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Ross

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[54] **ROADWAY-POWERED ELECTRIC VEHICLE SYSTEM**

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[51] **Int. Cl.**[6] **B60L 9/00**

[52] **U.S. Cl.** **191/10**; 320/2; 307/10.1

[58] **Field of Search** ..... 191/2, 3, 4, 5, 191/6, 7, 10; 180/165, 2.1; 320/2; 307/9.1, 10.1; 246/187 R, 187 A, 187 B, 187 C

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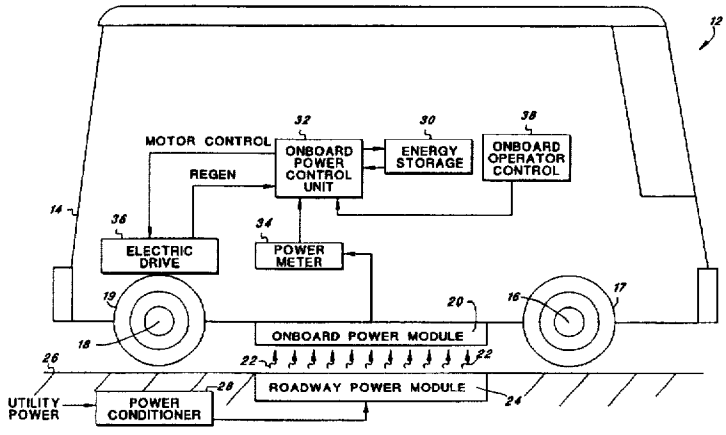
[57] **ABSTRACT**

A roadway-powered electric vehicle system includes: (1) an all-electric vehicle; and (2) a roadway network over which the vehicle travels. The all-electric vehicle has one or more onboard energy storage elements or devices that can be rapidly charged or energized with energy obtained from an electrical current, such as a network of electromechanical batteries. The electric vehicle further includes an on-board controller that extracts energy from the energy storage elements, as needed, and converts such extracted energy to electrical energy used to propel the electric vehicle. The energy storage elements may be charged while the vehicle is in operation. The charging occurs through a network of power coupling elements, e.g., coils, embedded in the roadway. As the vehicle passes over such power coupling elements as it is driven on the roadway network, electrical current is inductively coupled to corresponding onboard power coupling elements, e.g., coils, and used to charge the onboard energy storage devices. The roadway network need only be energized with the power coupling elements at strategic locations. The roadway network may comprise existing roadways and highways that have been modified to include the embedded power coupling elements, e.g., coils.

26 Claims, 10 Drawing Sheets



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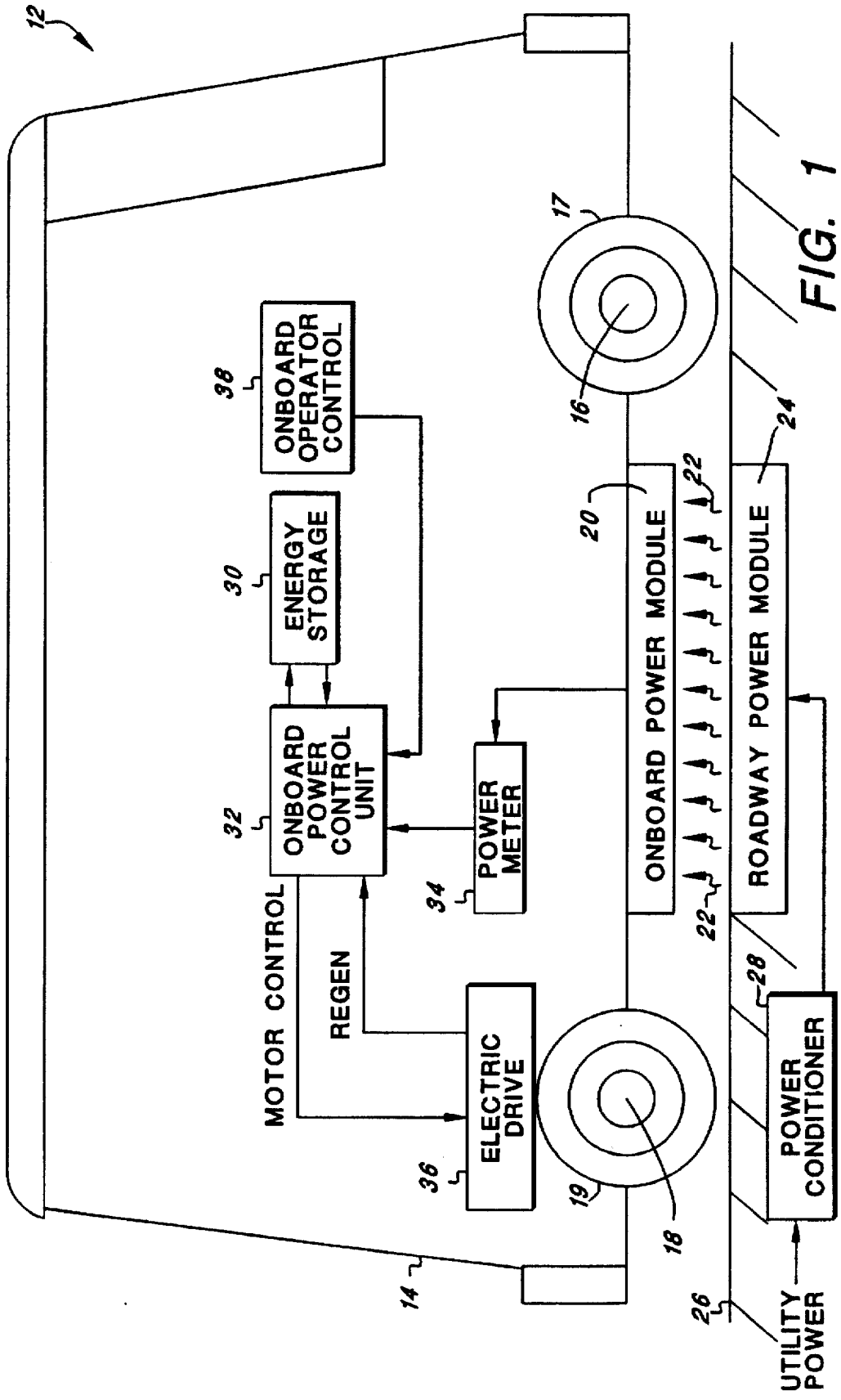
12
17
16
24
38
ONBOARD OPERATOR CONTROL
30
ENERGY STORAGE
20
22
ONBOARD POWER MODULE
ROADWAY POWER MODULE
32
ONBOARD POWER CONTROL UNIT
POWER METER
34
22
28
MOTOR CONTROL
REGEN
ELECTRIC DRIVE
36
19
18
POWER CONDITIONER
14
26
UTILITY POWER

