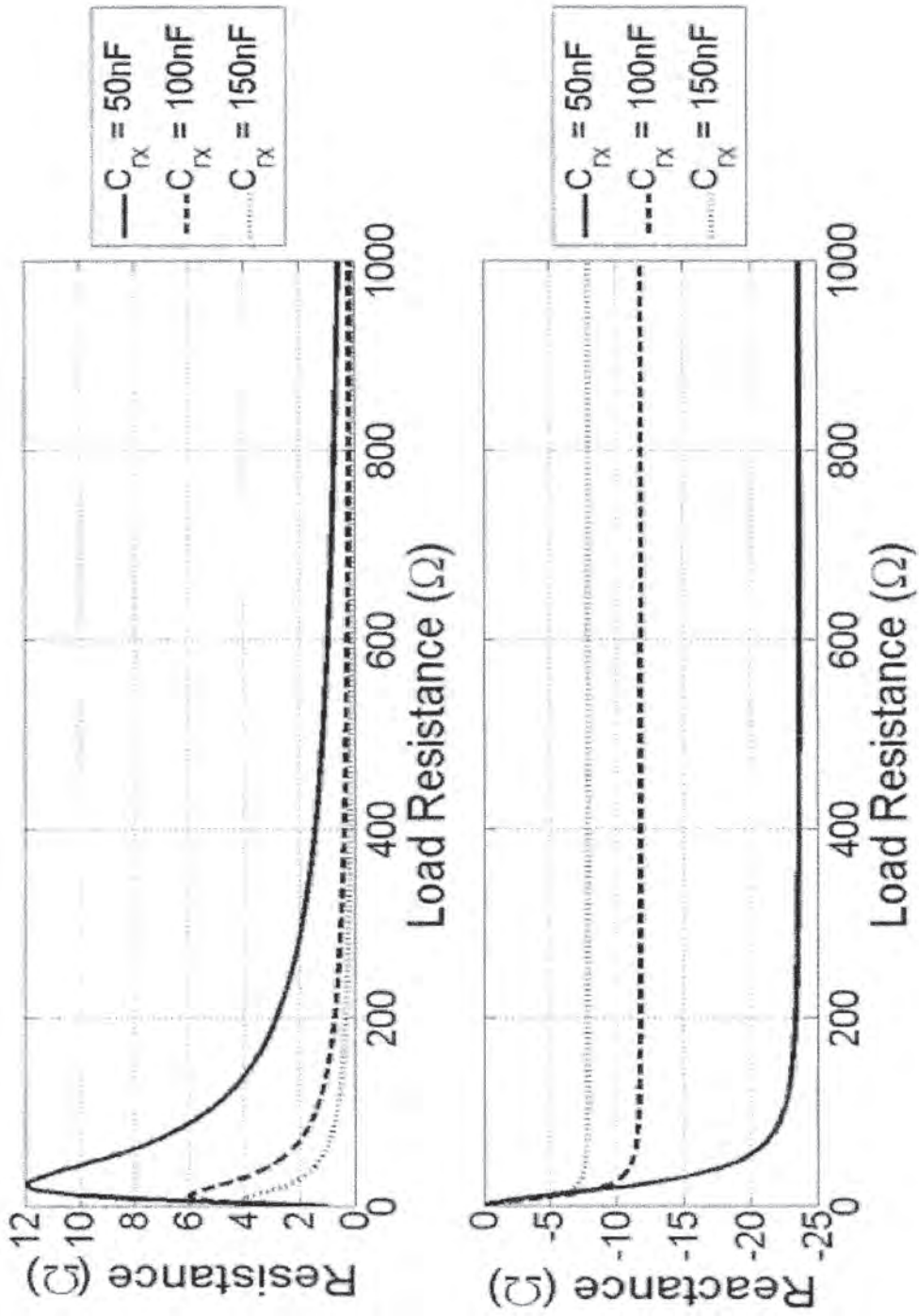

Resistance (Ω)
Load Resistance (Ω)
Reactance (Ω)
Load Resistance (Ω)
—C_rx = 50nF
---C_rx = 100nF
.....C_rx = 150nF
0
2
4
6
8
10
12
-5
-10
-15
-20
-25
200
400
600
800
1000

FIG. 46

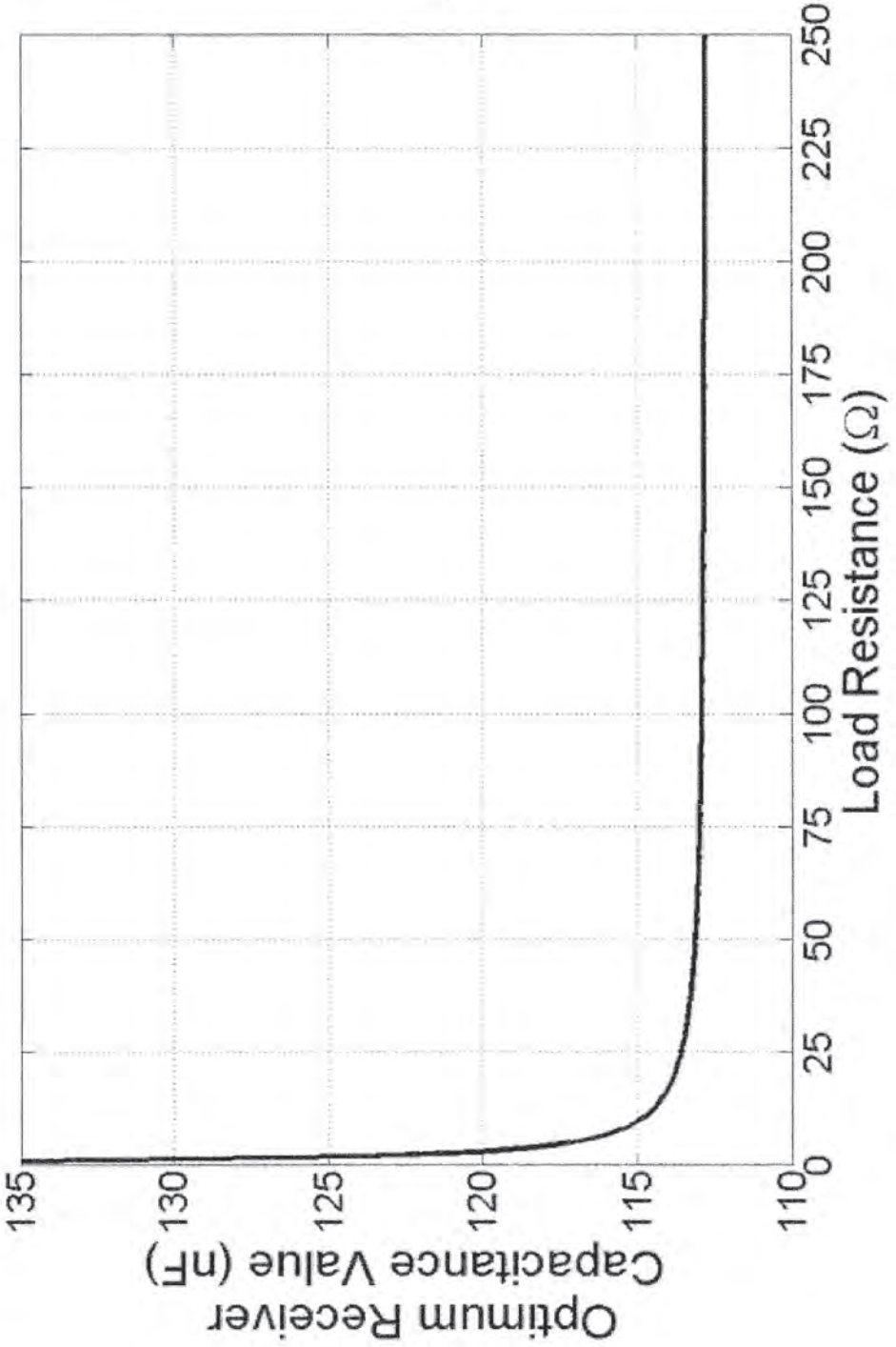

Optimum Receiver Capacitance Value (nF)
135
130
125
120
115
110
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)

FIG. 47

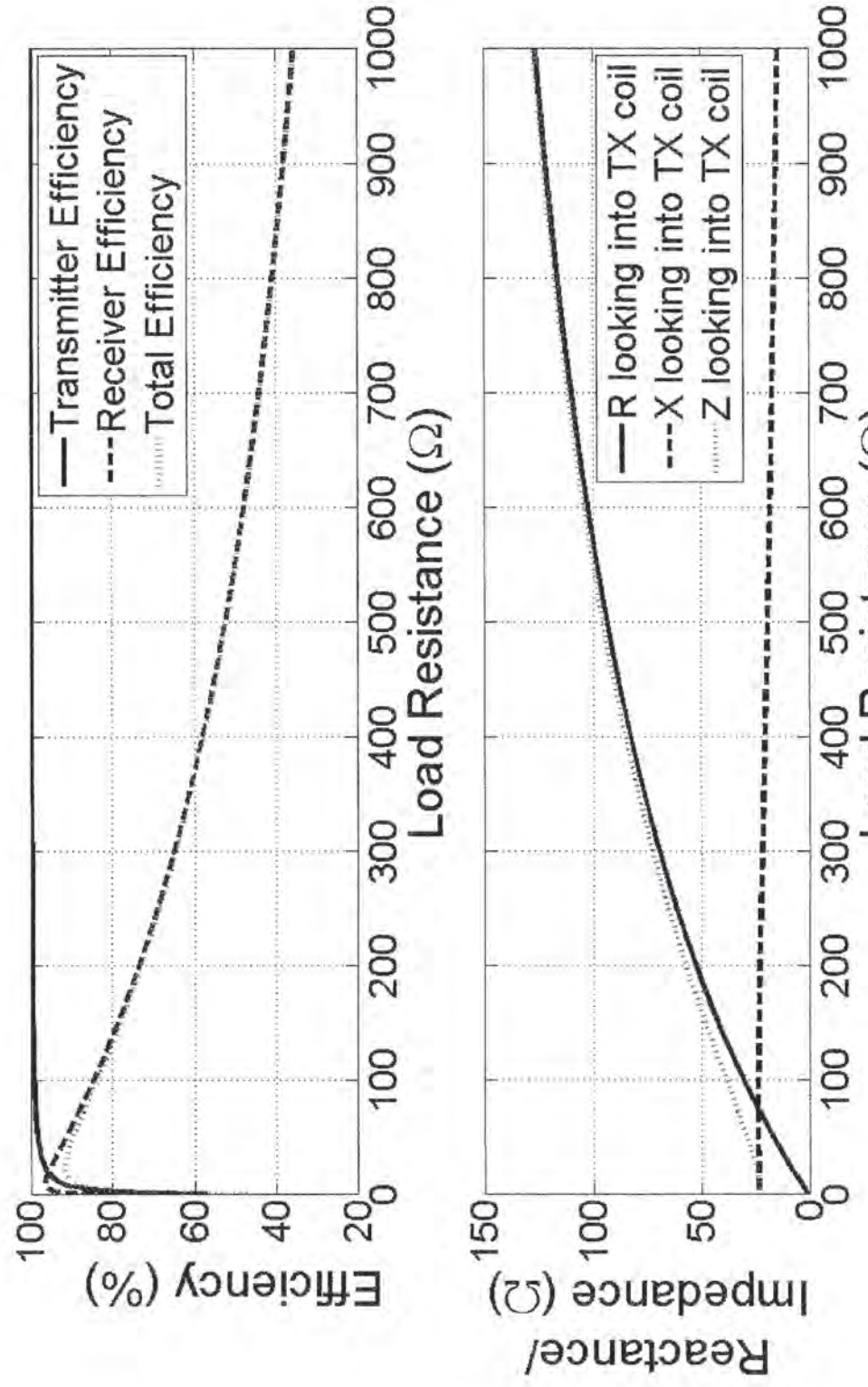

Efficiency (%)
Load Resistance (Ω)
Transmitter Efficiency
Receiver Efficiency
Total Efficiency
Reactance/ Impedance (Ω)
Load Resistance (Ω)
R looking into TX coil
X looking into TX coil
Z looking into TX coil

FIG. 48A

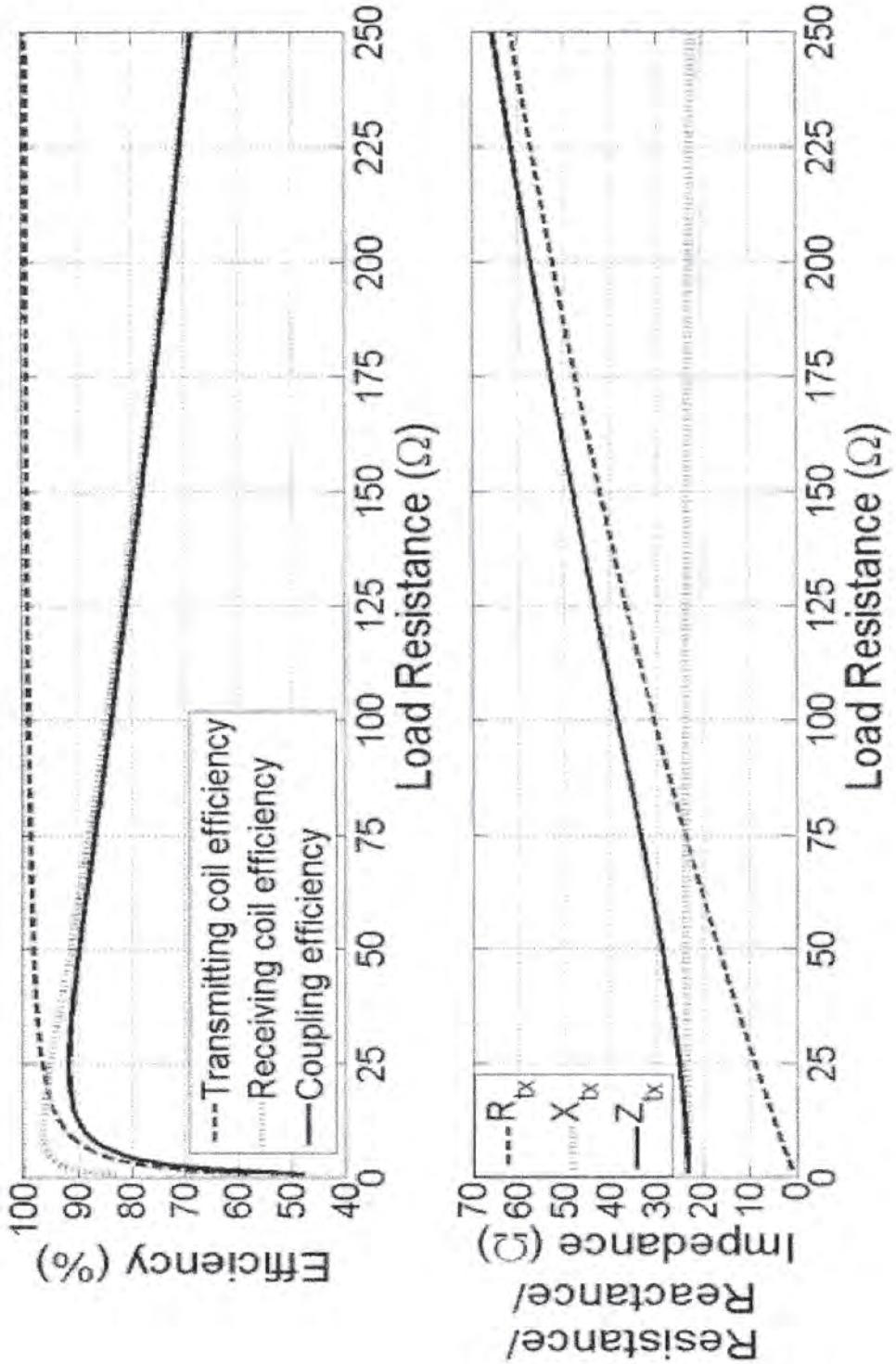


FIG. 48B

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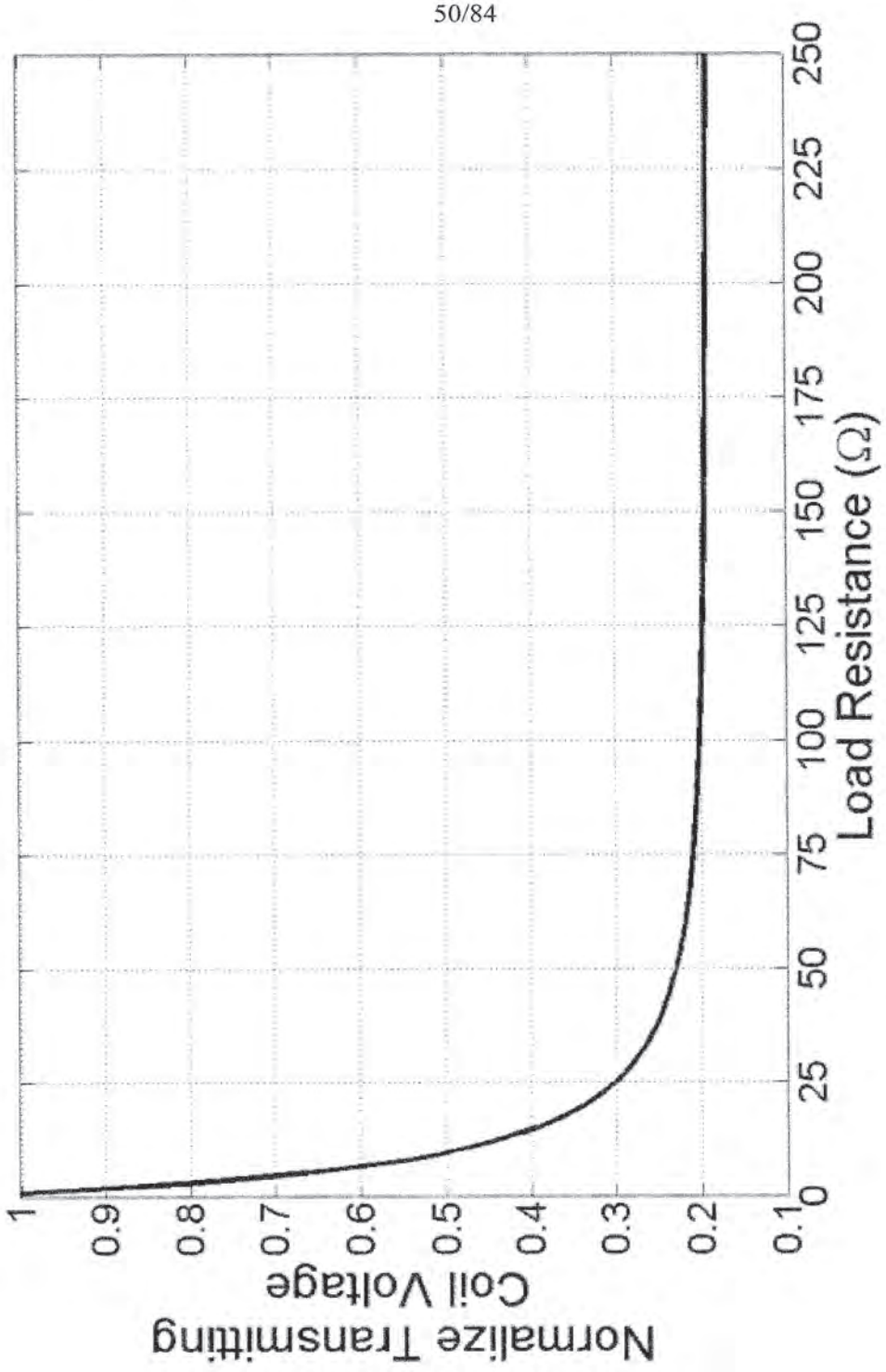

