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CONFIRMATION NO. 7543

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FILING RECEIPT



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The country code and number of your priority application, to be used for filing abroad under the Paris Convention, is **US 61/129,526**

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**** SMALL ENTITY ****

Title

Non-resonant inductive power transfer

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PTO/SB/16 (07-07)

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PROVISIONAL APPLICATION FOR PATENT COVER SHEET - Page 1 of 3

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No. _____

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Additional inventors are being named on the _____ separately numbered sheets attached hereto

TITLE OF THE INVENTION (500 characters max):

Non-Resonant Inductive Power Transfer

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ENCLOSED APPLICATION PARTS (check all that apply)

☐ Application Data Sheet. See 37 CFR 1.76

☐ CD(s). Number of CDs _____

☒ Drawing(s) Number of Sheets 5

☐ Other (specify) _____

☒ Specification (e.g. description of the invention) Number of Pages 16

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PROVISIONAL APPLICATION COVER SHEET
Page 3 of 3

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SIGNATURE /Yossi Azancot/ /Amir Ben Shalom/ /Arik Rofe/ /Oola Greenwald//Alfred Leibovitz/ Moti Ashery/ Date 2nd July 2008

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Docket Number 1052-42

Non-Resonant Inductive Power Transfer

Field of the Invention

The present invention is directed to providing an inductive power transfer system with a high tolerance to environmental fluctuations and variations in coil alignment.

Background

Inductive power coupling allows energy to be transferred from a power supply to an electric load without a wired connection therebetween. An oscillating electric potential is applied across a primary inductor. This sets up an oscillating magnetic field in the vicinity of the primary inductor. The oscillating magnetic field may induce a secondary oscillating electrical potential in a secondary inductor placed close to the primary inductor. In this way, electrical energy may be transmitted from the primary inductor to the secondary inductor by electromagnetic induction without a conductive connection between the inductors.

When electrical energy is transferred from a primary inductor to a secondary inductor, the inductors are said to be inductively coupled. An electric load wired in series with such a secondary inductor may draw energy from the power source wired to the primary inductor when the secondary inductor is inductively coupled thereto.

The strength of the induced voltage in the secondary inductor varies according to the oscillating frequency of the electrical potential provided to the primary inductor. The induced voltage is strongest when the oscillating frequency equals the resonant frequency of the system. The resonant frequency f_R depends upon the inductance L and the capacitance C of the system according to the equation $f_R = \frac{1}{2\pi\sqrt{LC}}$.

Known inductive power transfer systems typically transmit power at the resonant frequency of the inductive coupling. This can be difficult to maintain as the resonant frequency of the system may fluctuate during power transmission, for example in response to changing environmental conditions or variations in alignment between primary and secondary coils.

Inductive transfer systems designed to transmit at resonance therefore require tuning mechanisms for maintaining transmission at the resonant frequency of the

system. Tuning may be achieved by adjusting the driving frequency to seek resonance. For example, United States Patent No. 6,825,620, titled "Inductively coupled ballast circuit" to Kuennen et al. describes a resonance seeking ballast circuit for inductively providing power to a load. The ballast circuit includes an oscillator, a driver, a switching circuit, a resonant tank circuit and a current sensing circuit. The current sensing circuit provides a current feedback signal to the oscillator that is representative of the current in the resonant tank circuit. The current feedback signal drives the frequency of the ballast circuit causing the ballast circuit to seek resonance. The ballast circuit preferably includes a current limit circuit that is inductively coupled to the resonant tank circuit. The current limit circuit disables the ballast circuit when the current in the ballast circuit exceeds a predetermined threshold or falls outside a predetermined range.

Alternatively, tuning may be achieved by adjusting the characteristics of the inductive system. For example, United States Patent No. 7,212,414, titled "Adaptive inductive power supply" to Baarman describes a contactless power supply which has a dynamically configurable tank circuit powered by an inverter. The contactless power supply is inductively coupled to one or more loads. The inverter is connected to a DC power source. When loads are added or removed from the system, the contactless power supply is capable of modifying the resonant frequency of the tank circuit, the inverter frequency, the inverter duty cycle or the rail voltage of the DC power source.

Tuning mechanisms such as those described above are necessary in order to maintain transmission at resonance because resonant transmission is highly sensitive. At resonance small variations to the system result in large changes to the power transferred. A further problem associated with resonant transmission is the high transmission voltages involved. At high operating voltages, the capacitors and transistors in the circuit need to be relatively large.

There is a need for an inductive transfer system with a higher tolerance to environmental fluctuations and variations in inductive coil alignment and which transmits at low voltages. The present invention addresses this need.

Summary of the Invention

It is an aim of the invention to provide an inductive power transfer system comprising at least one primary inductive coil wired to a power supply via a driver; the primary inductive coil for forming an inductive couple with at least one secondary inductive coil wired to an electric load, wherein the driver is configured to provide a driving voltage across the primary inductive coil, the driving voltage oscillating at a transmission frequency significantly different from the resonant frequency of the inductive couple.

Typically, the driver comprises a switching unit for intermittently connecting the primary inductive coil to the power supply.