Normalize Transmitting Coil Voltage
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)

FIG. 49

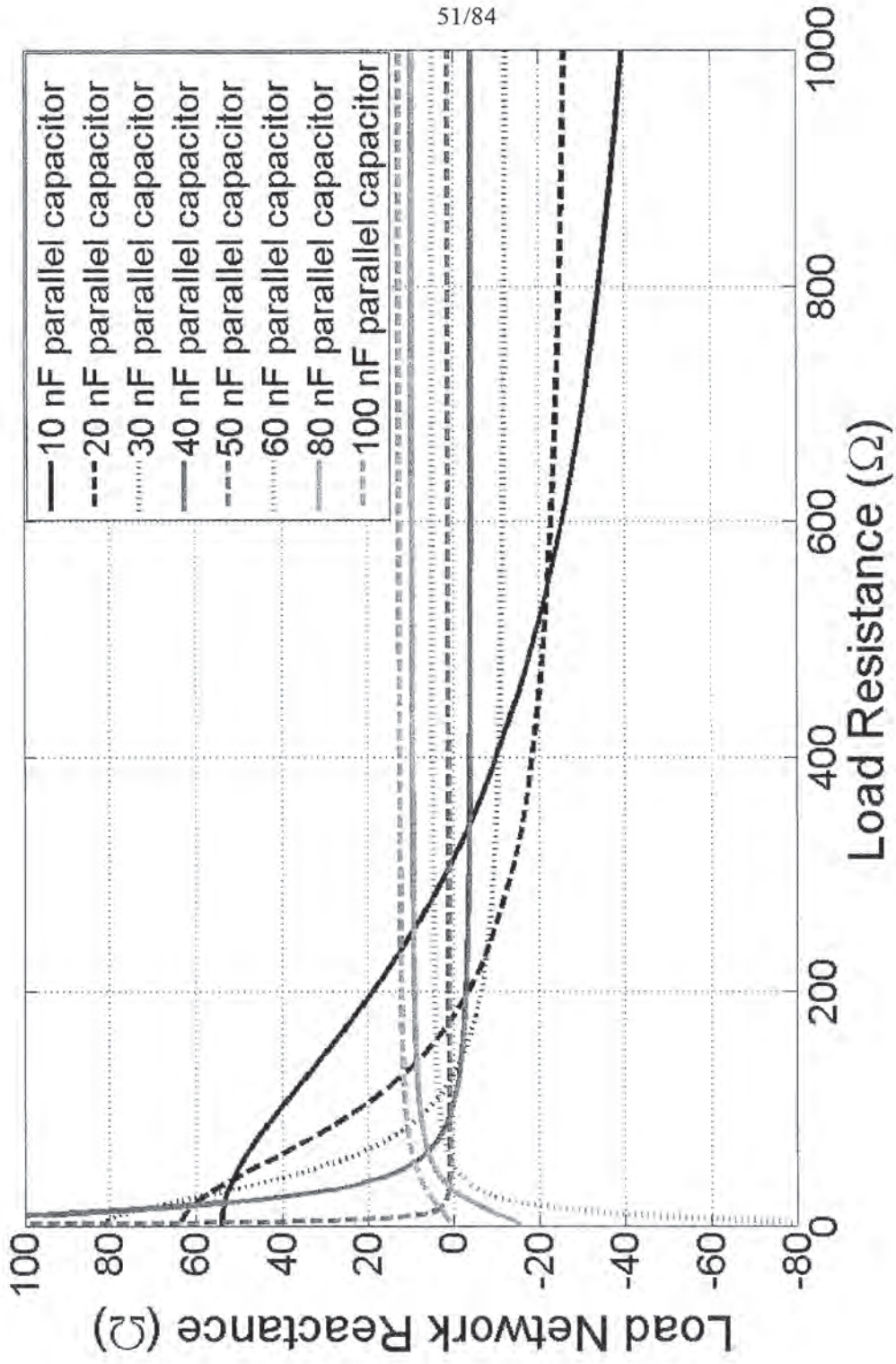

10 nF parallel capacitor
20 nF parallel capacitor
30 nF parallel capacitor
40 nF parallel capacitor
50 nF parallel capacitor
60 nF parallel capacitor
80 nF parallel capacitor
100 nF parallel capacitor
Load Network Reactance (Ω)
Load Resistance (Ω)
100
80
60
40
20
0
-20
-40
-60
-80
0
200
400
600
800
1000

FIG. 50

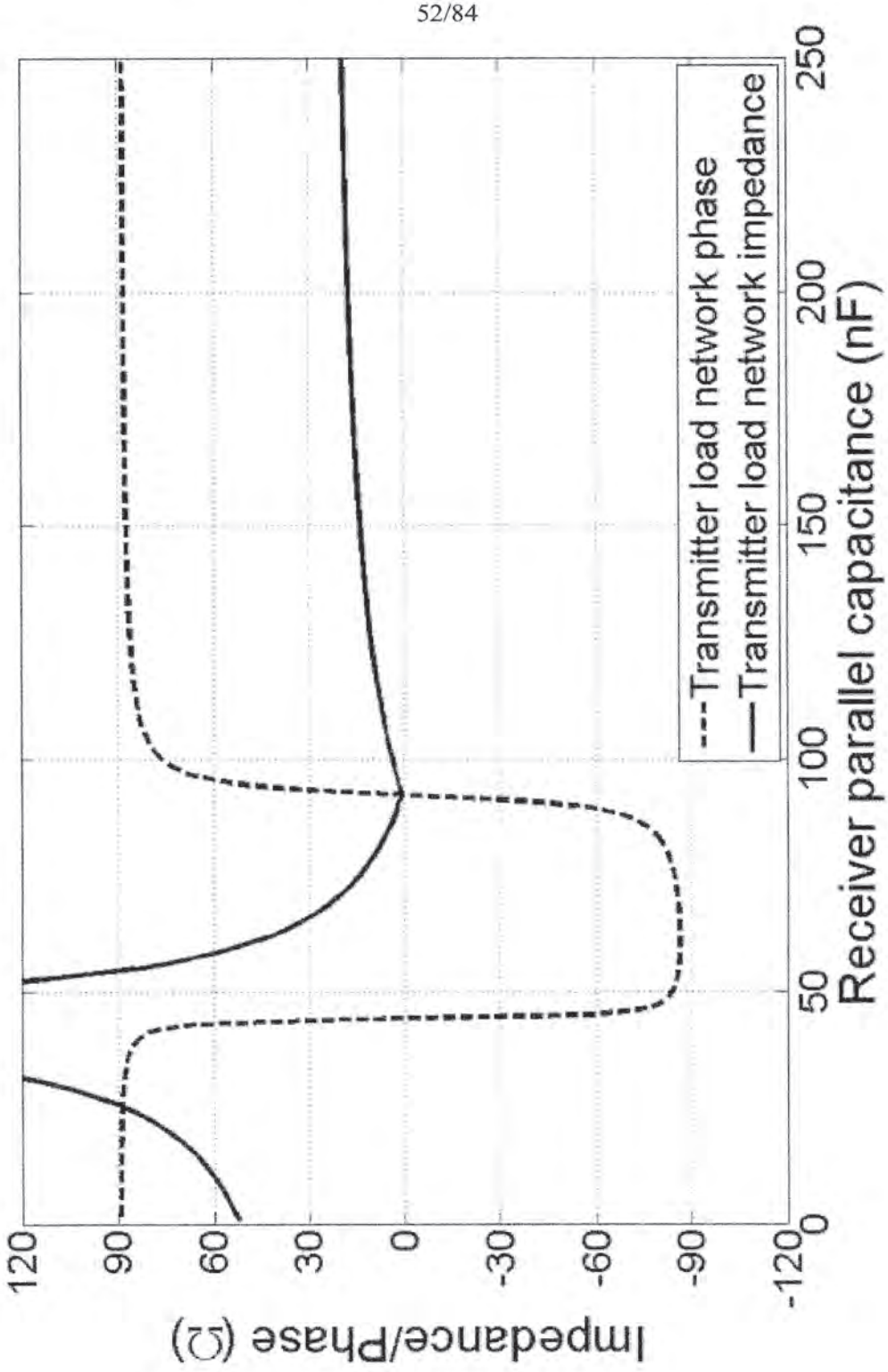

Impedance/Phase (Ω)
120
90
60
30
0
-30
-60
-90
-120
0
50
100
150
200
250
Receiver parallel capacitance (nF)
Transmitter load network phase
Transmitter load network impedance

FIG. 51

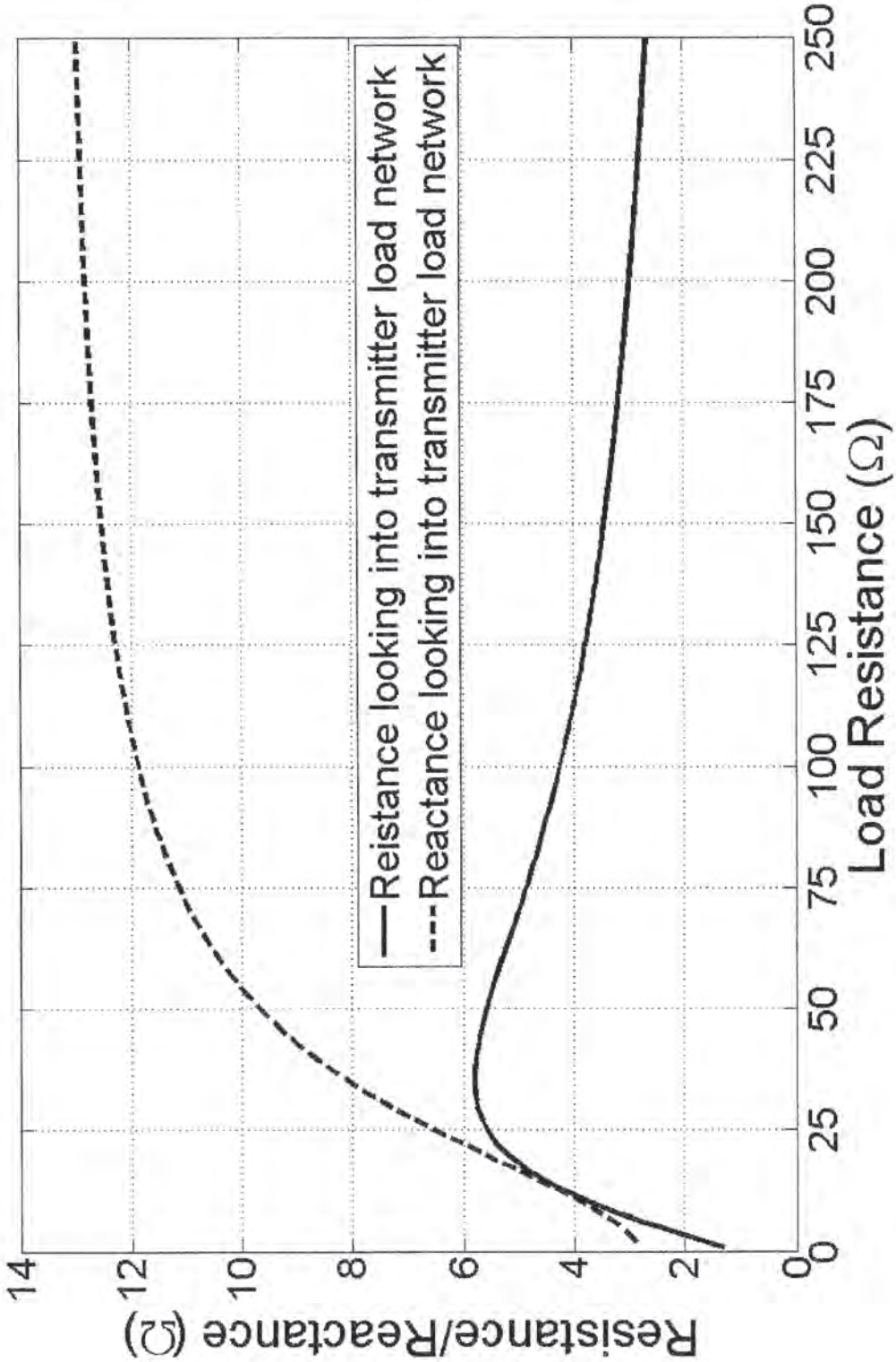

Resistance/Reactance (Ω)
Load Resistance (Ω)
Reistance looking into transmitter load network
Reactance looking into transmitter load network
0
2
4
6
8
10
12
14
0
25
50
75
100
125
150
175
200
225
250

FIG. 52

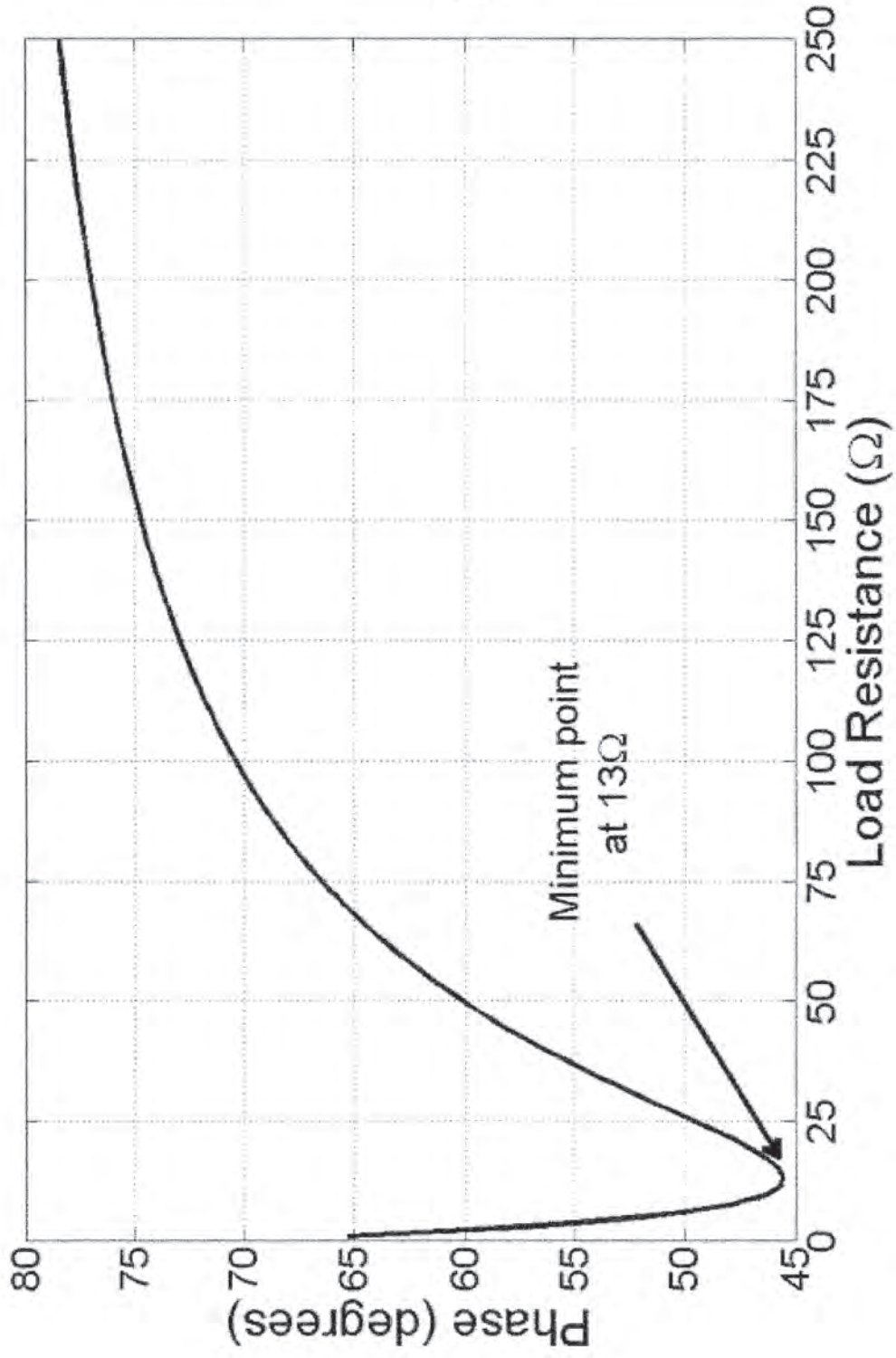

Phase (degrees)
80
75
70
65
60
55
50
45
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)
Minimum point
at 13Ω

FIG. 53

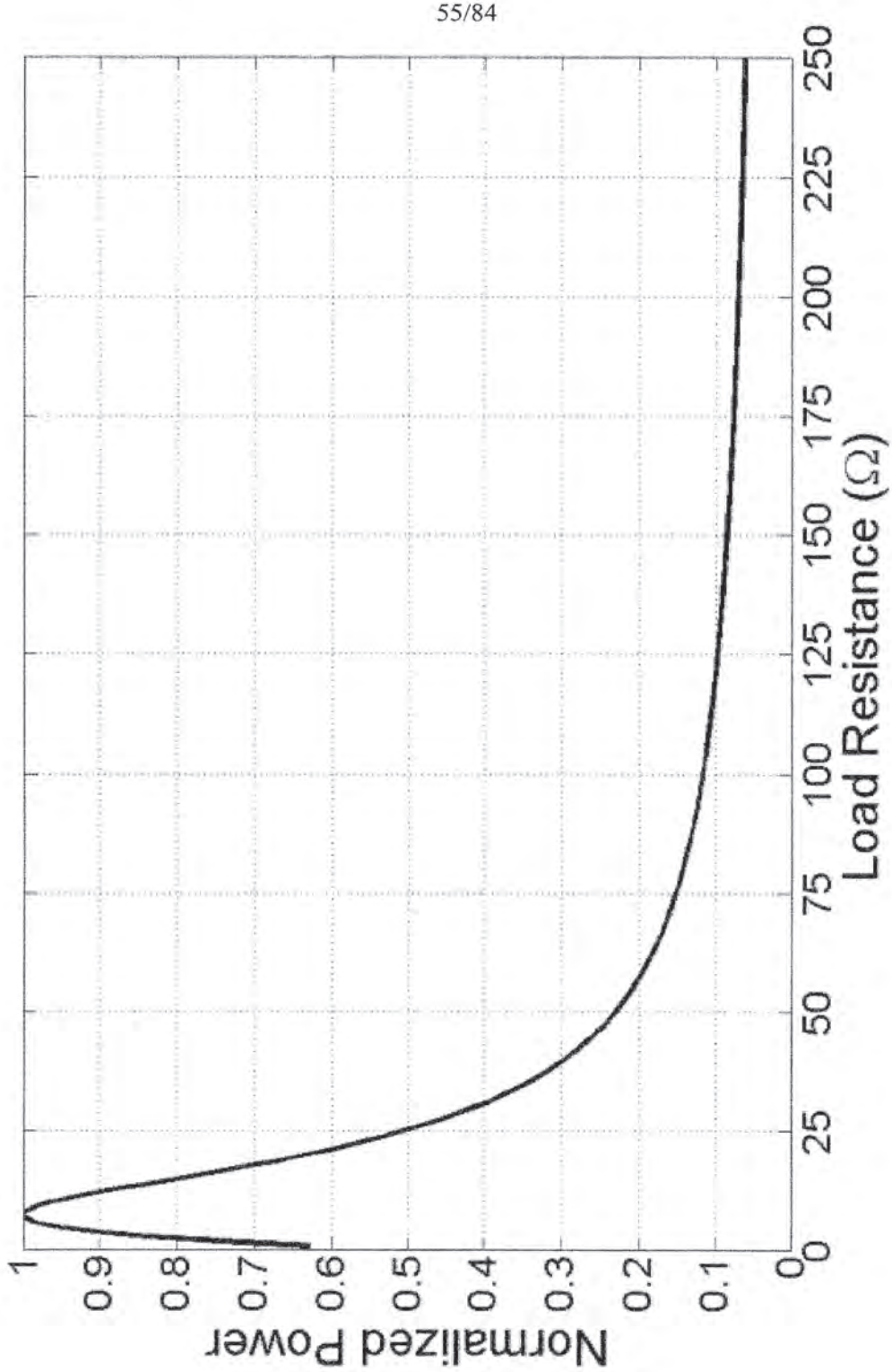

Normalized Power
Load Resistance (Ω)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
25
50
75
100
125
150
175
200
225
250

FIG. 54

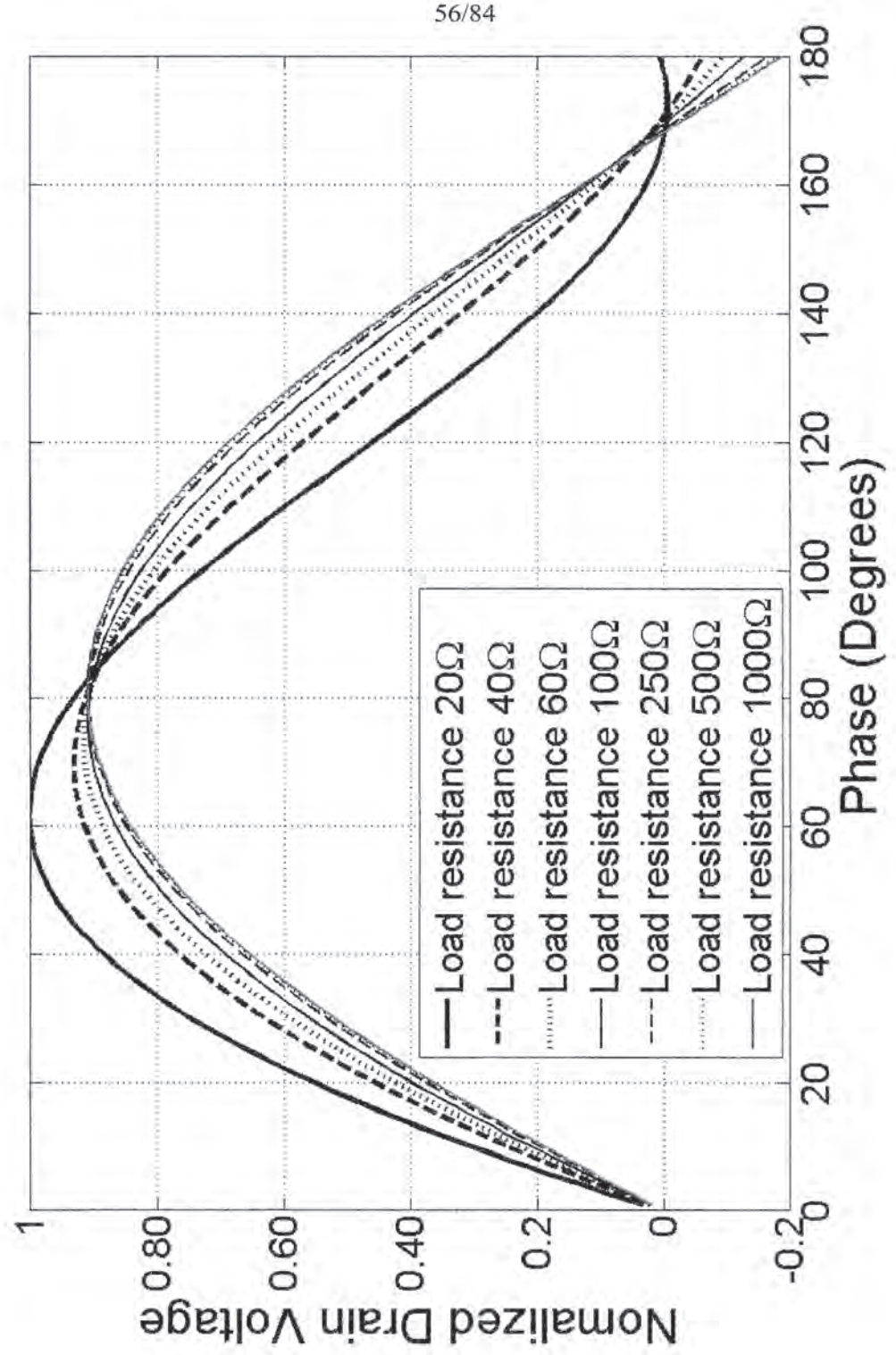
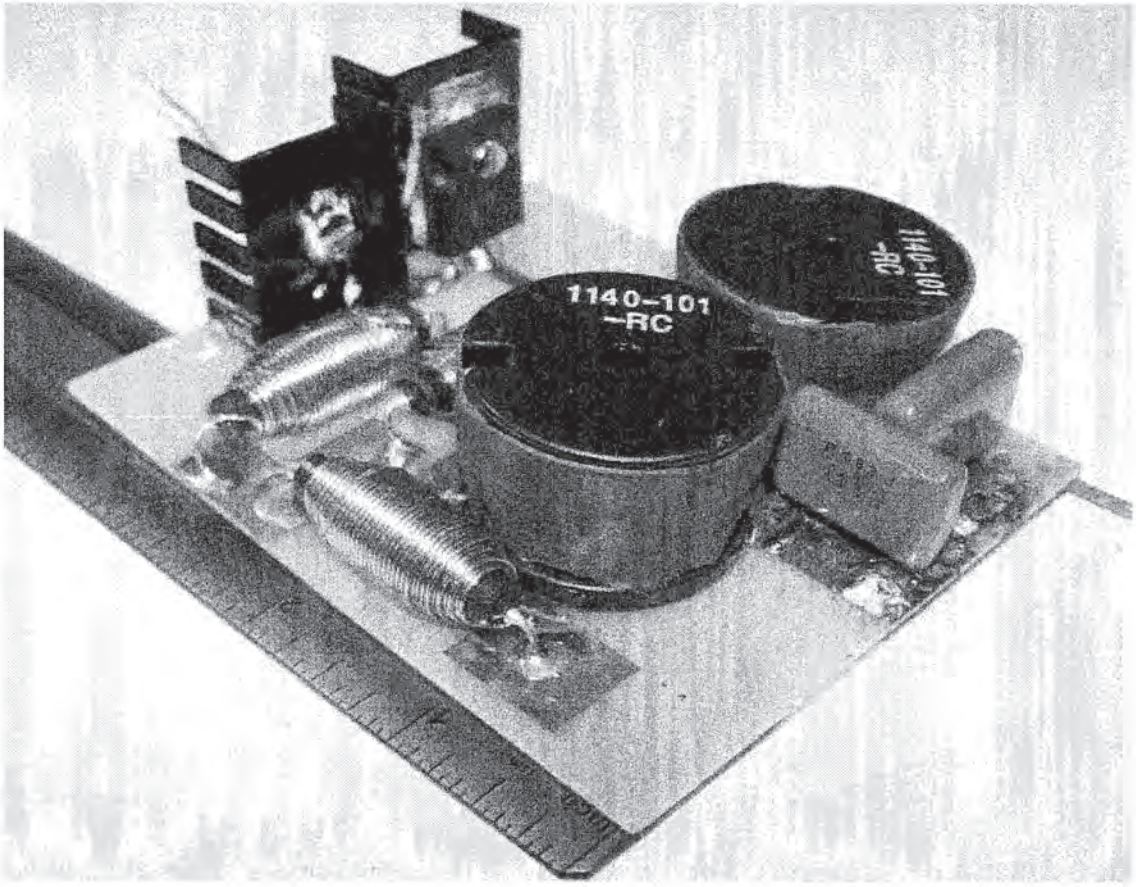

Normalized Drain Voltage
1
0.80
0.60
0.40
0.2
0
-0.2
0
20
40
60
80
100
120
140
160
180
Phase (Degrees)
Load resistance 20Ω
Load resistance 40Ω
Load resistance 60Ω
Load resistance 100Ω
Load resistance 250Ω
Load resistance 500Ω
Load resistance 1000Ω

FIG. 55


1140-101
-RC
1140-101
-RC

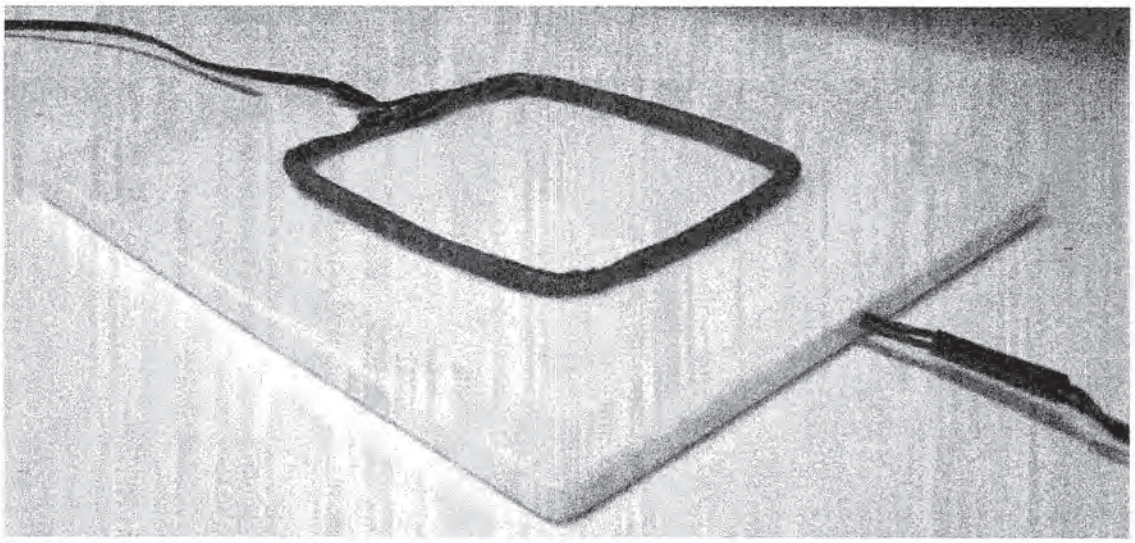


FIG. 57

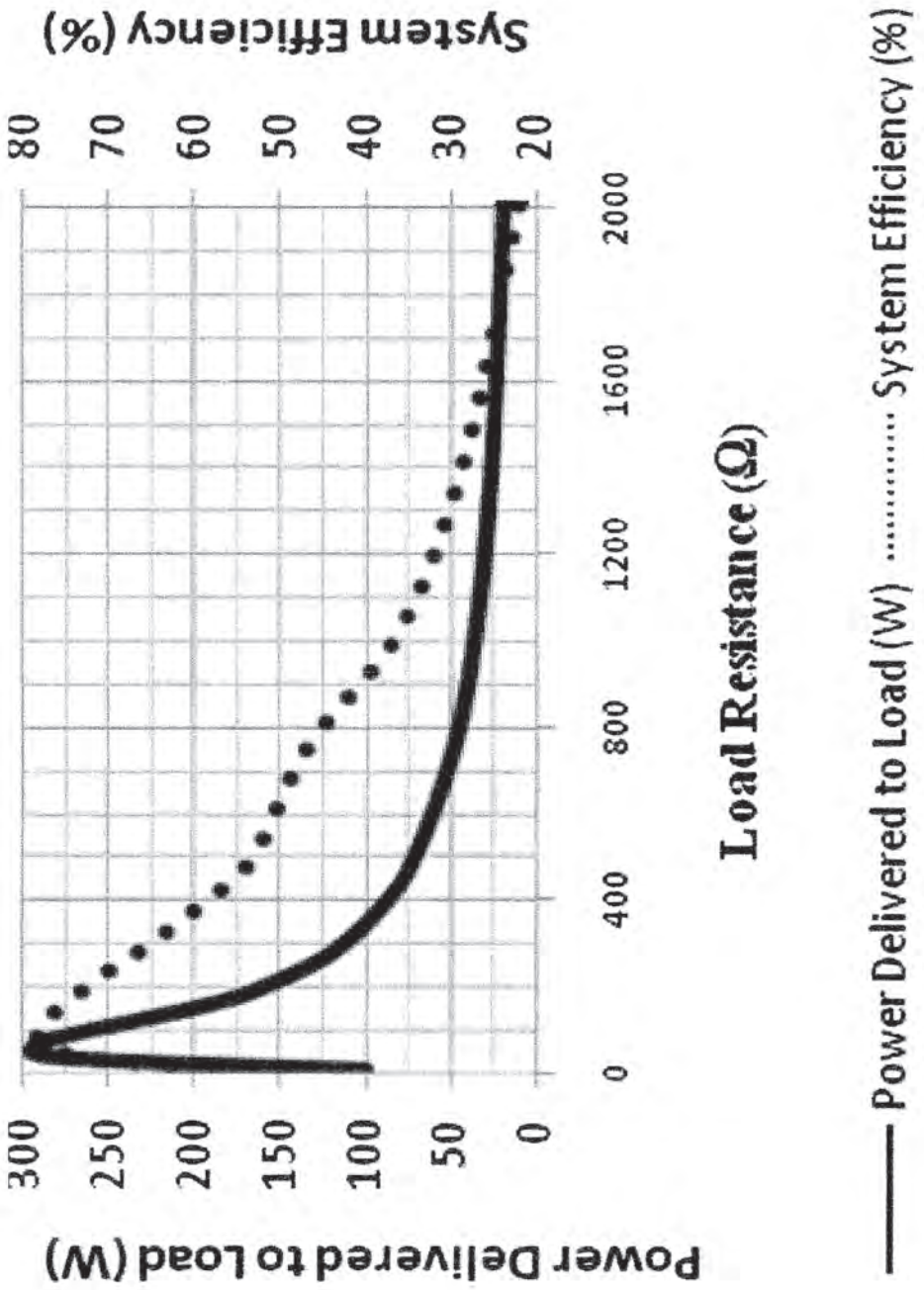
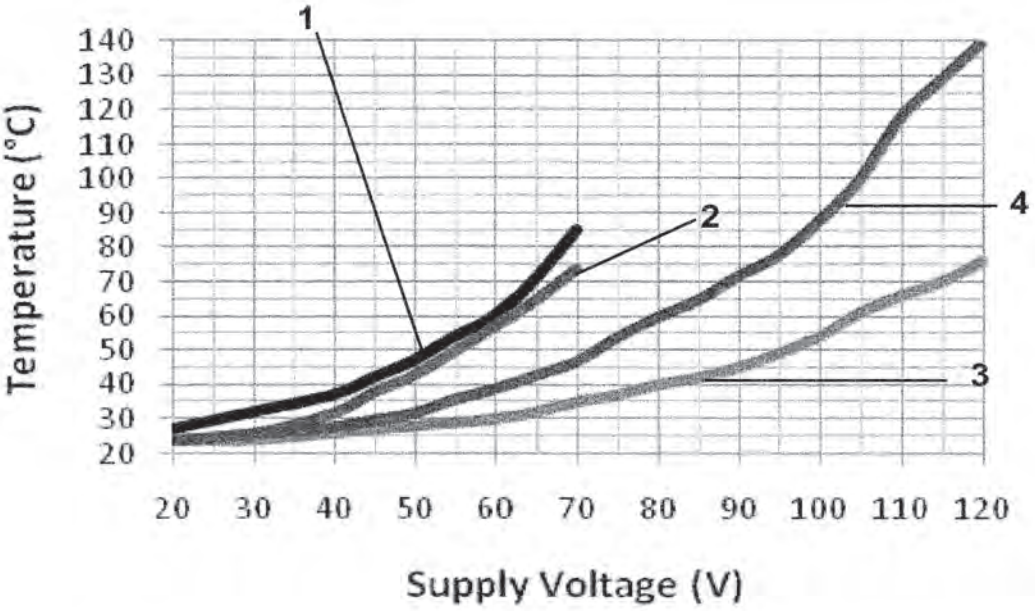