Preferably, the transmission frequency lies within a range in which induced voltage varies approximately linearly with frequency.

Optionally, the electric load comprises a rectifying unit.

In some embodiments, the driver additionally comprising a receiver for receiving feedback signals from the electric load. The receiver may be selected from the list comprising optical detectors, radio receivers, audio detectors and voltage peak detectors, for example. Typically, the driver is configured to adjust the transmission frequency in response to the feedback signals.

According to a preferred embodiment the receiver is adapted to receive a first signal and a second signal, and the driver is configured to:

- increase the transmission frequency when the first signal is received by the receiver, and
- decrease the transmission frequency when the second signal is received by the receiver.
- Optionally, the feedback signals carry data pertaining to the operational parameters of the electric load. For example the operational parameters may be selected from the group comprising:
 - required operating voltage for the electric load;
 - required operating current for the electric load;
 - required operating temperature for the electric load;
 - required operating power for the electric load;
 - measured operating voltage for the electric load;
 - measured operating current for the electric load;

- measured operating temperature for the electric load;
- measured operating power for the electric load;
- power delivered to the primary inductive coil;
- power received by the secondary inductive coil, and
- 5 ▪ a user identification code.

According to still other embodiments, the driver further comprises voltage monitor for monitoring the amplitude of a primary voltage across the primary coil. Preferably, the voltage monitor is configured to detect significant increases in primary voltage.

10 The power converter may be selected from the group comprising inter alia: a transformer, a DC-to-DC converter, an AC-to-DC converter, an AC-to-AC converter, a flyback transformer, a flyback converter, a full-bridge converter, a half-bridge converter and a forward converter.

15 It is a further aim of the current invention to teach a method for regulating power transmission inductive from a primary inductive coil, wired to a power supply via a driver, to a secondary inductive coil, wired to an electric load, the method comprising the following steps:

- 20 (a) providing an oscillating voltage to the primary inductive coil at an initial transmission frequency f_i which is substantially different from the resonant frequency f_R of the system;
- (b) inducing a secondary voltage in the secondary inductive coil;
- (c) monitoring power received by the electric load;
- (d) sending a feedback signal when the monitored power deviates from a predetermined range;
- 25 (e) the driver receiving the feedback signal;
- (f) the driver adjusting the transmission frequency; and
- (g) repeating steps b-f.

Optionally, step (d) further comprises:

- 30 i. sending a feedback signal of a first type S_a to the driver, whenever the power drops below a predetermined lower threshold, and
- ii. sending a feedback signal of a second type S_b to the driver, whenever the power exceeds a predetermined upper threshold.

According to preferred embodiments the initial transmission frequency f_i is higher than the resonant frequency f_R and step f further comprises:

- i. the driver reducing the transmission frequency by an incremental value $-\delta f_1$ when the received feedback signal is of the first type S_a ,
and
- ii. the driver increasing the transmission frequency by an incremental value $+\delta f_2$ when the received feedback signal is of the second type S_b .

5

10

Brief Description of the Figures

For a better understanding of the invention and to show how it may be carried into effect, reference will now be made, purely by way of example, to the accompanying drawings.

5 With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of the preferred embodiments of the present invention only, and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the invention. In this regard, no
10 attempt is made to show structural details of the invention in more detail than is necessary for a fundamental understanding of the invention; the description taken with the drawings making apparent to those skilled in the art how the several forms of the invention may be embodied in practice. In the accompanying drawings:

 Fig. 1 is a block diagram showing the main elements of an inductive power
15 transfer system with a feedback signal path;

 Fig. 2 is a graph showing how the amplitude of operational voltage varies according to frequency;

 Fig. 3 is a schematic diagram representing a laptop computer drawing power from an inductive power outlet;

20 Fig. 4 is a flowchart showing a method for regulating power transfer by varying the power transmission frequency in an inductive power transfer system; and

 Fig. 5 is a circuit diagram of an inductive power transfer system including a peak detector for detecting large increases in transmission voltage.

25 Description of the Preferred Embodiments

 Reference is now made to Fig. 1 showing a block diagram of the main elements of an inductive power transfer system 100 consisting of an inductive power outlet 200 configured to provide power to a remote secondary unit 300 according to a first embodiment of the invention.

30 The inductive power outlet 200 includes a primary inductive coil 220 is wired to a power source 240 via a driver 230. The driver 230 is configured to provide an oscillating driving voltage to the primary inductive coil 220.

The secondary unit 300 includes a secondary inductive coil 320, wired to an electric load 340, which is inductively coupled to the primary inductive coil 220. The electric load 340 draws power from the power source 240. Optionally, a communication channel 120 is provided between a transmitter 122 associated with the secondary unit 300 and a receiver 124 associated with the inductive power outlet 200. The communication channel may provide feedback signals S and the like to the driver 230.

In some embodiments, a voltage peak detector 140 is provided to detect large increases in the transmission voltage. As will be described below the peak detector 140 may be used to detect the removal of the secondary unit 200, the introduction of power drains, short circuits or the like.