System Efficiency (%)
80
70
60
50
40
30
20
300
250
200
150
100
50
0
Power Delivered to Load (W)
0
400
800
1200
1600
2000
Load Resistance (Ω)
Power Delivered to Load (W)
System Efficiency (%)

FIG. 58



1 —— Transistor Temperature (natural convection cooling)

2 —— Inductor Temperature (natural convection cooling)

3 —— Transistor Temperature (forced cooling)

4 —— Inductor Temperature (forced cooling)

FIG. 59

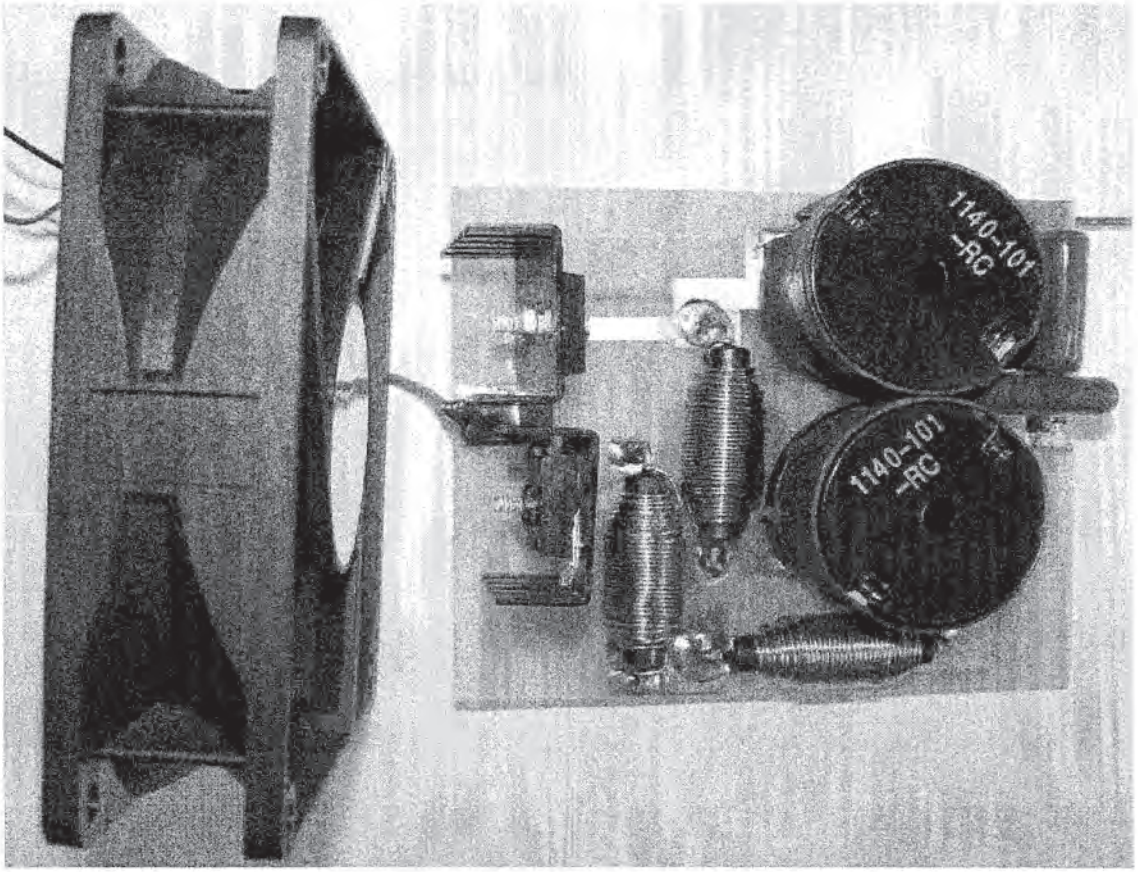


FIG. 60

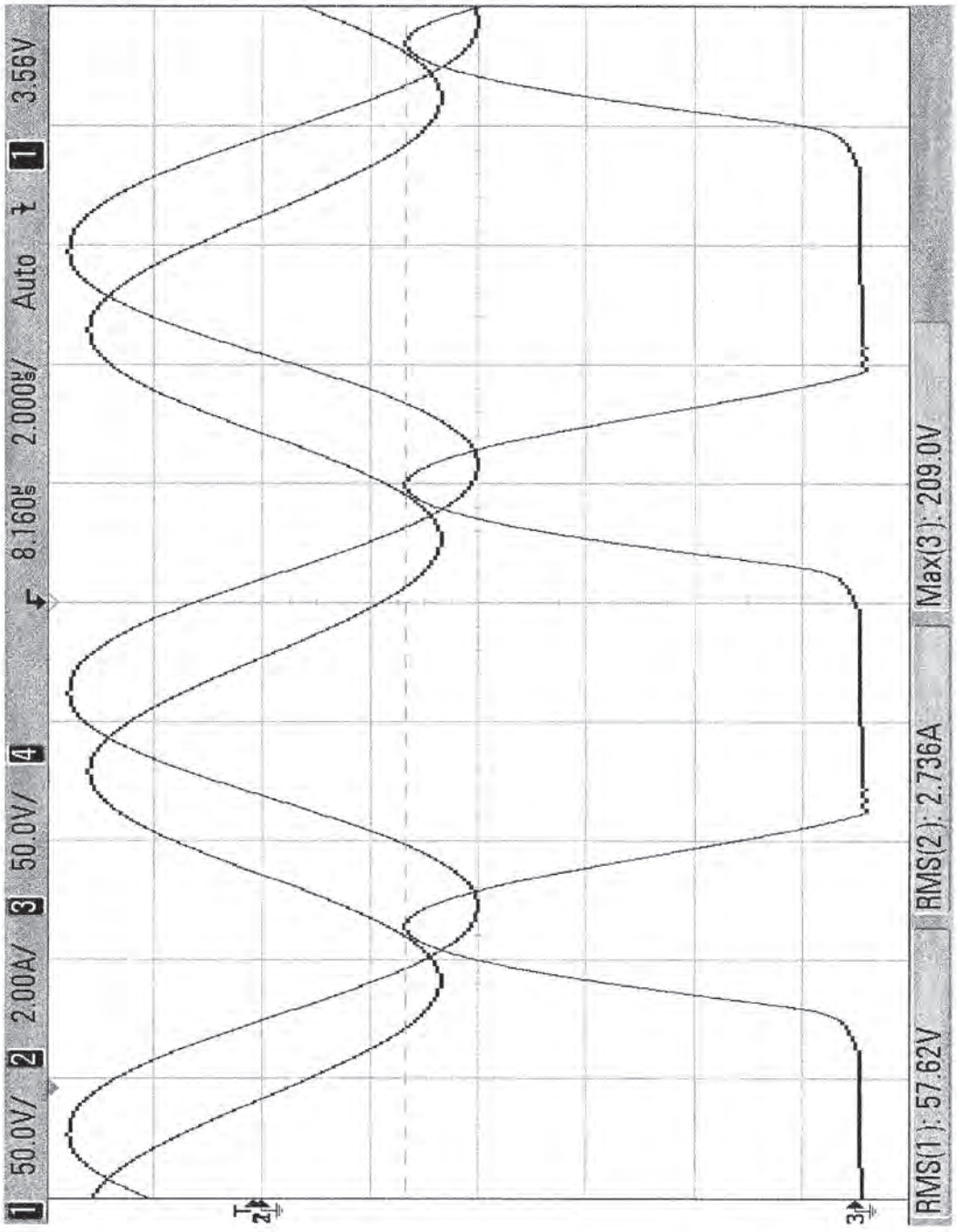

1 50.0V/
2 2.00A/
3 50.0V/
4
8.160µs
2.000µs/
Auto
1 3.56V
RMS(1): 57.62V
RMS(2): 2.736A
Max(3): 209.0V

FIG. 61

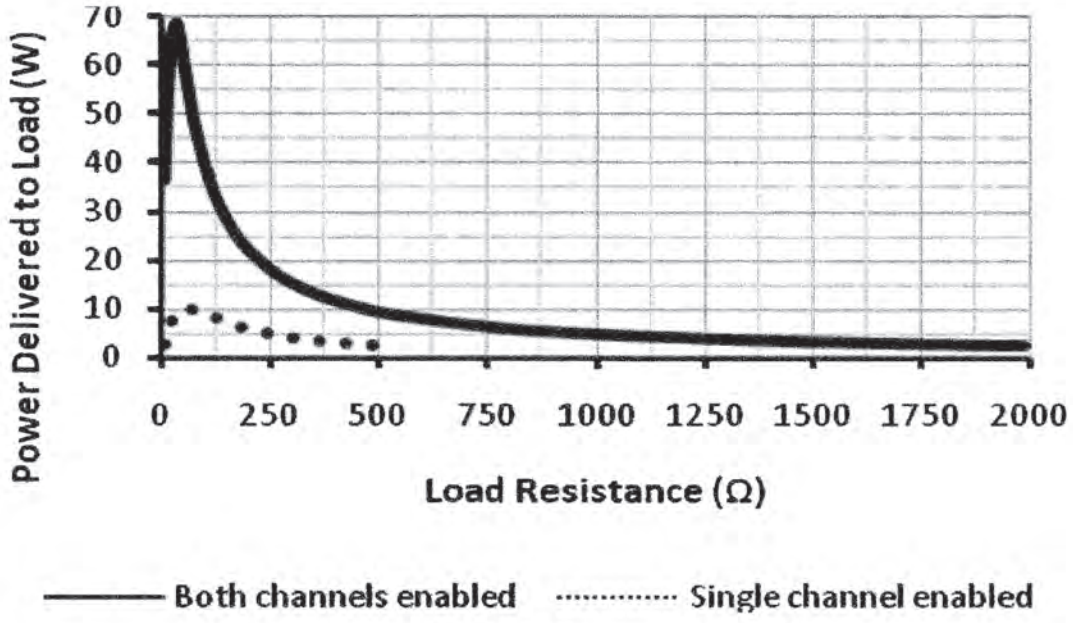


FIG. 62A

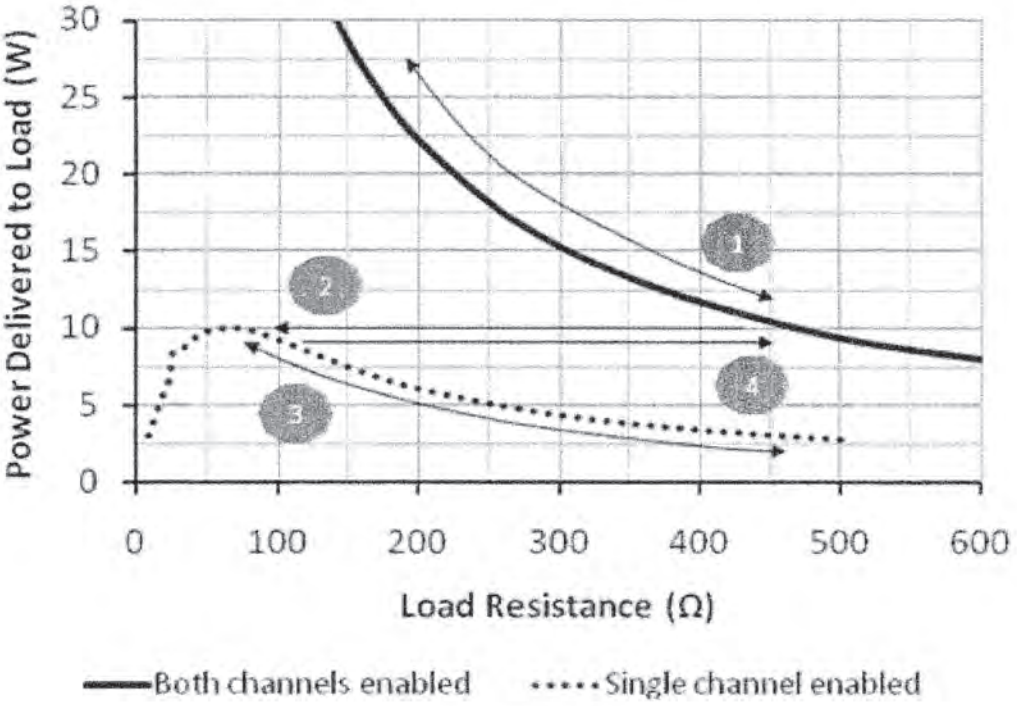


FIG. 62B

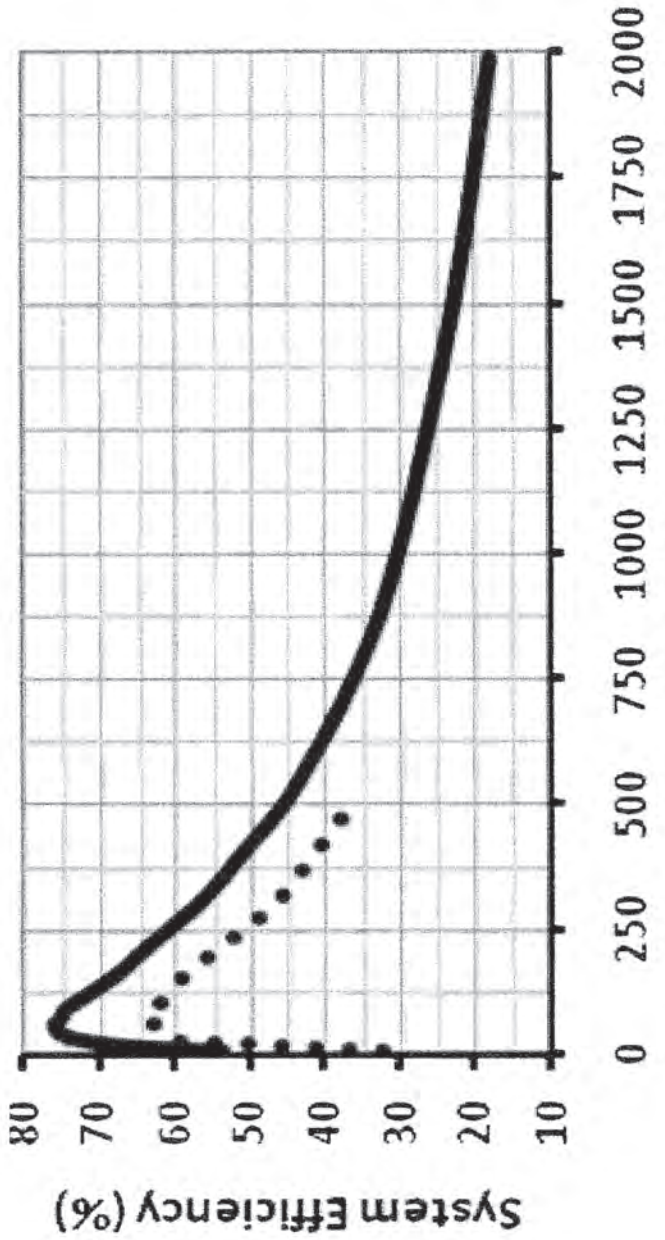

System Efficiency (%)
80
70
60
50
40
30
20
10
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 63

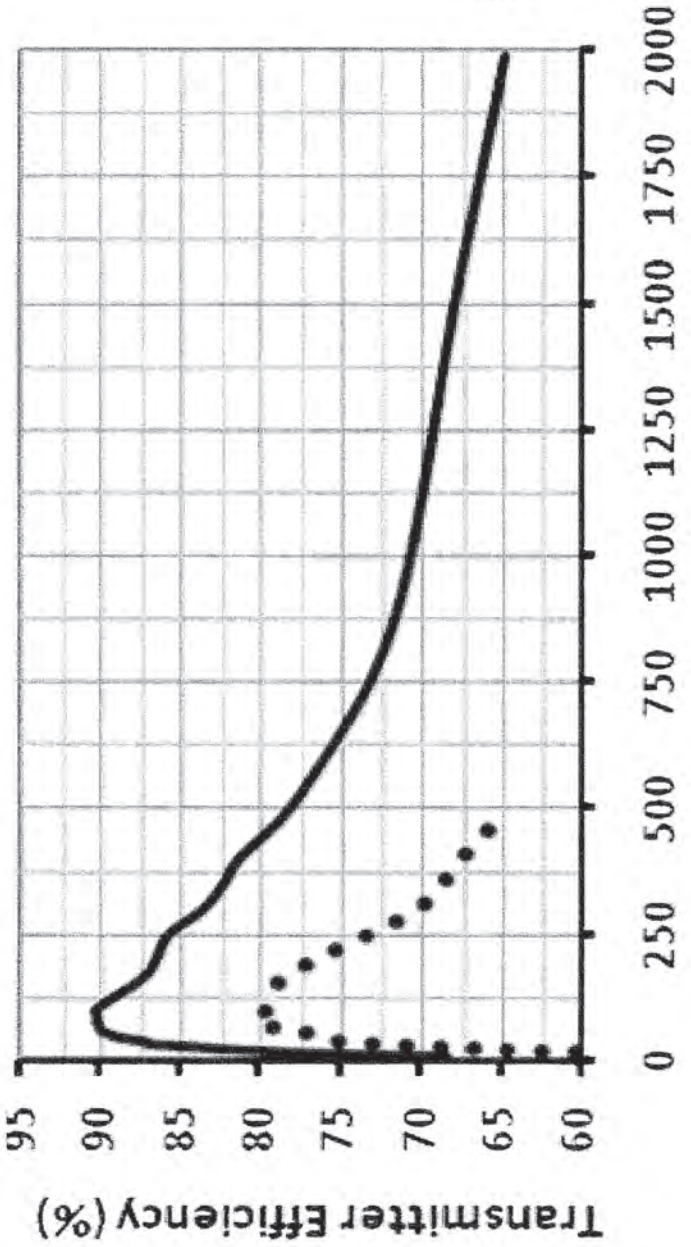

Transmitter Efficiency (%)
95
90
85
80
75
70
65
60
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 64

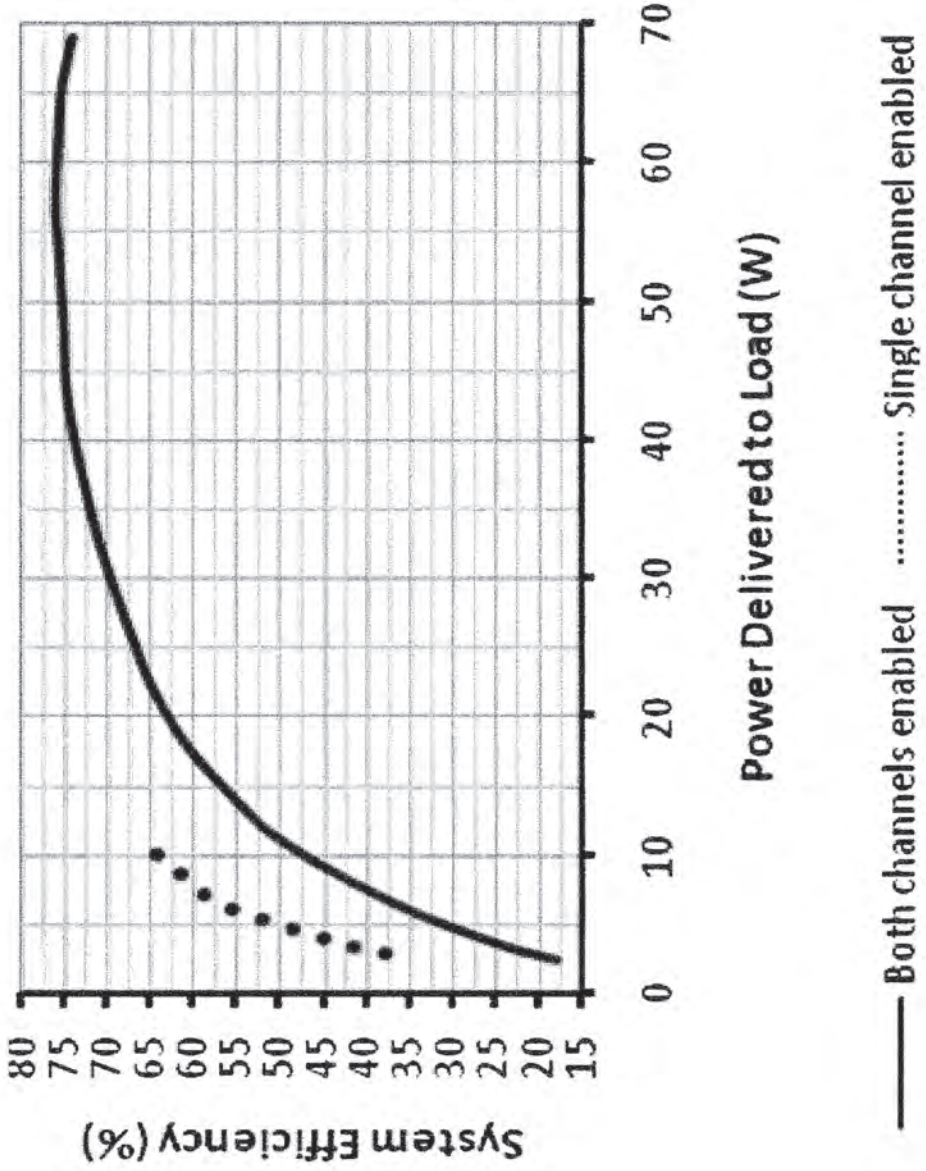

System Efficiency (%)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
0
10
20
30
40
50
60
70
Power Delivered to Load (W)
Both channels enabled
Single channel enabled

FIG. 65

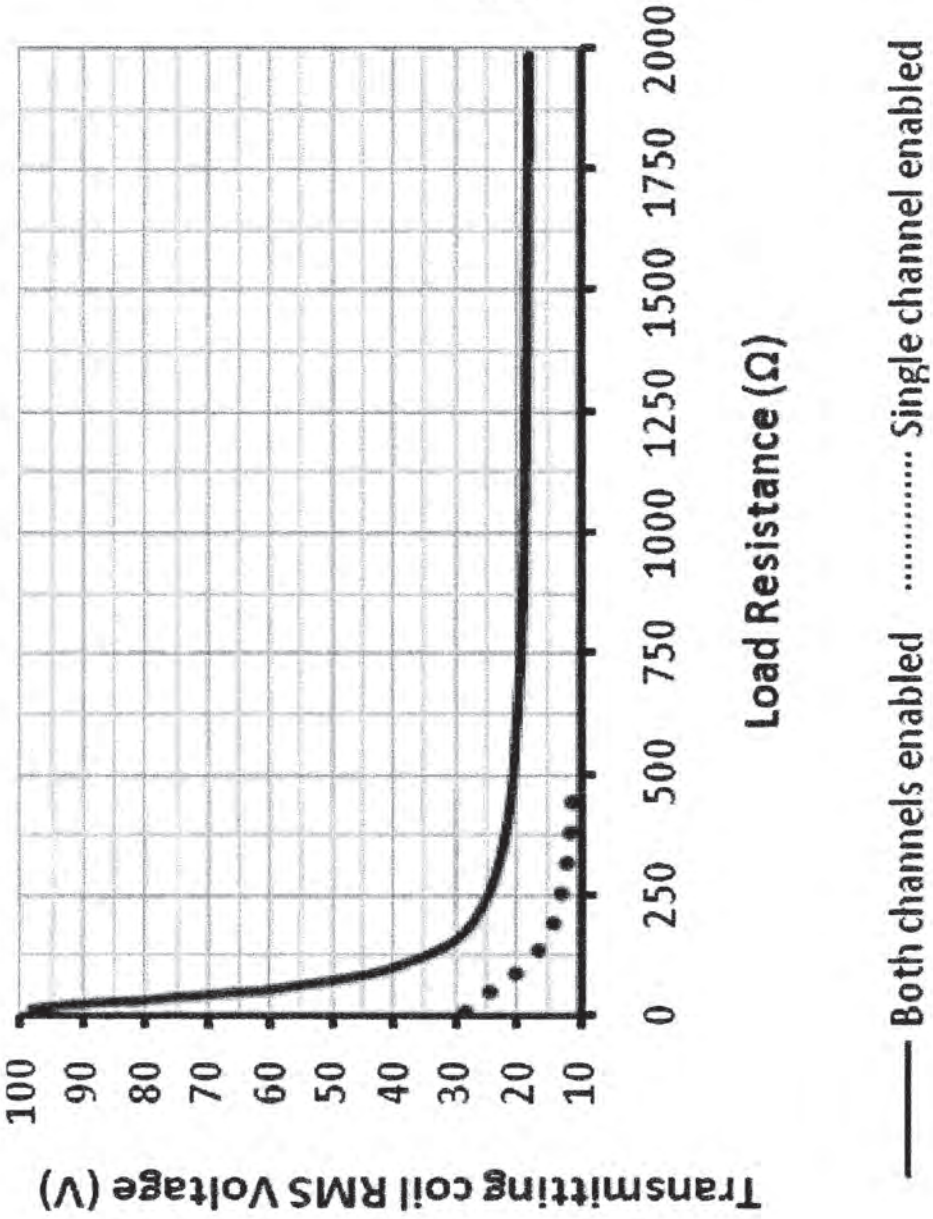

Transmitting coil RMS Voltage (V)
100
90
80
70
60
50
40
30
20
10
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 66

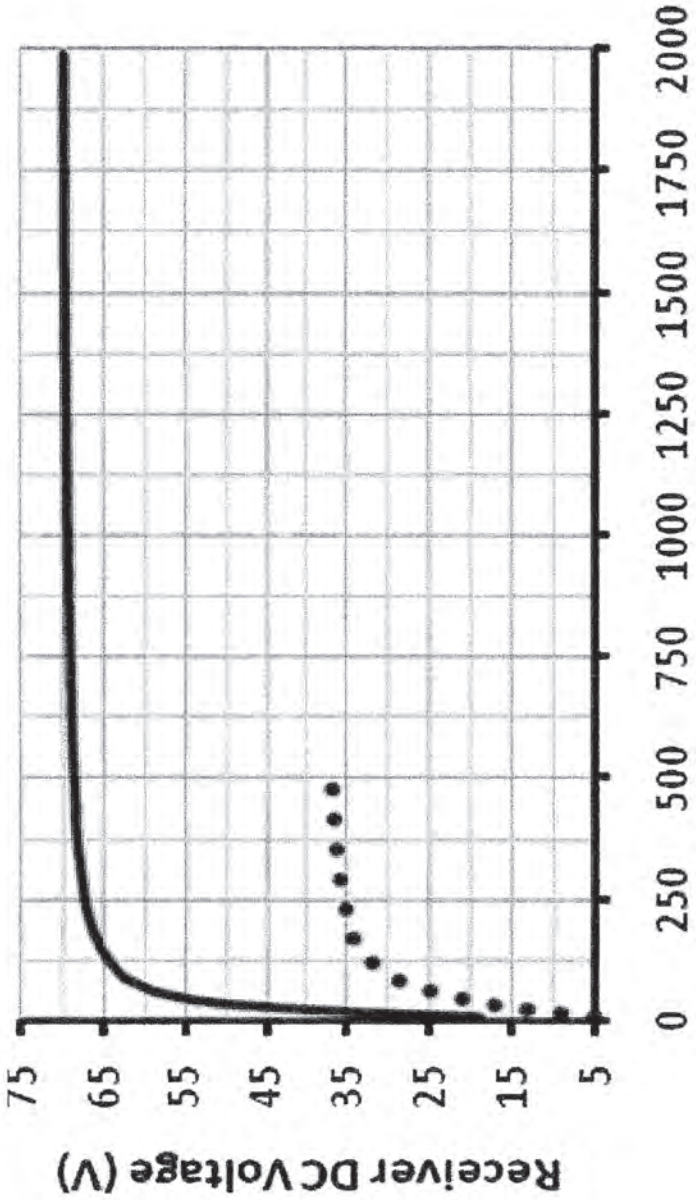

Receiver DC Voltage (V)
75
65
55
45
35
25
15
5
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 67

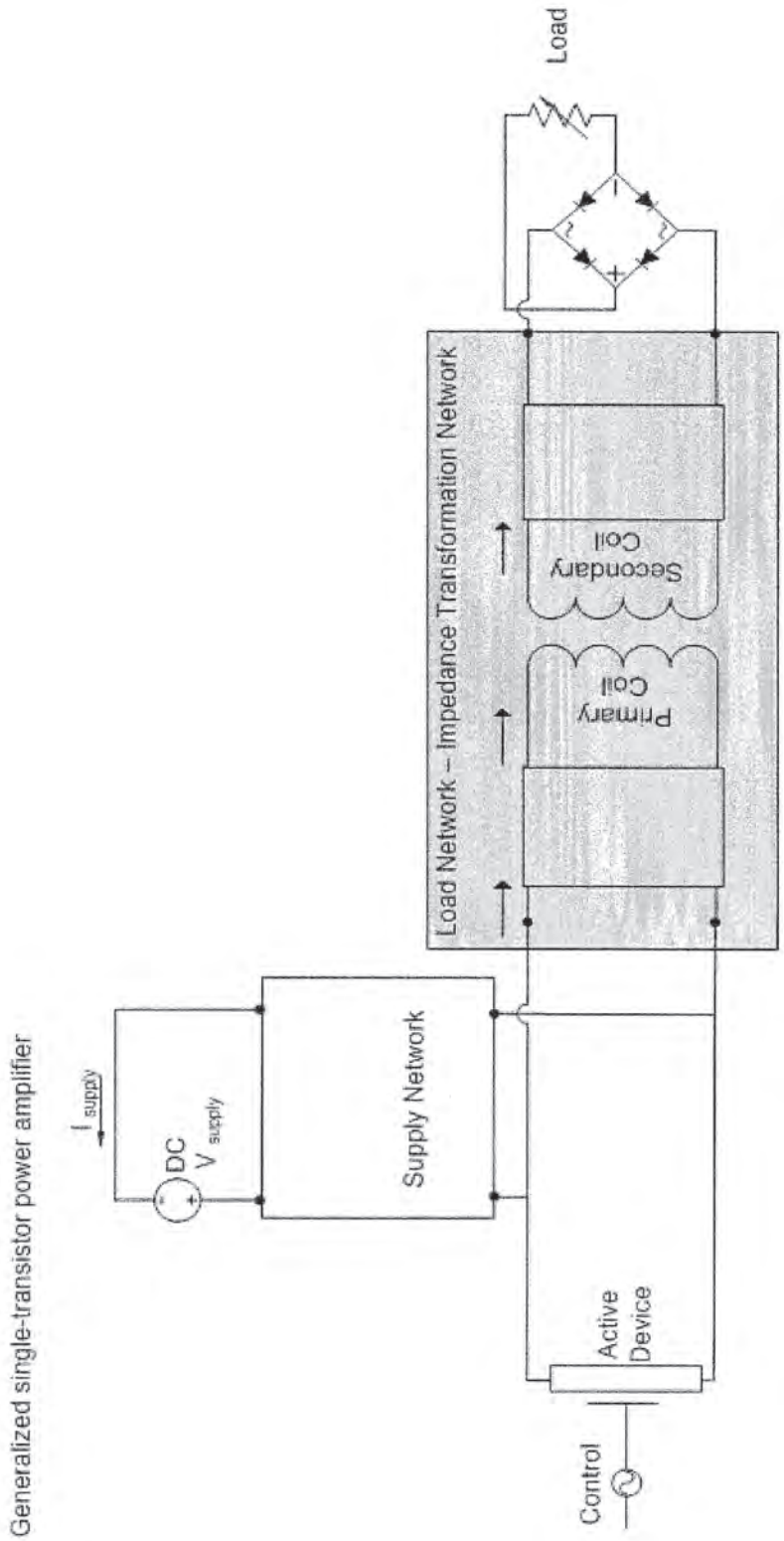

Generalized single-transistor power amplifier
I supply
DC
V supply
Supply Network
Load Network – Impedance Transformation Network
Primary Coil
Secondary Coil
Load
Active Device
Control

FIG. 68

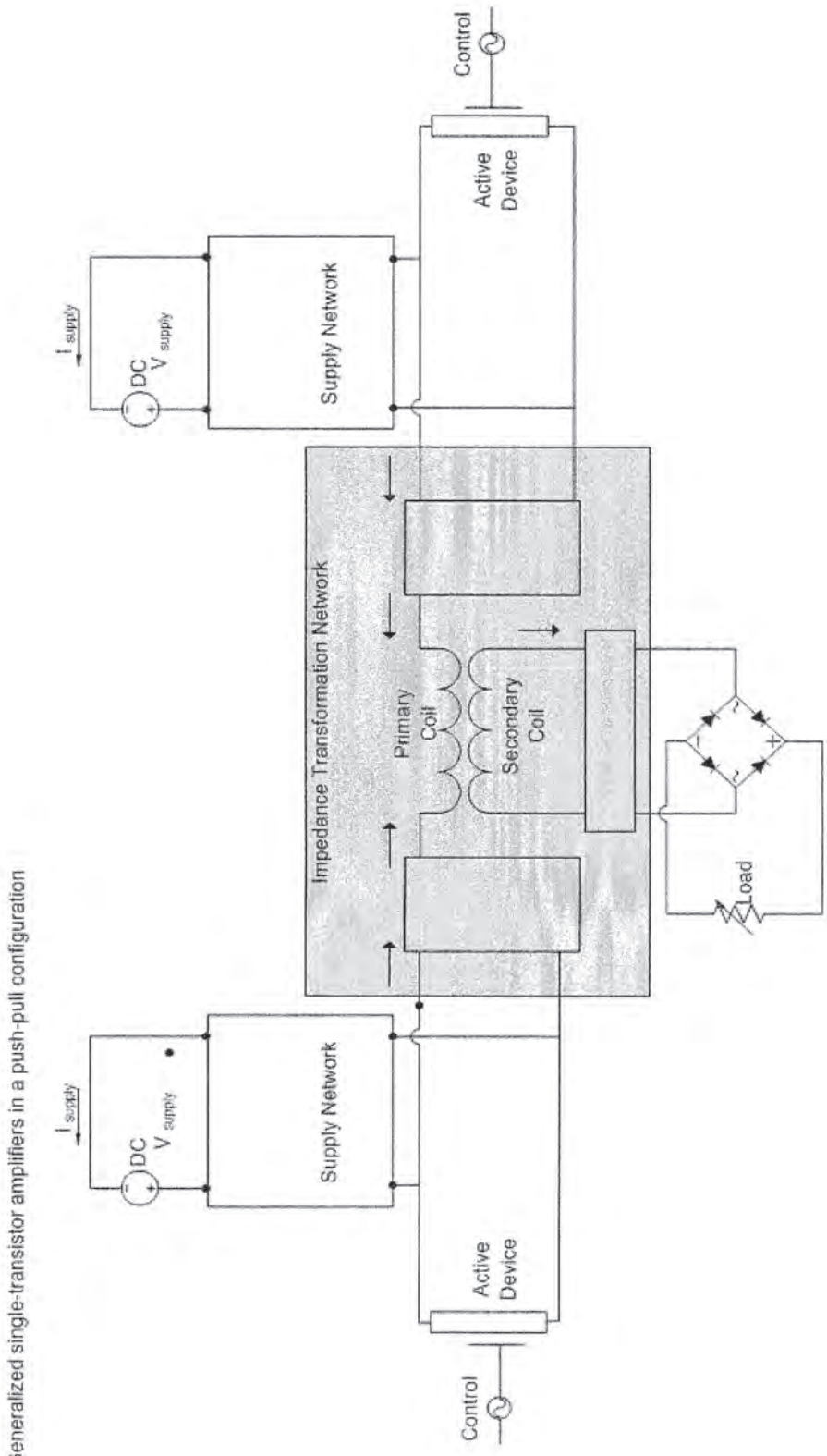

Generalized single-transistor amplifiers in a push-pull configuration
Control
Active Device
Supply Network
DC
V supply
I supply
Impedance Transformation Network
Primary Coil
Secondary Coil
Load
Supply Network
DC
V supply
I supply
Active Device
Control