Fig. 2 is a graph showing how the amplitude of the operational voltage varies according to the transmission frequency. It is noted that the voltage is at its highest when the transmission frequency is equal to the resonant frequency f_R of the system, this maximum amplitude is known as the resonance peak 2. It is further noted that the slope of the graph is steepest in the regions 4a, 4b to either side of the resonance peak 2. Thus in inductive transfer systems, which operate at or around resonance, a small variation in frequency results in a large change in induced voltage. Similarly, a small change in the resonant frequency of the system results in a large change in the induced voltage. For this reason prior art inductive transfer systems are typically very sensitive to small fluctuations in environmental conditions or variations in alignment between the induction coils.

It is a particular feature of embodiments of the current invention that the driver 230 (Fig. 1) is configured and operable to transmit a driving voltage which oscillates at a transmission frequency which is substantially different from the resonant frequency of the inductive couple. Preferably the transmission frequency is selected to lie within one of the near-linear regions 6, 8 where the slope of the frequency-amplitude graph is less steep.

REDUCED SENSITIVITY TO FLUCTUATIONS

One advantage of the present invention may be demonstrated with reference now to Fig. 3. A schematic diagram is shown representing a laptop computer 1340 drawing power from an inductive power outlet 1200 via a secondary power receiving unit 1300. The power receiving unit 1300 includes a secondary inductive coil 1320

which is aligned to a primary inductive coil 1220 in the inductive power outlet 1200. Any lateral displacement of the secondary power receiving unit 1300 changes the alignment between the secondary inductive coil 1320 to the primary inductive coil 1220. As a result of the changing alignment, the combined inductance of the coil pair
5 changes which in turn changes the resonant frequency of the system.

If the inductive power outlet 1200 transmits power at the resonant frequency of the system, even a small lateral movement would reduce significantly the amplitude of the induced voltage. In contradistinction, according to embodiments of the present invention, the inductive power outlet 1200 transmits power at a frequency
10 in one of the regions 6, 8 to either side of the resonance peak 2 (Fig. 2) where the slope of the resonance graph is much shallower. Consequently, the system has a much larger tolerance of variations such as lateral movement.

FREQUENCY CONTROLLED POWER REGULATION

15 In known inductive power transfer systems, power is typically regulated by altering the duty cycle of the transmission voltage provided by the driver. It will be appreciated that when the transmission frequency is not equal to the resonance frequency of the system, the driver 230 may be configured to adjust the transmission frequency in order to regulate the power transfer.

20 Referring back to Fig. 2, the frequency of transmission is selected to be in the approximately linear region 8 of the curve between a lower frequency value of f_L and an upper frequency value of f_U . A transmission frequency f_t , higher than the resonant frequency f_R of the system, produces an induced voltage of V_t . The induced voltage can be increased by reducing the transmission frequency and can be reduced by
25 increasing the transmission frequency. For example, an increase in transmission frequency of δf produces a decrease in induced voltage of δV .

In some embodiments, a communication channel 120 (Fig. 1) is provided between the secondary unit 300 and the inductive power outlet 200. Such a communication channel 120, may be used to communicate required operating
30 parameters which, for example, may indicate the transmission frequency required by the electric load 340 to the driver 230.

Various transmitters 122 and receivers 124 may be used with the communication channel 120. Where, as is often the case for inductive systems, the

primary and secondary coils 220, 320 are galvanically isolated for example, optocouplers may have a light emitting diode serving as a transmitter which sends encoded optical signals over short distances to a photo-transistor which serves as a receiver. Optocouplers typically need to be aligned such that there is a line-of-sight
5 between transmitter and receiver. In systems where alignment between the transmitter and receiver may be difficult to achieve, optocoupling may be inappropriate and alternative systems may be preferred such as ultrasonic signals transmitted by piezoelectric elements or radio signals such as Bluetooth, WiFi and the like. Alternatively the primary and secondary coils 220, 320 may themselves serve as the
10 transmitter 122 and receiver 124.

In certain embodiments, an optical transmitter, such as a light emitting diode (LED) for example, is incorporated within the secondary unit 300 and is configured and operable to transmit electromagnetic radiation of a type and intensity capable of penetrating the casings of both the secondary unit 300, and the power outlet 200. An
15 optical receiver, such as a photodiode, a phototransistor, a light dependent resistors of the like, is incorporated within the power outlet 200 for receiving the electromagnetic radiation.

It is noted that many materials are partially translucent to infra-red light. It has been found that relatively low intensity infra-red signals from LEDs and the like, penetrate several hundred microns of common materials such as plastic, cardboard, Formica or paper sheet, to a sufficient degree that an optical receiver, such as a photodiode, a phototransistor, a light dependent resistors or the like, behind a sheet of from 0.1 mm to 2 mm of such materials, can receive and process the signal. For example a signal from an Avago HSDL-4420 LED transmitting at 850nm over 24
20 degrees, may be detected by an Everlight PD15-22C-TR8 NPN photodiode, from behind a 0.8 mm Formica sheet. For signalling purposes, a high degree of attenuation may be tolerated, and penetration of only a small fraction, say 0.1% of the transmitted signal intensity may be sufficient. Thus an infra-red signal may be used to provide a communication channel between primary and secondary units galvanically isolated
25 from each other by a few hundred microns of wood, plastic, Formica, wood veneer, glass or the like.
30

The communication channel 120 may further provide a feedback signal during power transmission. The feedback transmission may communicate required or monitored operating parameters of the electric load 240 such as:

- 5 ▪ required operating voltage, current, temperature or power for the electric load 240,
- the measured voltage, current, temperature or power supplied to the electric load 240 during operation,
- the measured voltage, current, temperature or power received by the electric load 240 during operation and the like.