FIG. 69

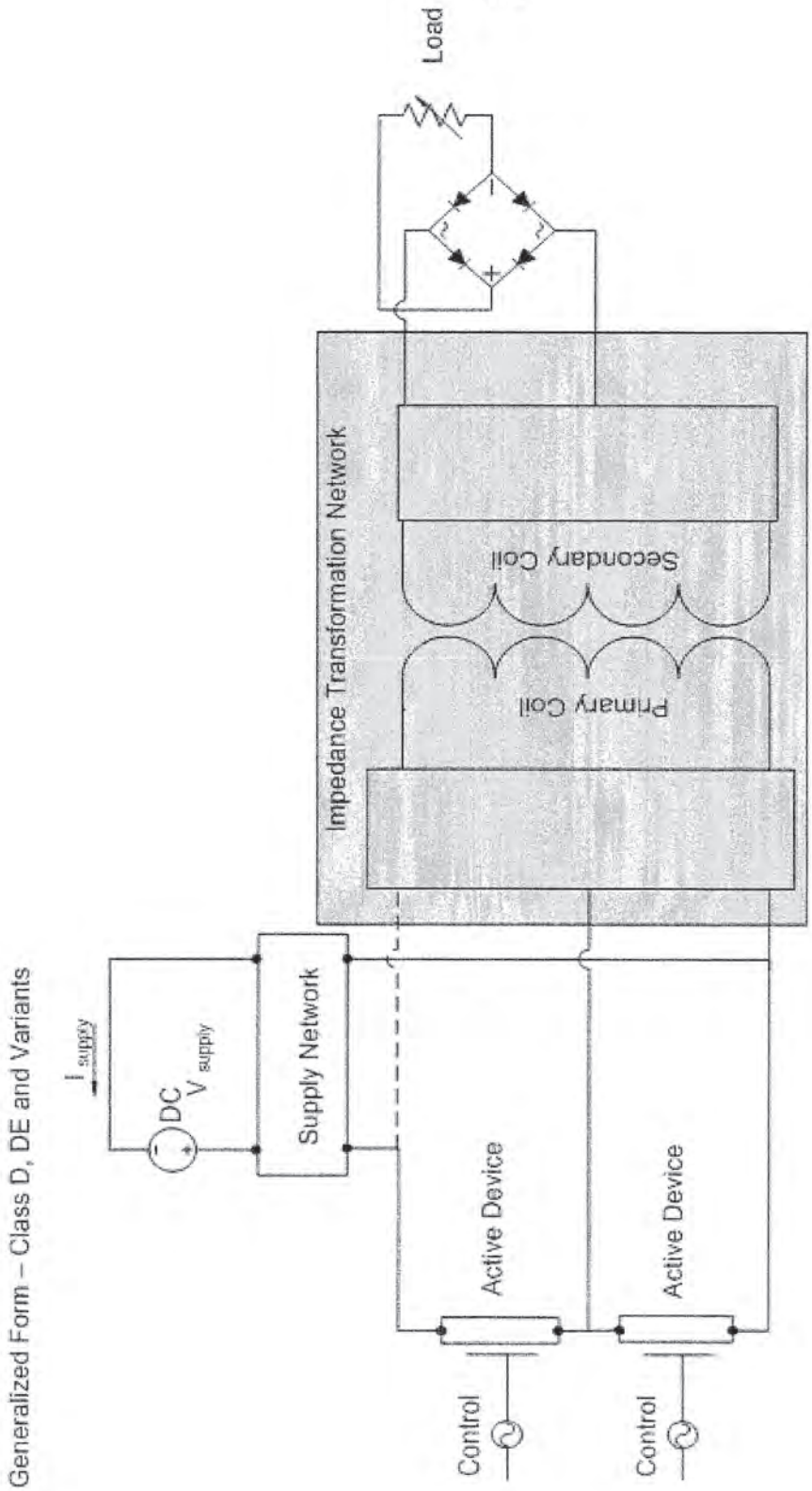

Generalized Form – Class D, DE and Variants
I supply
DC
V supply
Supply Network
Impedance Transformation Network
Secondary Coil
Primary Coil
Load
Active Device
Active Device
Control
Control

FIG. 70

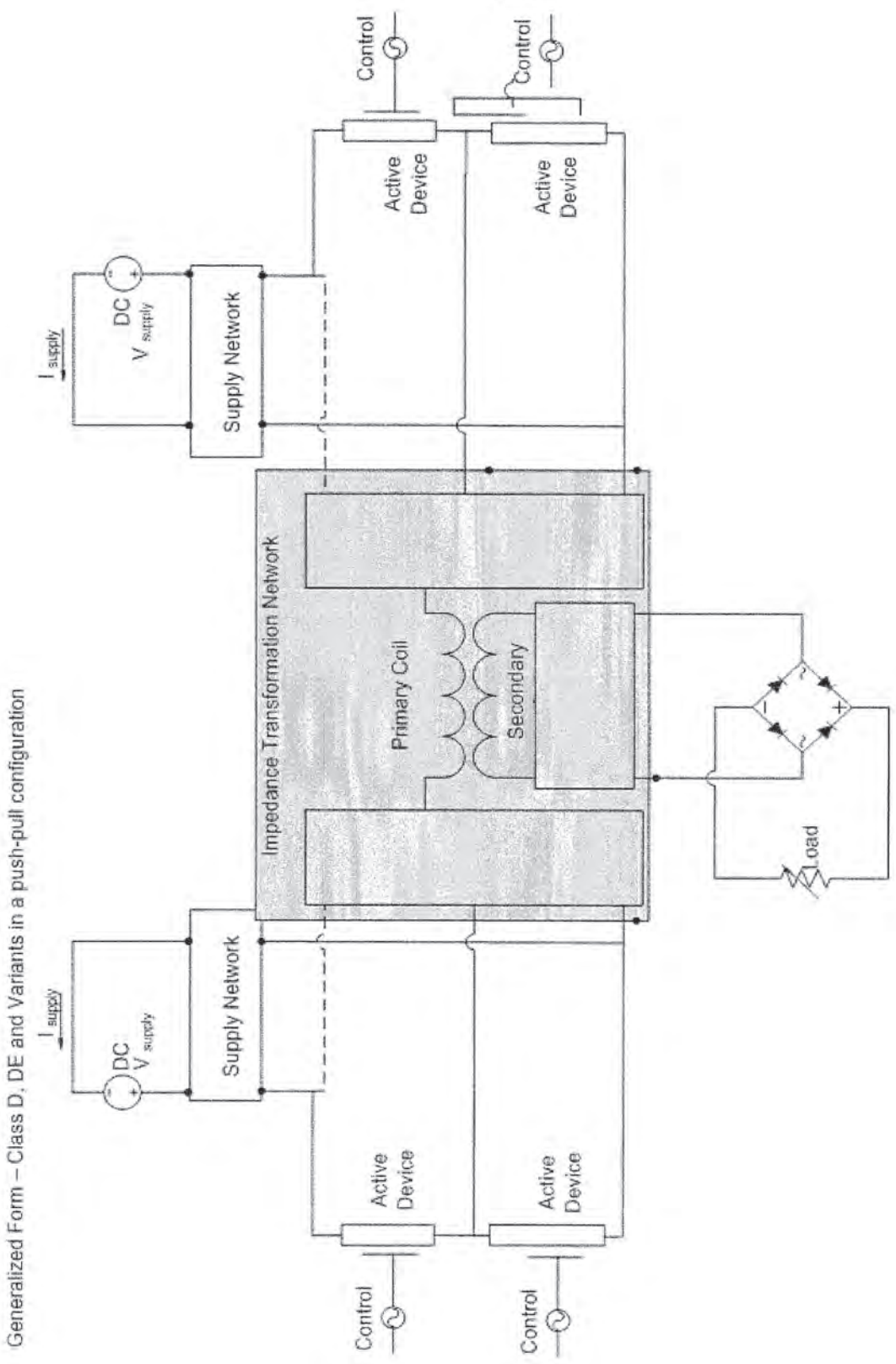

Generalized Form – Class D, DE and Variants in a push-pull configuration
I supply
DC
V supply
Supply Network
Active Device
Control
Impedance Transformation Network
Primary Coil
Secondary
Load

FIG. 71

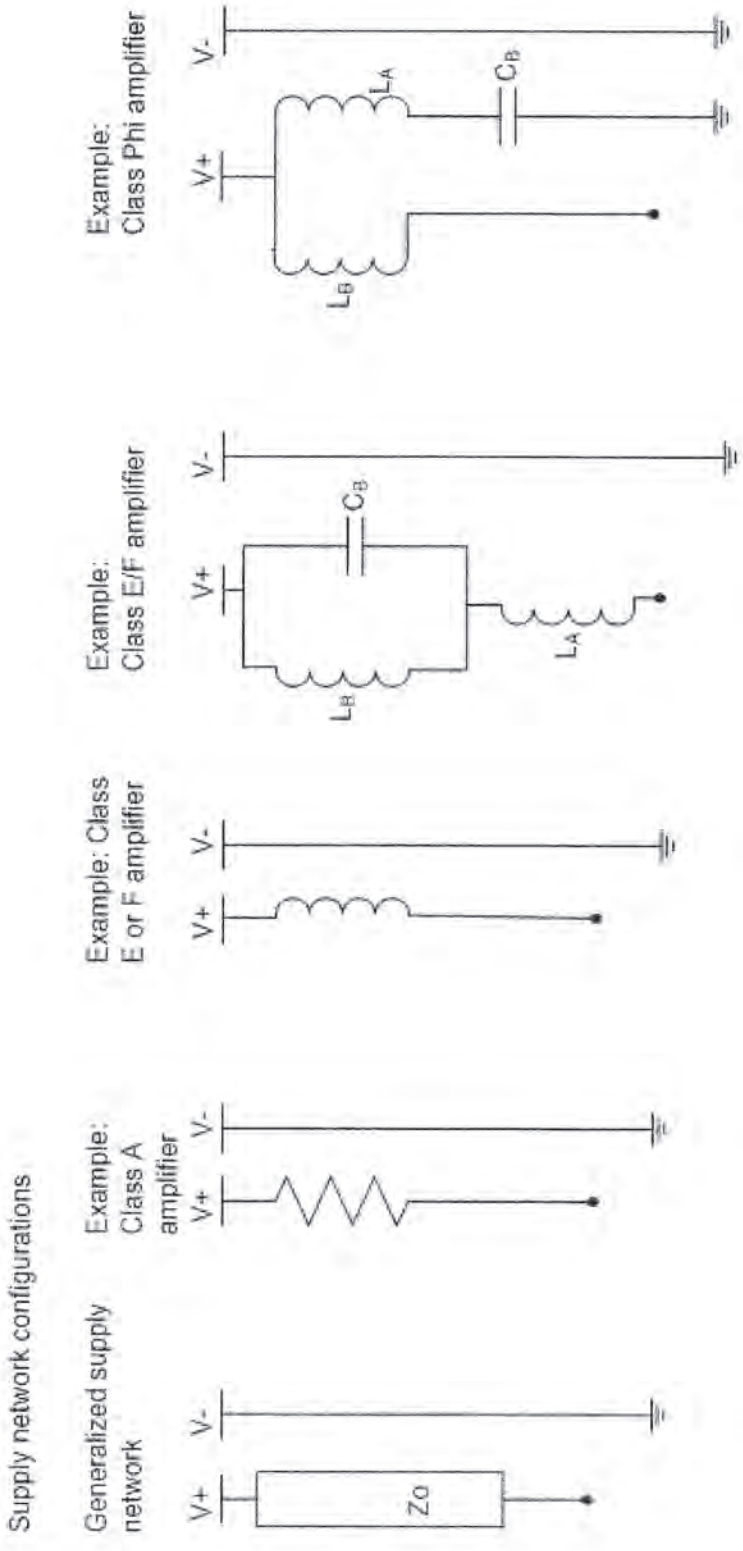


FIG. 72

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Load network functions – Impedance Transformation Network
Generalized form - single-end drive
Impedance Transformation Network
A. Frequency Filter
B. Reactance shifting
C. Correlation inversion (Phase vs. Load resistance)
D. Primary to secondary side coupling
F. Resistance Compression

FIG. 73

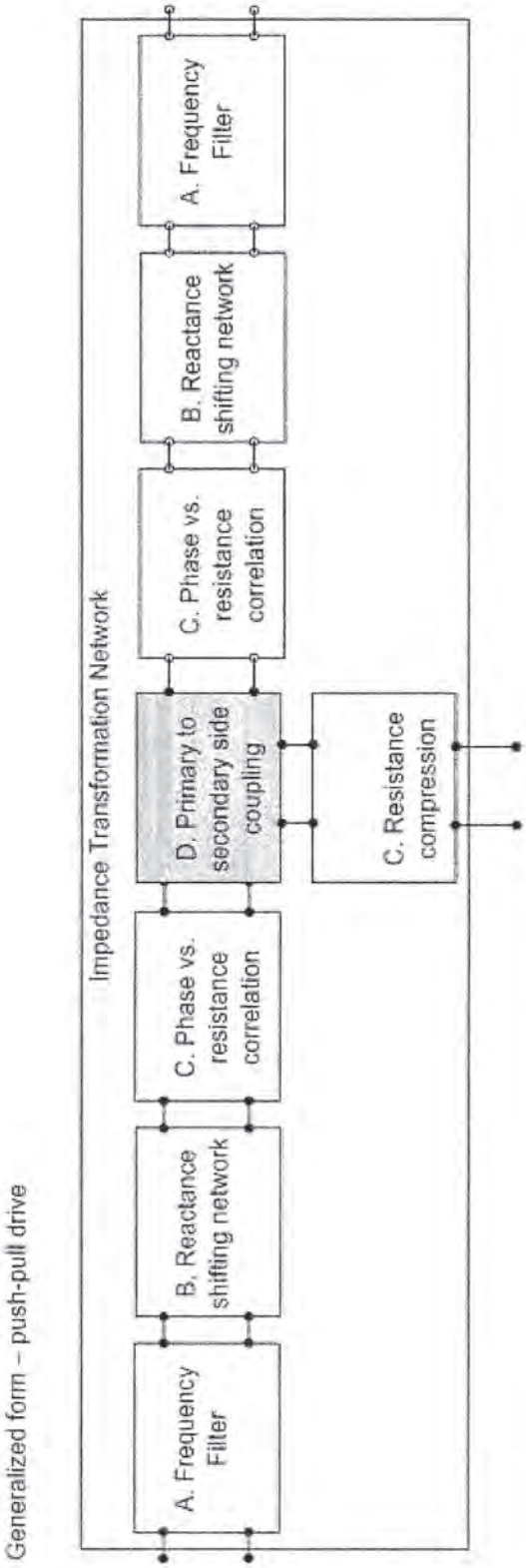

Generalized form – push-pull drive
Impedance Transformation Network
A. Frequency Filter
B. Reactance shifting network
C. Phase vs. resistance correlation
D. Primary to secondary side coupling
C. Resistance compression
C. Phase vs. resistance correlation
B. Reactance shifting network
A. Frequency Filter

FIG. 74

FIG. 75

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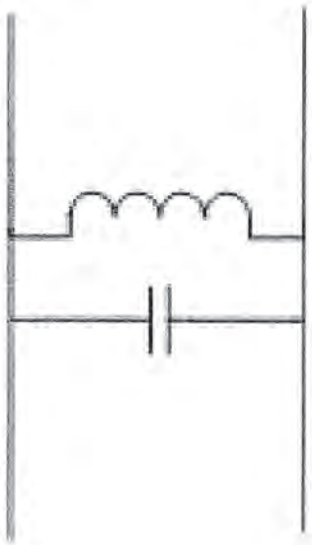