10 In some embodiments, a microcontroller in the driver 230 may use such feedback parameters to calculate the required transmission frequency and to adjust the driver accordingly. Alternatively, simple feedback signals may be provided indicating whether more or less power is required.

15 One example of a power regulation method using simple feedback signals is shown in the flowchart of Fig. 4. The method involves the following steps:

- (a) The driver 230 provides an oscillating voltage at a transmission frequency f_i which is higher than the resonant frequency f_R of the system.
- (b) A secondary voltage is induced in the secondary coil 320.
- (c) A power monitor in the secondary unit 300, monitors the power received
20 by the electric load 340.
- (d) If the power received by the electric load 340 lies within a predetermined range then no action is taken. If the power received by the electric load 340 is below the predetermined range, then a feedback signal of a first type S_a is sent to the driver. If the power received by the electric load 340 is above
25 the predetermined range, then a feedback signal of a second type S_b is sent to the driver.
- (e) a feedback signal is received by the driver 230.
- (f) If the received feedback signal is of the first type S_a , then the transmission frequency is increased by an incremental value $+\delta f_1$. If the received
30 feedback signal is of the second type S_b , then the transmission frequency is decreased by an incremental value $-\delta f_2$.

It is noted that by using the power regulation method described above, when the power received by the load is too high, a series of feedback signals of the first type

S_a will be transmitted until the power is reduced into the acceptable range. Likewise when the power received by the load is too low, a series of feedback signals of the second type S_b will be transmitted until the power is increased into the acceptable range. It is noted that the positive incremental value δf_1 may be greater than, less than
5 or equal to the negative incremental value δf_2 .

Alternatively, other power regulation methods using frequency adjustment may be used. For example, in alternative embodiments, the operating parameters of the electric load may be monitored and their values may be transmitted to the power outlet via the communications channel 120. A processor in the power outlet may then
10 calculate the required transmission frequency directly.

In the method described hereabove, the non-resonant transmission frequency lies within the linear region 8 (Fig. 2), higher than the resonant peak 2. It will be appreciated however that in alternative embodiments frequency controlled power regulation may be achieved when the transmission frequency lies in either the lower
15 linear region 6 of the resonance curve. Nevertheless, as explained below, for certain embodiments, the selection of transmission frequencies in the higher linear region 8 may be preferred.

VOLTAGE PEAK DETECTION

20 As described above, the resonant frequency f_R of an inductive couple is given by the formula $f_R = \frac{1}{2\pi\sqrt{LC}}$, where L is the inductance of the system and C is the capacitance of the system. Any decrease in either the inductance L or the capacitance C of the system thereby increases its resonant frequency.

In inductive power outlets transmitting at frequencies above the normal
25 resonant frequency of the system, an increase in resonant frequency of the system causes a large increase in the transmission voltage. In preferred embodiments, a peak detector 140 (Fig. 1) is be provided to monitor the transmission voltage of the power outlet 200 and is configured to detect large increases in the transmission voltage indicating an increase in resonant frequency. Such increases in transmission voltage
30 may be indicative of power drains, short circuits, removal of the secondary unit or the like.

As an example of the use of a peak detector reference is again made to Fig. 3. It will be appreciated that in a desktop environment, conductive bodies such as a paper clip, metal rule, the metal casing a stapler, a hole-punch or any metallic objects may be introduced between the the inductive power outlet 1200 and the secondary power receiving unit 1300. The oscillating magnetic field produced by the primary coil 1220 would then produce eddy currents in the conductive body heating it and thereby draining power from the primary coil 1220. Such a power drain may be wasteful and/or dangerous.

Power drains such as described above reduce the inductance L of the system. The inductance L may also be reduced by the removal of the secondary coil 1220, a short circuit or the like. A peak detector 140, wired to the inductive power outlet, would detect any of these scenarios as a large increase in transmission voltage. Preferably, the power transfer system may be further configured to shut down, issue a warning or otherwise protect the user and the system in the event that the peak detector 140 detects such an increase in transmission voltage.

Fig. 5 is a circuit diagram of an inductive power outlet 2200 and a secondary unit 2300. The secondary unit 2300 comprises a secondary coil 2320 wired to an electric load 2340 via a rectifier 2330.

The inductive power outlet 2200 comprises a primary coil 2220 driven by a half-bridge converter 2230 connected to a power source 2240. The half-bridge converter 2230 is configured to drive the primary coil 2220 at a frequency higher than the resonant frequency of the system and a peak detector 2140 is configured to detect increases in the transmission voltage.

Although only a half-bridge converter is represented in Fig. 6, it is noted that other possible driving circuits include: a DC-to-DC converter, an AC-to-DC converter, an AC-to-AC converter, a flyback transformer, a full-bridge converter, a flyback converter or a forward converter for example.

Thus, by using a transmission voltage oscillating at a frequency different from the resonant frequency of the system, the inductive transfer system has a higher tolerance to environmental fluctuations and variations in inductive coil alignment than other transfer systems and the frequency may be used to regulate power transfer. Moreover, when the transmission frequency is higher than the resonant frequency of the system, a peak detector may be used to indicate hazards.

The scope of the present invention is defined by the appended claims and includes both combinations and sub combinations of the various features described hereinabove as well as variations and modifications thereof, which would occur to persons skilled in the art upon reading the foregoing description.

- 5 In the claims, the word “comprise”, and variations thereof such as “comprises”, “comprising” and the like indicate that the components listed are included, but not generally to the exclusion of other components.

Claims

2. An inductive power transfer system comprising at least one primary inductive coil wired to a power supply via a driver; said primary inductive coil for forming an inductive couple with at least one secondary inductive coil wired to an electric load, wherein said driver is configured to provide a driving voltage across said primary inductive coil, said driving voltage oscillating at a transmission frequency significantly different from the resonant frequency of said inductive couple.
3. The system of claim 1 wherein said driver comprises a switching unit for intermittently connecting said primary inductive coil to said power supply.
4. The system of claim 1 wherein said transmission frequency lies within a range in which induced voltage varies approximately linearly with frequency.
5. The system of claim 1 wherein said electric load comprises a rectifying unit.
6. The system of claim 1 said driver additionally comprising a receiver for receiving feedback signals from said electric load.
7. The system of claim 5 said driver being configured to adjust said transmission frequency in response to said feedback signals.
8. The system of claim 5 in which said receiver is adapted to receive a first signal and a second signal, and said driver is configured to:
 - a. increase said transmission frequency when said first signal is received by the receiver, and
 - b. decrease said transmission frequency when said second signal is received by the receiver.
9. The system of claim 5 wherein said feedback signals carry data pertaining to the operational parameters of said electric load.
10. The system of claim 8 wherein said operational parameters are selected from the group comprising:
 - a. required operating voltage for said electric load;
 - b. required operating current for said electric load;
 - c. required operating temperature for said electric load;

- d. required operating power for said electric load;
 - e. measured operating voltage for said electric load;
 - f. measured operating current for said electric load;
 - g. measured operating temperature for said electric load;
 - 5 h. measured operating power for said electric load;
 - i. power delivered to said primary inductive coil;
 - j. power received by said secondary inductive coil, and
 - k. a user identification code.
11. The system of claim 5 wherein said receiver is selected from the list comprising
10 optical detectors, radio receivers, audio detectors and voltage peak detectors.
12. The system of claim 1 wherein said driver further comprises voltage monitor for monitoring the amplitude of a primary voltage across said primary coil.
13. The system of claim 11 wherein said voltage monitor is configured to detect significant increases in primary voltage.
- 15 14. The system of claim 1 comprising a power converter selected from the group comprising: a transformer, a DC-to-DC converter, an AC-to-DC converter, an AC-to-AC converter, a flyback transformer, a flyback converter, a full-bridge converter, a half-bridge converter and a forward converter.
- 20 15. A method for regulating power transmission inductive from a primary inductive coil, wired to a power supply via a driver, to a secondary inductive coil, wired to an electric load, said method comprising the following steps:
- a. providing an oscillating voltage to said primary inductive coil at an initial transmission frequency f_i which is substantially different from the resonant frequency f_R of the system;
 - 25 b. inducing a secondary voltage in said secondary inductive coil;
 - c. monitoring power received by said electric load;
 - d. sending a feedback signal when the monitored power deviates from a predetermined range;
 - e. said driver receiving said feedback signal;

- f. said driver adjusting said transmission frequency; and
- g. repeating steps b-f.

16. The method of claim 14 wherein step d further comprises:

- i. sending a feedback signal of a first type S_a to said driver, whenever
5 said power drops below a predetermined lower threshold, and
- ii. sending a feedback signal of a second type S_b to said driver,
whenever said power exceeds a predetermined upper threshold.

17. The method of claim 15 wherein said initial transmission frequency f_i is higher
than the resonant frequency f_R

10 18. The method of claim 16 wherein step f further comprises:

- i. said driver reducing said transmission frequency by an incremental
value $-\delta f_1$ when the received feedback signal is of the first type S_a ,
and
- 15 ii. said driver increasing said transmission frequency by an
incremental value $+\delta f_2$ when the received feedback signal is of the
second type S_b .