FIG. 76

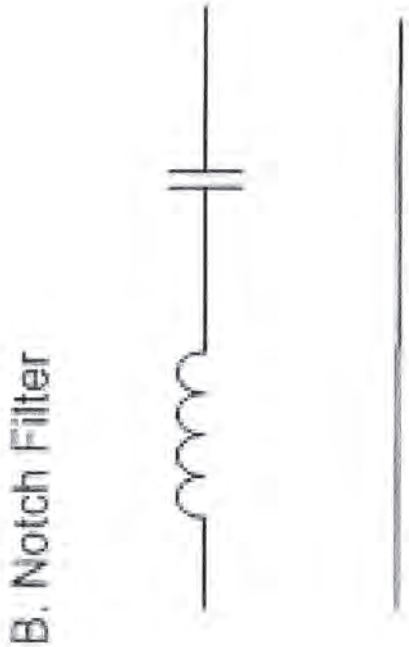




FIG. 77

D. Primary to Secondary Side Coupling
One primary:
One secondary
One primary:
Multiple secondary
Multiple primary:
One secondary
Multiple primary:
Multiple secondary

FIG. 78

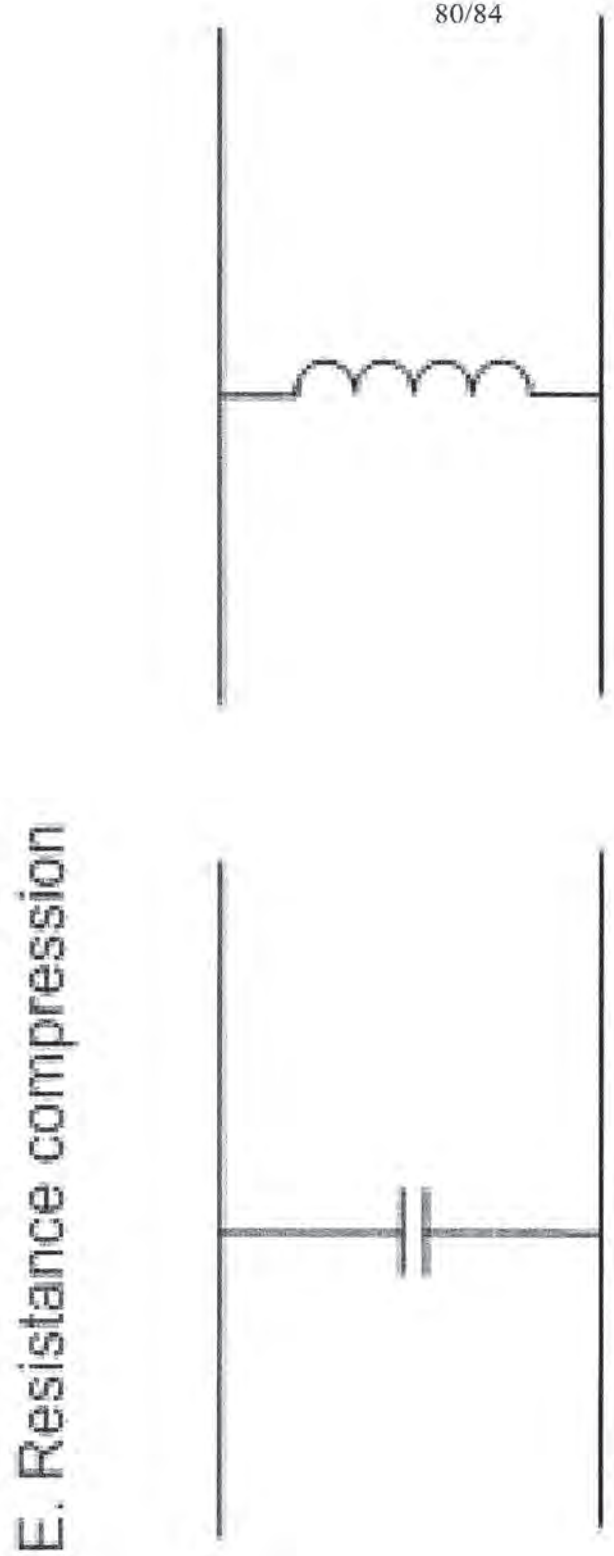


FIG. 79

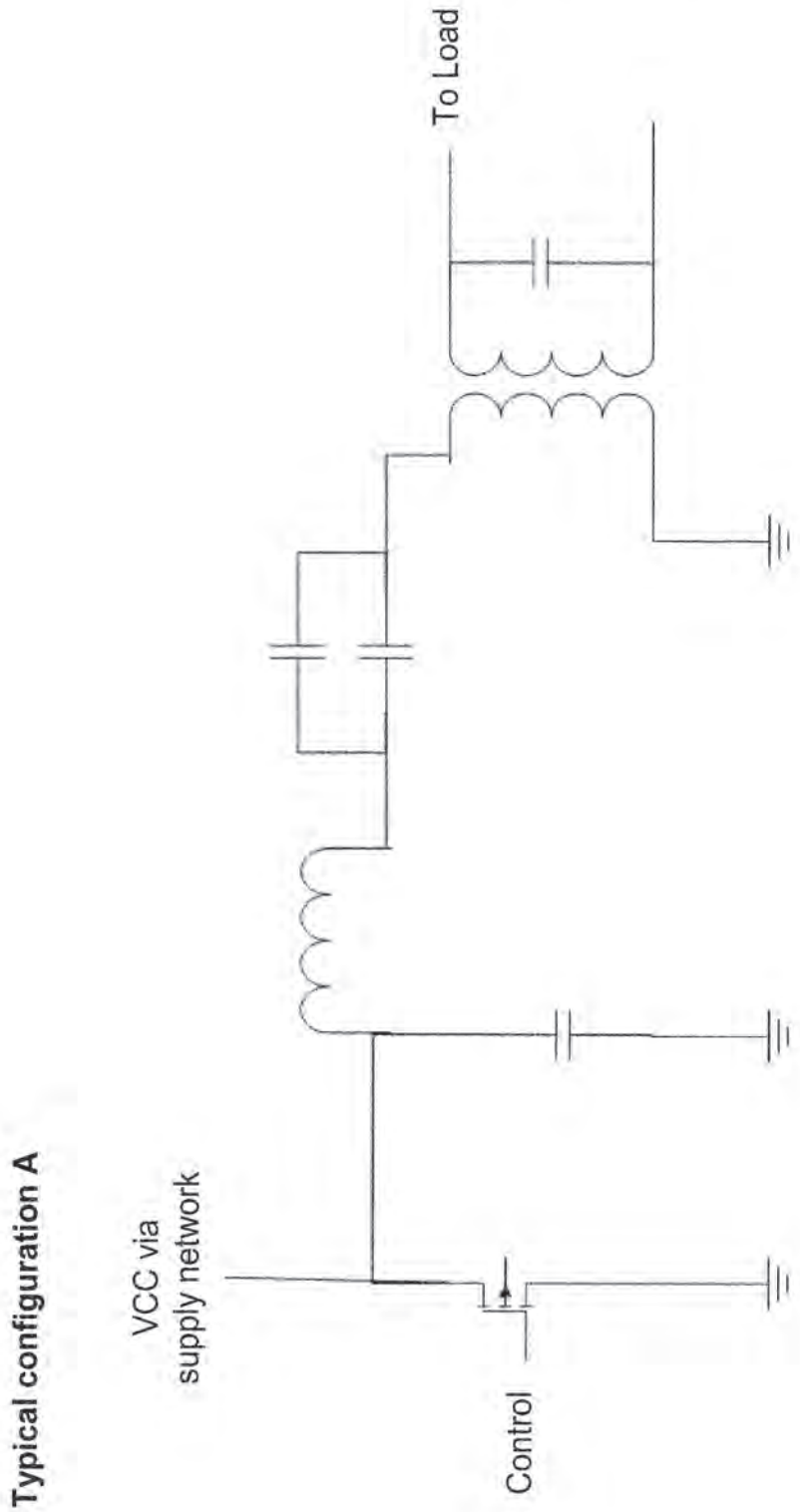

Typical configuration A
VCC via
supply network
Control
To Load

FIG. 80

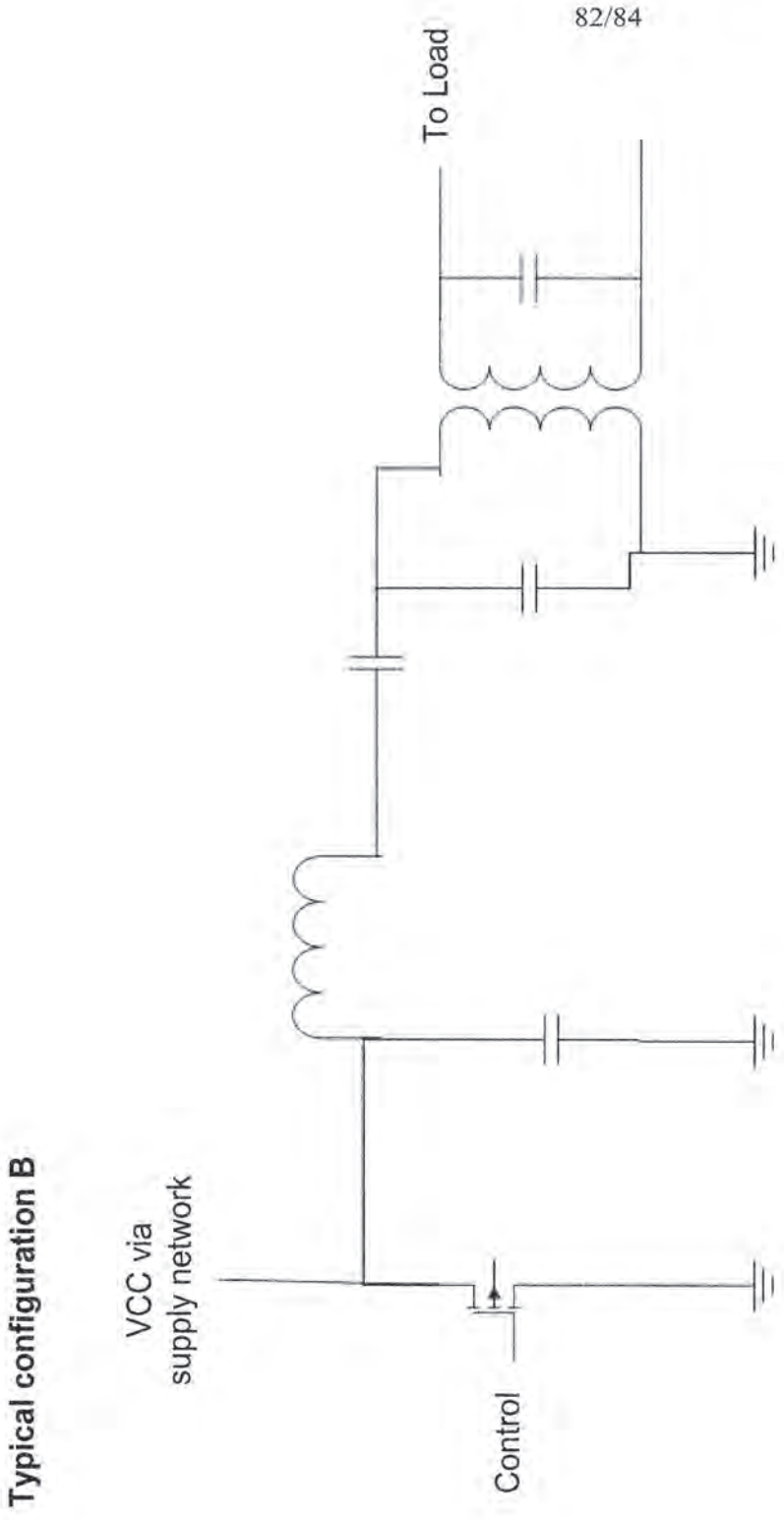

Typical configuration B
VCC via
supply network
Control
To Load

FIG. 81

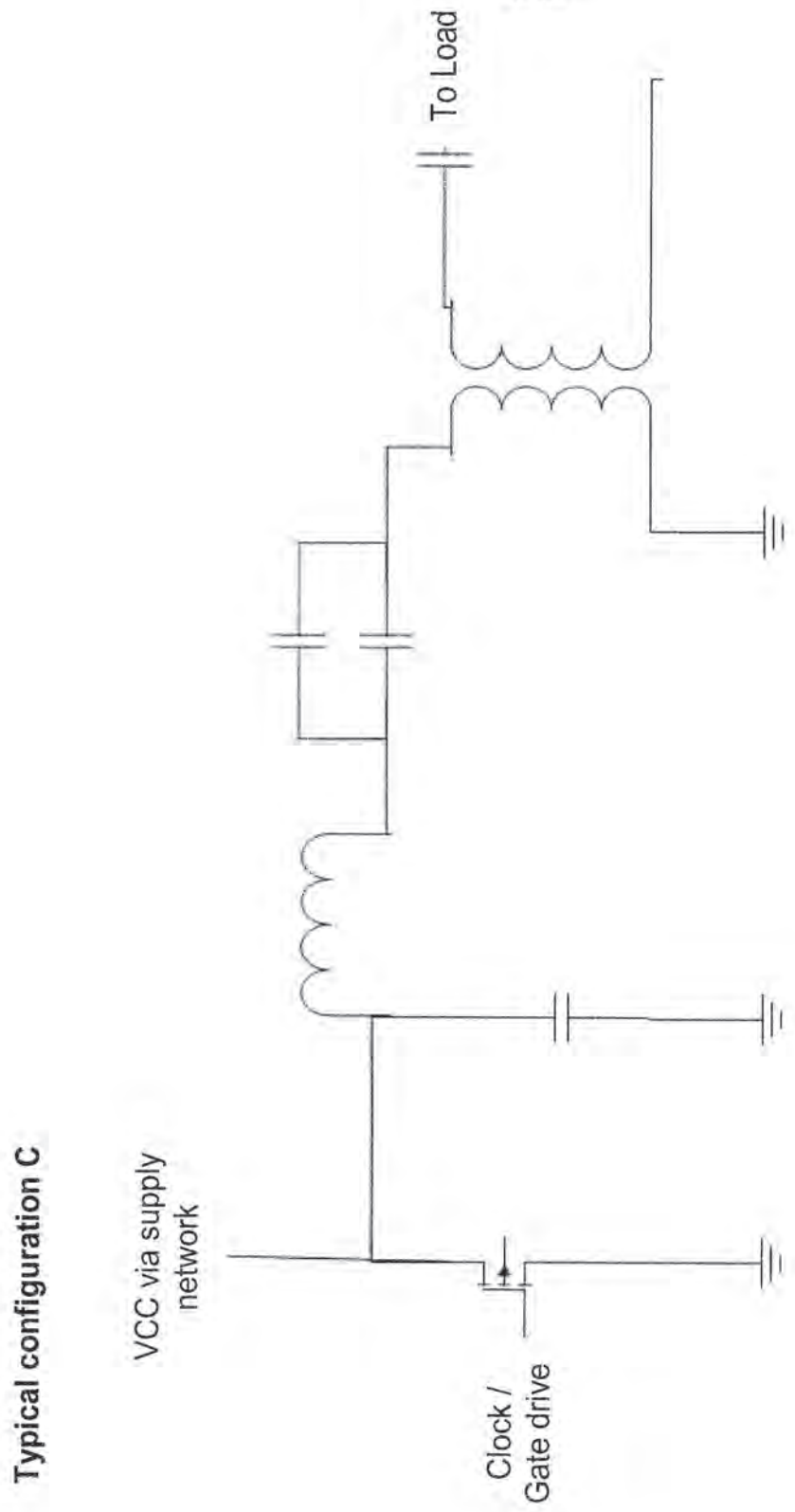


FIG. 82

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Page 334

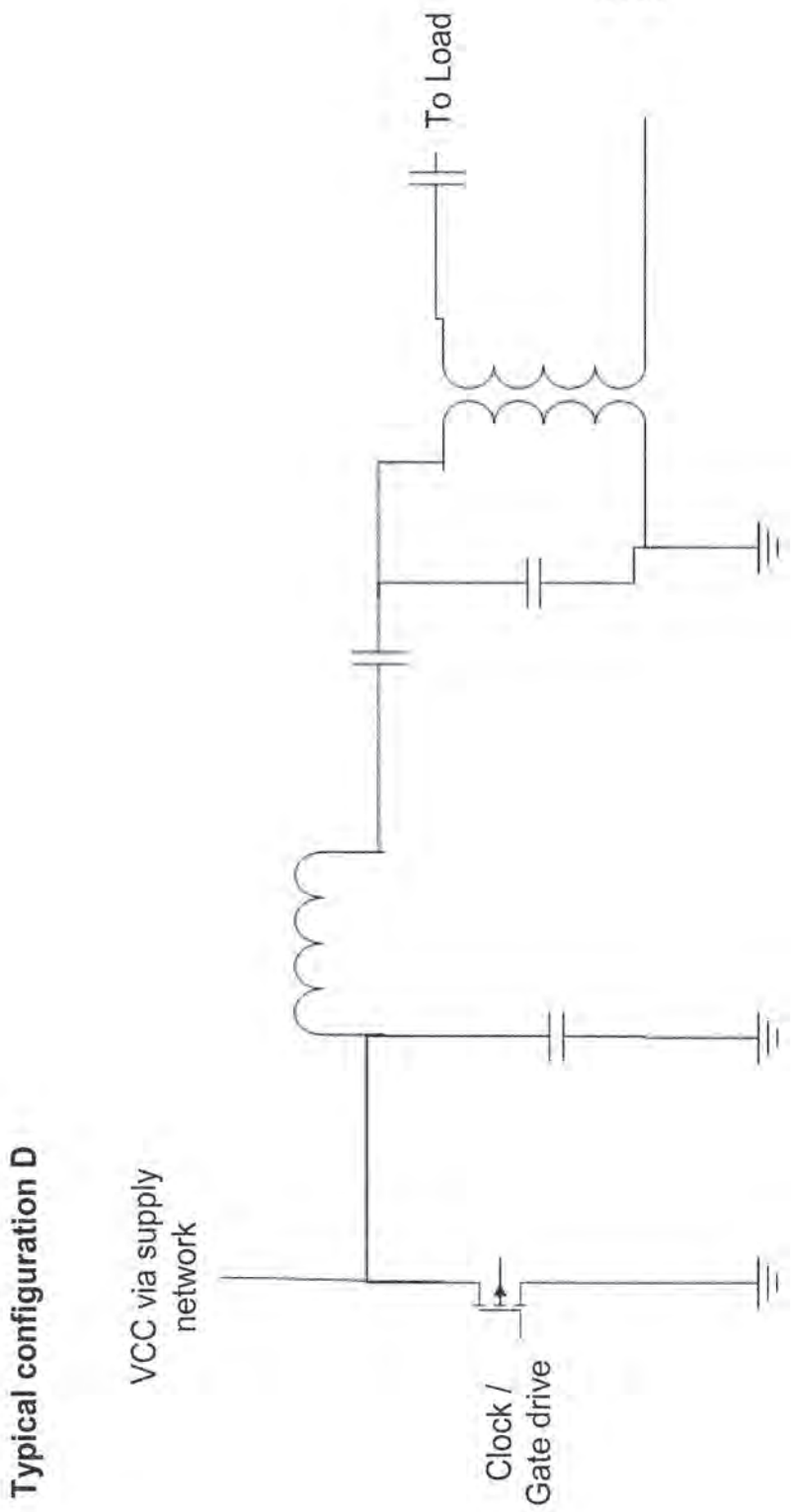


FIG. 83

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Page 335

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(71) Applicant *(for all designated States except US)*: **UNIVERSITY OF FLORIDA RESEARCH FOUNDATION, INC.** [US/US]; 223 Grinter Hall, Gainesville, FL 32611 (US).

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

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(54) Title: METHOD AND APPARATUS FOR CONTACTLESS POWER TRANSFER

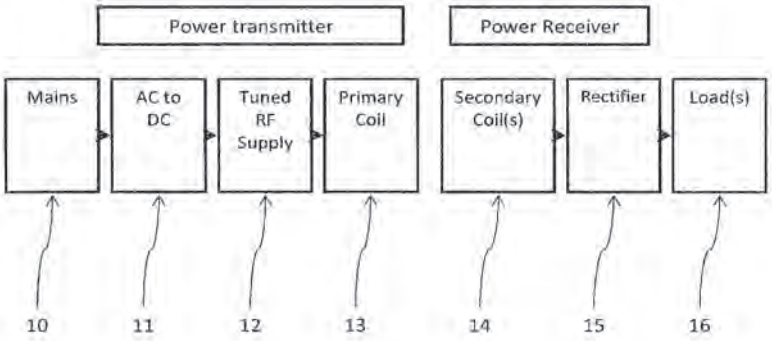


FIG. 1

(57) Abstract: Embodiments of the subject invention pertain to a method and apparatus for contactless power transfer. A specific embodiment relates to an impedance transformation network, a new class of load network for application to a contactless power system. Embodiments of the impedance transformation network enable a contactless power system to operate without encountering the common problems of: 1) over-voltage and/or under-voltage conditions; 2) over-power and/or under-power conditions; 3) power oscillations; and 4) high heat dissipation.

WO 2009/149464 A3

INTERNATIONAL SEARCH REPORT

International application No.
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A. CLASSIFICATION OF SUBJECT MATTER

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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02J 17/00; C12M 1/34; H02M 3/335; H02M 7/537; H03F 1/22; H05B 3/00; H05B 37/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models
(Chinese Patents and application for patent)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PAJ, FPD, USPAT, eKIPASS "Keyword: primary coil, secondary coil, inductive coupling, variable impedance"

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2006-0076338 A1 (VALERY KAGAN) 13 April 2006 See the abstract; figure 1.	1-111
A	US 2005-0140456 A1 (NUNTHA KUMAR KRISHNASAMY MANIAM et al.) 30 June 2005 See the abstract; figure 1.	1-111
A	US 6088249 A (ADAMSON; HUGH PATRICK) 11 July 2000 See the abstract; figure 8.	1-111
A	US 5818702 A (FAULK; RICHARD A.) 06 October 1998 See the abstract; figures 2B, 3A.	1-111

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
11 FEBRUARY 2010 (11.02.2010)	**17 FEBRUARY 2010 (17.02.2010)**
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Information on patent family members

International application No.
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(74) Agent: **PARKER, James, S.**; Saliwanchik, Lloyd, Saliwanchik, P.O. Box 142950, Gainesville, FL 32614-2950 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) **Title**: METHOD AND APPARATUS FOR PRODUCING SUBSTANTIALLY UNIFORM MAGNETIC FIELD

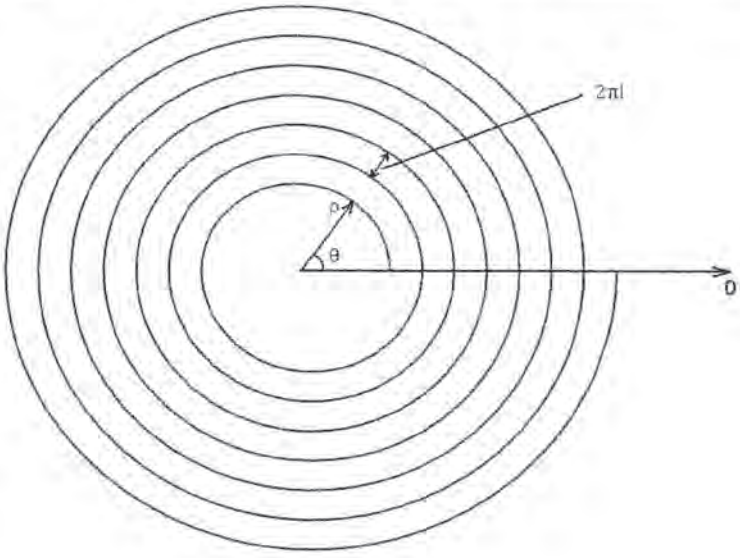


FIG. 1

(57) **Abstract**: A planar wireless power transmitter coil design and method are provided. A single spiral coil can be used to provide a uniform magnetic field across its surface area for location-independent planar wireless power charging. The spiral coil can be designed to have a non- constant gap between adjacent loops such that the gap between adjacent loops decreases towards the outer loops.

WO 2009/155000 A2

Published:

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DESCRIPTION

METHOD AND APPARATUS FOR PRODUCING SUBSTANTIALLY UNIFORM MAGNETIC FIELD

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 61/056,354, filed May 27, 2008, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

In recent years, consumer electronics devices such as cell phones, personal digital assistants (PDAs), and laptops are using more wireless components such as a Bluetooth headset, wireless mouse, and wireless LAN. However, the wired power line remains to impair wireless freedom. Many designs and research has been conducted to provide solutions to get rid of this wire. Inductive wireless power transmission appears to be the most promising solution to this problem.

In wireless power charging, AC current passes through a transmitter coil, inducing magnetic flux on and/or above the surface of a power platform. A receiver coil generates voltage when magnetic flux passing through the receiver coil's loop(s) changes. In many cases, the transmitter coil and the receiver coil are not of the same size.

However, when the transmitter coil and receiver coil have significantly different sizes, the voltage generated on the receiving side can be greatly affected by the receiver coil's placement on the surface of the transmitter coil.

Specifically, a typical transmitter coil has a non-uniform magnetic field across its surface area, which may cause voltage variation and impedance matching difficulty.

A normal spiral coil as shown in Figure 1 usually has constant gap between adjacent loops. For example, the circular spiral coil of Figure 1 follows the equation of

$$\rho = \rho_0 + l\theta . \quad (1)$$

where ρ is the radius, θ is the angle, ρ_0 is the initial radius and l is a constant. In Figure 1, the distance between adjacent wires is a constant $2p/$.

The magnetic field near the surface for the coil shown in Figure 1 is shown in Figure 2, which illustrates a high magnetic field strength at the center of the coil. Each loop of the coil contributes magnetic field in the area it encloses, and the magnetic field in the center is the superposition of magnetic field contributions from all the loops.

For a regular coil, the density of magnetic flux generated in the coil has a maximum value at a position closest to the coil, and has a minimum value at a position at the center of the coil. Thus, the charging efficiency may be abruptly deteriorated leading to significant variation in charging efficiency.

One approach to solve this problem is discussed in WO2007/013725A1 (Gwon *et al.*), which discloses a wireless charger having decreased variation of charging efficiency. According to Gwon *et al.*, a smaller coil is placed in the center of an outer coil, which reinforces the magnetic flux density in the center of the outer and inner coils. Thus the entire magnetic flux density is flattened as a whole in comparison to the magnetic flux density formed by only the outer coil. Though the design disclosed in Gwon *et al.* reduces the effect of variation of the magnetic flux density of the outer coil, the variation can still be significant. In addition, when the receiver coil is much smaller than the transmitter coil, the location of the receiver coil can often affect its performance.

In a similar approach, WO2007/019806A1 (Hui *et al.*) provides a design of an auxiliary winding for improved performance of a planar inductive charging platform. According to Hui *et al.* an auxiliary winding is introduced to compensate the magnetic field generated by a principle winding. The design taught by Hui *et al.* uses a similar mechanism as that taught by Gwon *et al.* in that separate coils are used to improve charging efficiency.

Thus, there exists in the art a need for improved inductive wireless power transmission.

BRIEF SUMMARY

Embodiments of the subject invention relate to a method and apparatus for providing a planar spiral transmitter coil that produces a substantially uniform magnetic field over a region of interest near the surface of the coil. Embodiments of the invention provide a planar inductive wireless power transmission system incorporating a planar spiral transmitter coil and a receiver coil.

According to embodiments of the invention, a single coil design can provide improved charging efficiency to a wireless power transmission apparatus.

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Coils in accordance with embodiments of the invention can provide for a system that uses near-field coupling to transfer power. Advantageously, embodiments of the invention do not require the alignment of the two axes of two coils. Certain embodiments of the invention provide improved robustness for wireless power transfer.

According to an embodiment of the invention, a single spiral coil can be used to provide a uniform magnetic field across the coil's surface area for location-independent planar wireless power charging. Embodiments of the invention generate a uniform magnetic field across an area that enables uniform wireless power transfer insensitive to the location of the device being charged.

In one embodiment, a circular spiral coil can be used. In another embodiment, a rectangular spiral coil can be used. Other shapes can also be utilized for the coil, such as elliptical, rectangular, hexagonal, and other polygonal shapes. The spiral coil can be designed to have a non-constant gap between adjacent loops such that the gap between adjacent loops decreases towards the outer loops.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 shows a normal spiral coil having a constant gap between adjacent loops.

Figure 2 shows a plot of the magnetic field of the normal spiral coil shown in Figure 1.

Figure 3 shows a spiral coil according to an embodiment of the invention.

Figure 4 shows a plot of the magnetic field of the spiral coil shown in Figure 3.

Figure 5 shows a rectangular spiral coil according to an embodiment of the invention.

Figure 6 shows a plot of the magnetic field of the rectangular spiral coil shown in Figure 5.

DETAILED DISCLOSURE

Embodiments of the subject invention relate to a spiral coil that can generate a substantially uniform magnetic field near the surface of the coil, across at least a portion of the surface area of the coil. Embodiments provide a location-independent planar wireless power charging system. Embodiments of the spiral coil can generate a substantially uniform magnetic field near the surface of the coil, across a portion of the surface area of the coil. A wireless power transmission system in accordance with an embodiment of the invention can have performance insensitive to the placement of the receiver coil within the substantially

uniform magnetic field. The transmitter coil can be driven by a driver. In specific embodiments, the driver is a current source or a voltage source.

Specific embodiments can provide magnetic fields where the magnitude of the magnetic field in a direction perpendicular to the plane of the coil is substantially uniform over the region of interest such that $\frac{MAX - MIN}{AVERAGE}$ is less than or equal to 0.2 over the region of interest, where MAX and MIN are the maximum magnitude, and minimum magnitude, of the magnet field over the region of interest, respectively, and AVERAGE is $\frac{MAX + MIN}{2}$. Further specific embodiments can have the $\frac{MAX - MIN}{AVERAGE}$ of less than or equal to 0.1 over the region of interest and the $\frac{MAX - MIN}{AVERAGE}$ is less than or equal to 0.05 over the region of interest.

In an embodiment of a wireless power charging system, AC current passes through a transmitter coil, inducing magnetic flux on the surface of a power platform. In a specific embodiment, the frequency of the transmitter is between 1kHz and 10MHz. In a preferred embodiment, the frequency of the transmitter is in the range 100 kHz to 400 kHz, and in another embodiment, less than 1MHz. In specific embodiments, the region of interest can be a plane parallel to the plane of the coil offset from the plane of the coil by less than R, less than 30 cm, and/or less than 10 cm. The region of interest can cover a portion of, or all of the area of the coil. A receiver coil generates voltage when magnetic flux passing through the loop of the receiver coil changes. In specific embodiments, the transmitter coil and the receiver coil are not of the same size. A normal coil in accordance with an embodiment of the subject charging system can have a uniform magnetic field across its surface area, which reduces voltage variation and improves impedance matching. In a specific embodiment, the uniformity of the magnetic field can be less than 10% across the surface area of the coil, where the surface of the coil is the area enclosed by the outermost turn of the coil.

According to embodiments of the invention, to generate a more uniform field near the surface of the spiral coil, the distance between two adjacent loops can be adjusted. To reduce the magnetic field density at the center, the density of the inner loops should be less than the outer loops. In a specific embodiment, the gap between two adjacent coils decreases continuously toward the outer loops of the coil. A formula that describes the curve of a

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circular spiral inductor according to an embodiment of the invention is

$$\rho(\theta) = \rho_0 + l(\theta)\theta \tag{2}$$

where $l(\theta)$ is a function of θ. θ can vary from 0 to $2\pi N$, where N is the number of turns of the coil. In an embodiment, the derivative of $l(\theta)$ is positive and decreases as θ increases. Specific functions allow $l(\theta)$, the distance between adjacent loops, to be adjusted, and can allow the field across the surface of the coil to be substantially uniform. In another embodiment, the derivative of $l(\theta)$ is such that the spacing between adjacent loops can decrease or remain the same as θ increases such that as the coil moves from the innermost radius to the outermost radius the spacing decreases.

According to an embodiment of the invention, a circular spiral coil, which can be used to obtain the formula for $l(\theta)$, is

$$\rho(\theta) = r + (1 - (1 - \frac{\theta}{2\pi N})^4)(R - r) \tag{3}$$

where R is the outermost radius, r is the innermost radius, and N is the total turns of the coil. $l(\theta)$ can be obtained by setting the right side of equation (2) equal to the right side of equation (3) and solving $l(\theta)$, where r has the same meaning as ρ_0. According to one embodiment, r is 1/4 to 1/3 of R. In another embodiment, the coil can be elliptical with appropriate modifications to equations (2) and (3).

Figure 3 shows a coil with non-constant gap between adjacent loops, in accordance with an embodiment of the subject invention. The curvature of the spiral coil of Figure 3 follows equation 3, in which R = 200 mm, r = 50 mm, and N = 8. Figure 4 shows the magnetic field strength in a perpendicular direction across the surface area of the coil of Figure 3. As shown in Figure 4, the uniformity of the magnetic field for the coil of Figure 3 is significantly improved over the uniformity of the magnetic field for the coil of Figure 1.

For a rectangular spiral inductor, narrower gaps can be used between adjacent loops as the loops become farther from the center. According to an embodiment of the present invention, the gap between adjacent loops can be derived from

$$\rho(2n\pi) - \rho[2(n-1)\pi], \text{ n=1, 2,..., N.} \tag{4}$$

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where ρ is the same function as Equation 3. Figure 5 shows a rectangular spiral coil according to an embodiment of the invention. The design of the coil of Figure 5 follows equation 4, in which $R = 200$ mm, $r = 50$ mm, and $N = 8$mm. The magnetic field strength in a perpendicular direction for the coil of Figure 5 is shown in Figure 6.

The results, as shown in Figures 4 and 6, demonstrate that a substantially uniform magnetic field of spiral coil can be generated in accordance with embodiments of the invention.

Additional embodiments utilize polygonal coils, such as rectangles, squares, hexagons, and other multisided shapes, to produce the magnetic fields. The spacing between adjacent coils can decrease or stay the same at each corner of the polygon such that the spacing decreases as the coil goes from the innermost radius to the outermost radius. In specific embodiments, the spacing can continuously decrease, the spacing can be the same between two corners (along one side of the polygonal) and decrease from before each corner to after each corner, the spacing can remain the same for a portion or all of a loop (as shown in Figure 5) and have decreases as the coil moves outward, and/or combinations of these changes.

In specific embodiments, a receiver coil can be inductively coupled to the transmitter coil so as to transfer power to the receiver coil. Embodiments can use receiver coils that have areas such that the transmitter coil area is 2 to 12 times as large, 2 to 8 times as large, or 2 to 4 times as large as the receiver coil area.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

CLAIMS

What is claimed is:

1. An apparatus for producing a magnetic field, comprising:

a coil, wherein the coil is a planar spiral coil, where the coil has at least two loops, wherein a spacing between adjacent loops decreases continuously from an inner loop toward an outer loop of the coil, and

a driver, wherein the driver drives the coil to produce a magnetic field, wherein a magnitude of the magnetic field in a direction perpendicular to a plane of the coil is substantially uniform over a region of interest.

2. The apparatus according to claim 1, wherein the magnitude of the magnetic field in a direction perpendicular to the plane of the coil is substantially uniform over the region of interest such that $\frac{MAX - MIN}{AVERAGE}$ is less than or equal to 0.2 over the region of interest, where MAX and MIN are the maximum magnitude, and minimum magnitude, of the magnet field over the region of interest, respectively, and AVERAGE is $\frac{MAX + MIN}{2}$.

3. The apparatus according to claim 2, wherein the $\frac{MAX - MIN}{AVERAGE}$ is less than or equal to 0.1 over the region of interest.

4. The apparatus according to claim 2, wherein the $\frac{MAX - MIN}{AVERAGE}$ is less than or equal to 0.05 over the region of interest.

5. The apparatus according to claim 1, wherein the magnetic field is time-varying.

6. The apparatus according to claim 5, wherein the time-varying magnetic field has a frequency in the range 1 kHz to 10 MHz.