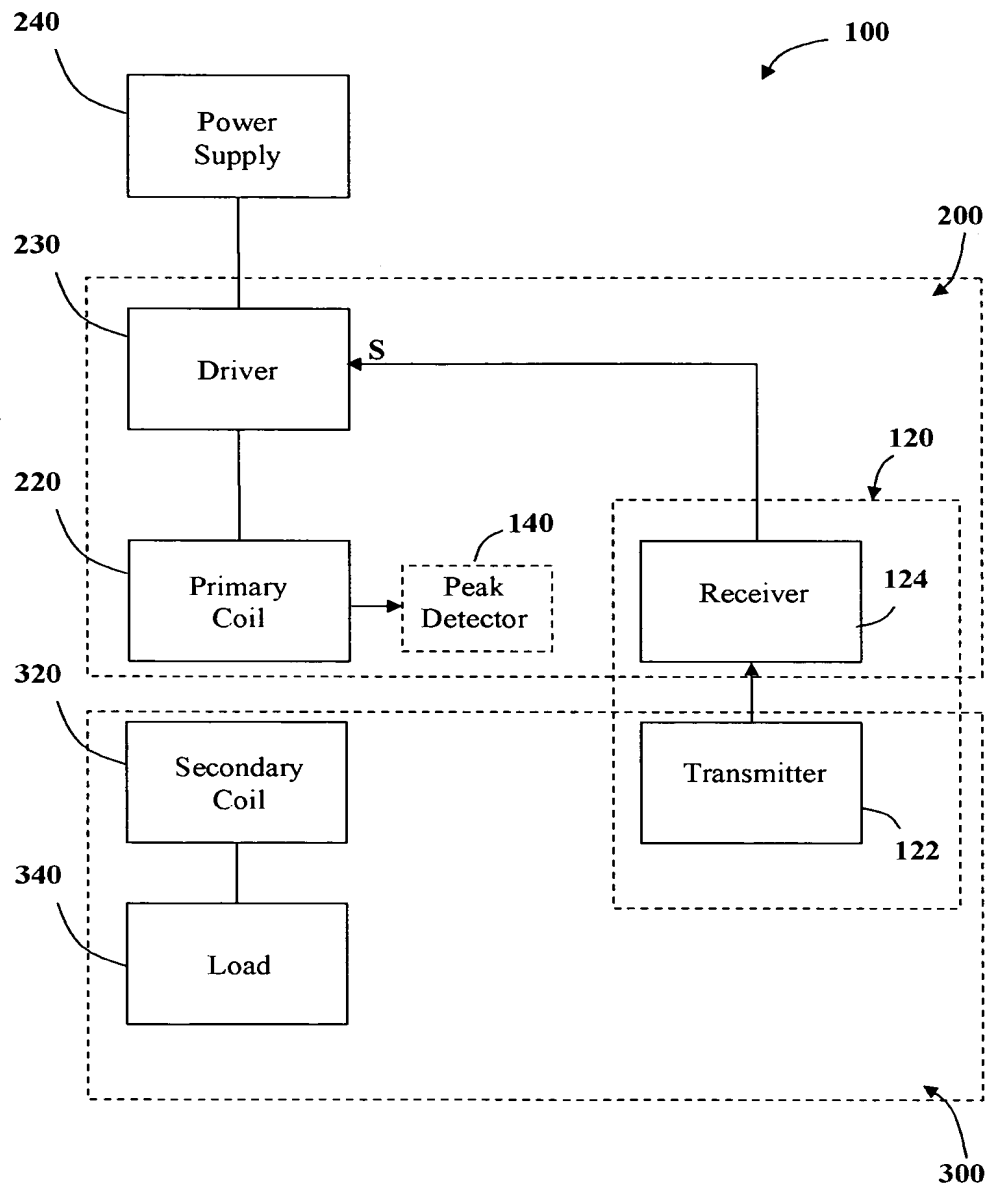


Fig. 1

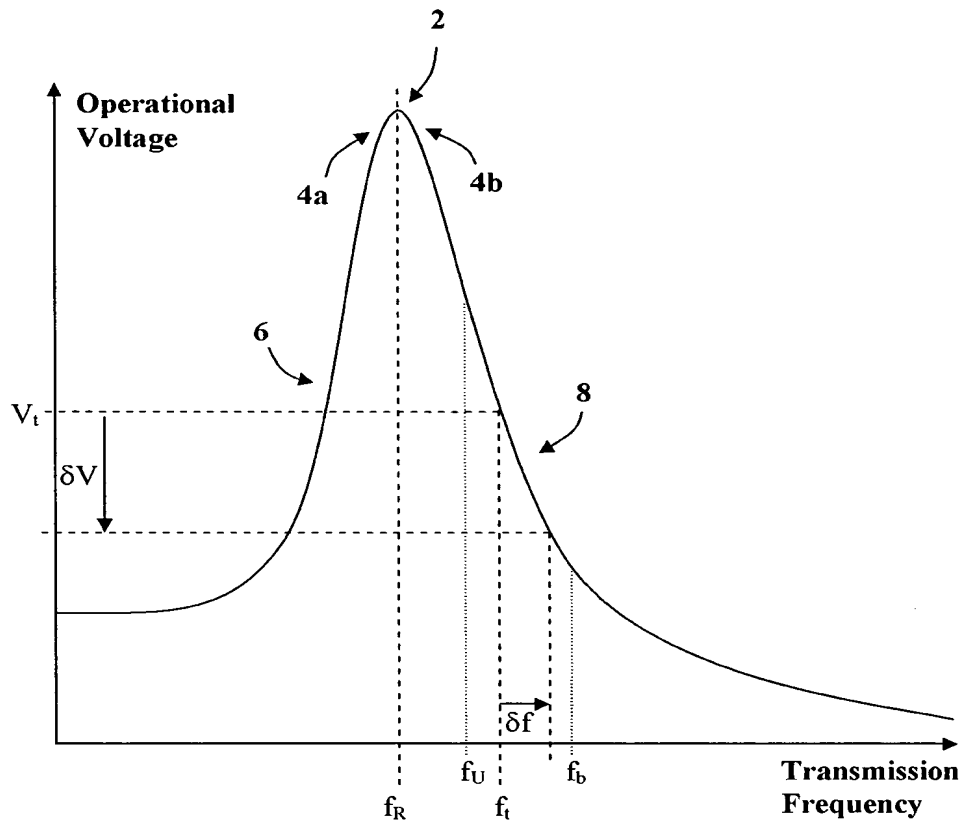


Fig. 2

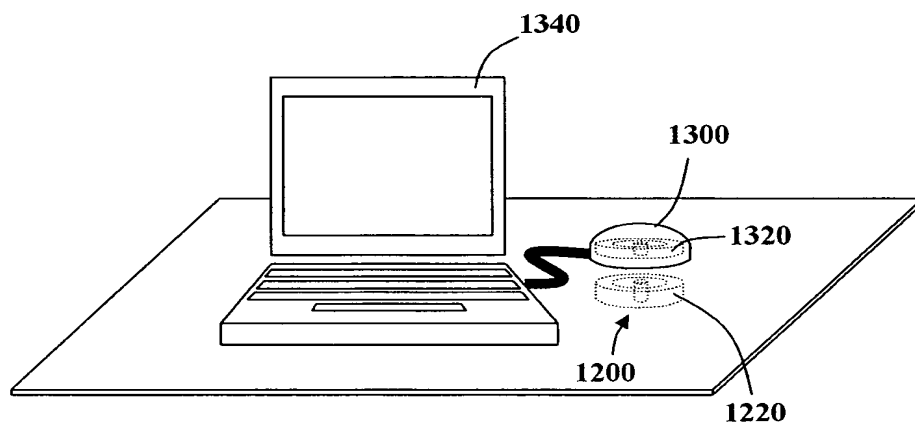


Fig. 3

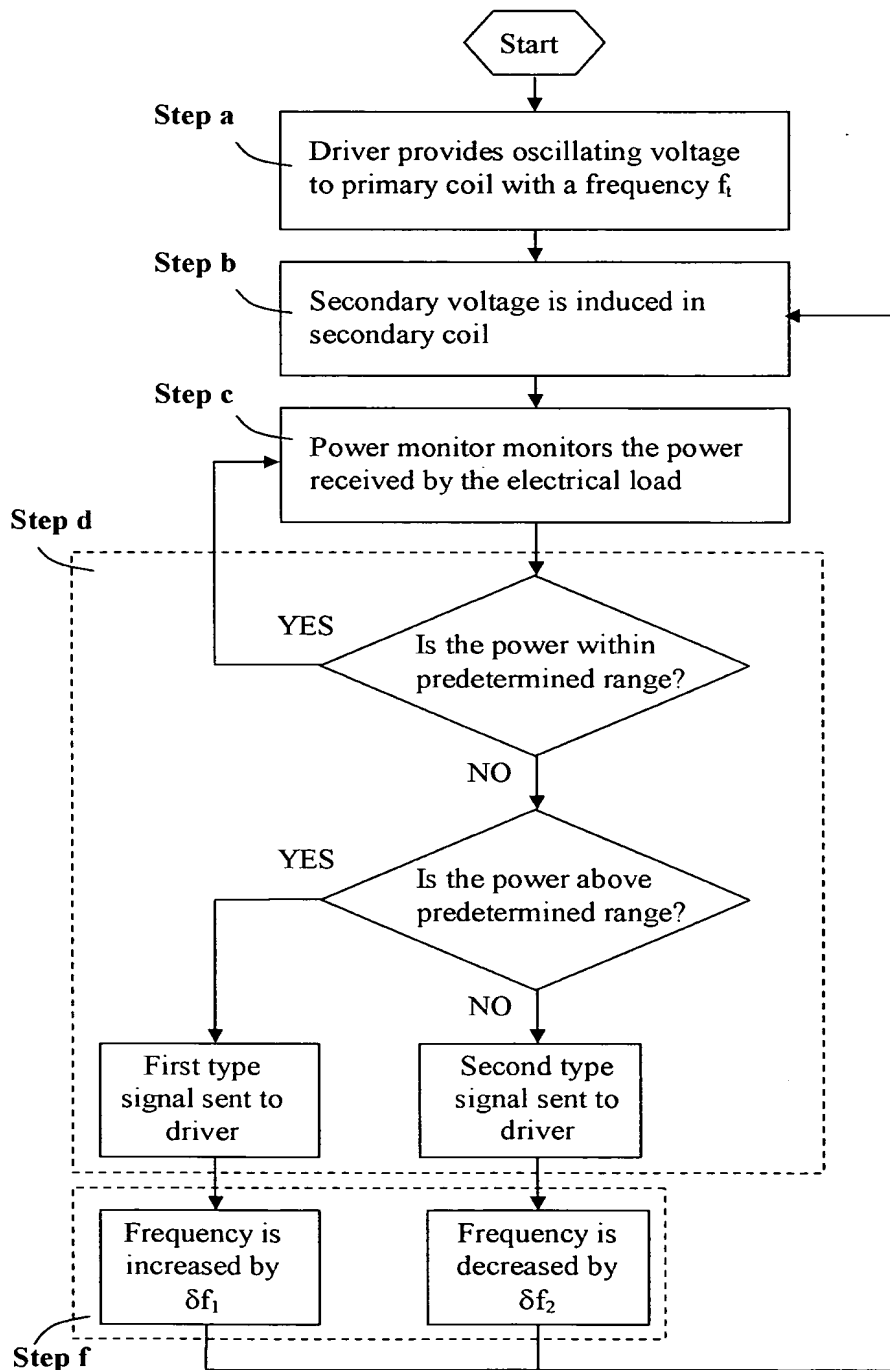


Fig. 4

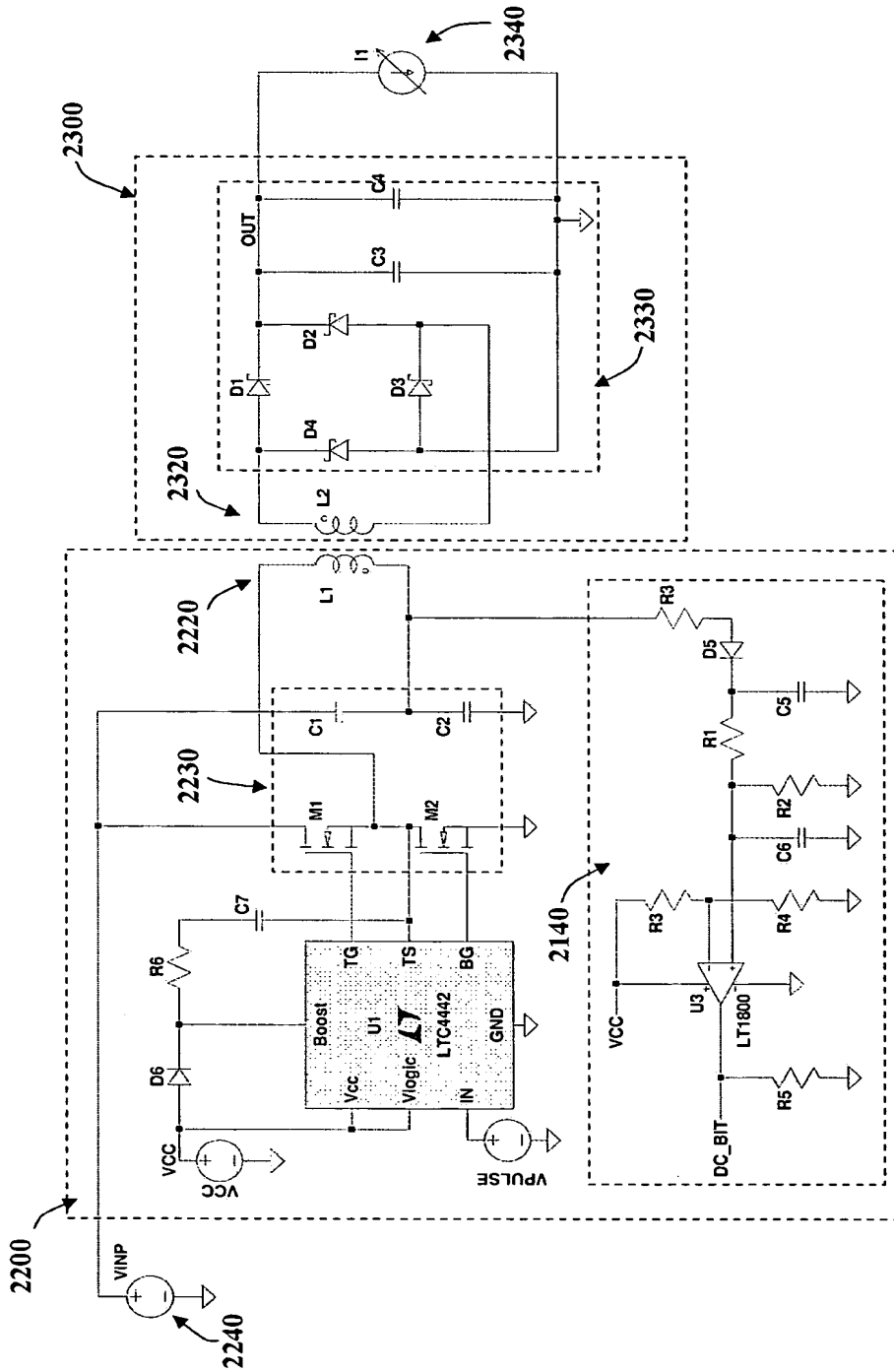


Fig. 5

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