FIG. 1

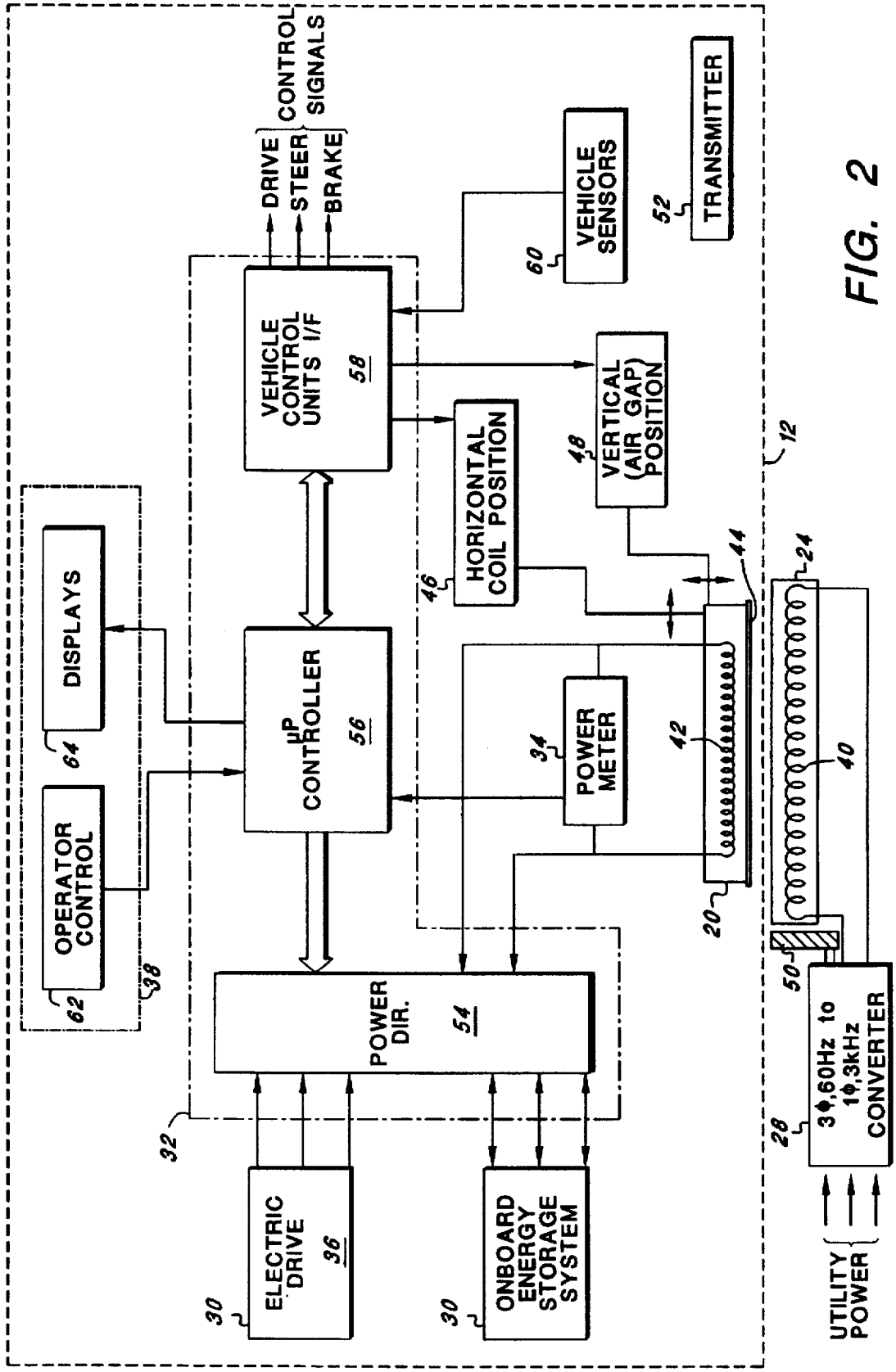
CONTROL SIGNALS
DRIVE
STEER
BRAKE
VEHICLE CONTROL UNITS I/F 58
VEHICLE SENSORS 60
TRANSMITTER 52
VERTICAL (AIR GAP) POSITION 48
HORIZONTAL COIL POSITION 46
12
DISPLAYS 64
OPERATOR CONTROL 62
38
μP CONTROLLER 56
POWER METER 34
42
44
24
40
20
50
POWER DIR. 54
32
3φ,60Hz to 1φ,3kHz CONVERTER 28
ELECTRIC DRIVE 36
30
ONBOARD ENERGY STORAGE SYSTEM
30
UTILITY POWER

FIG. 2

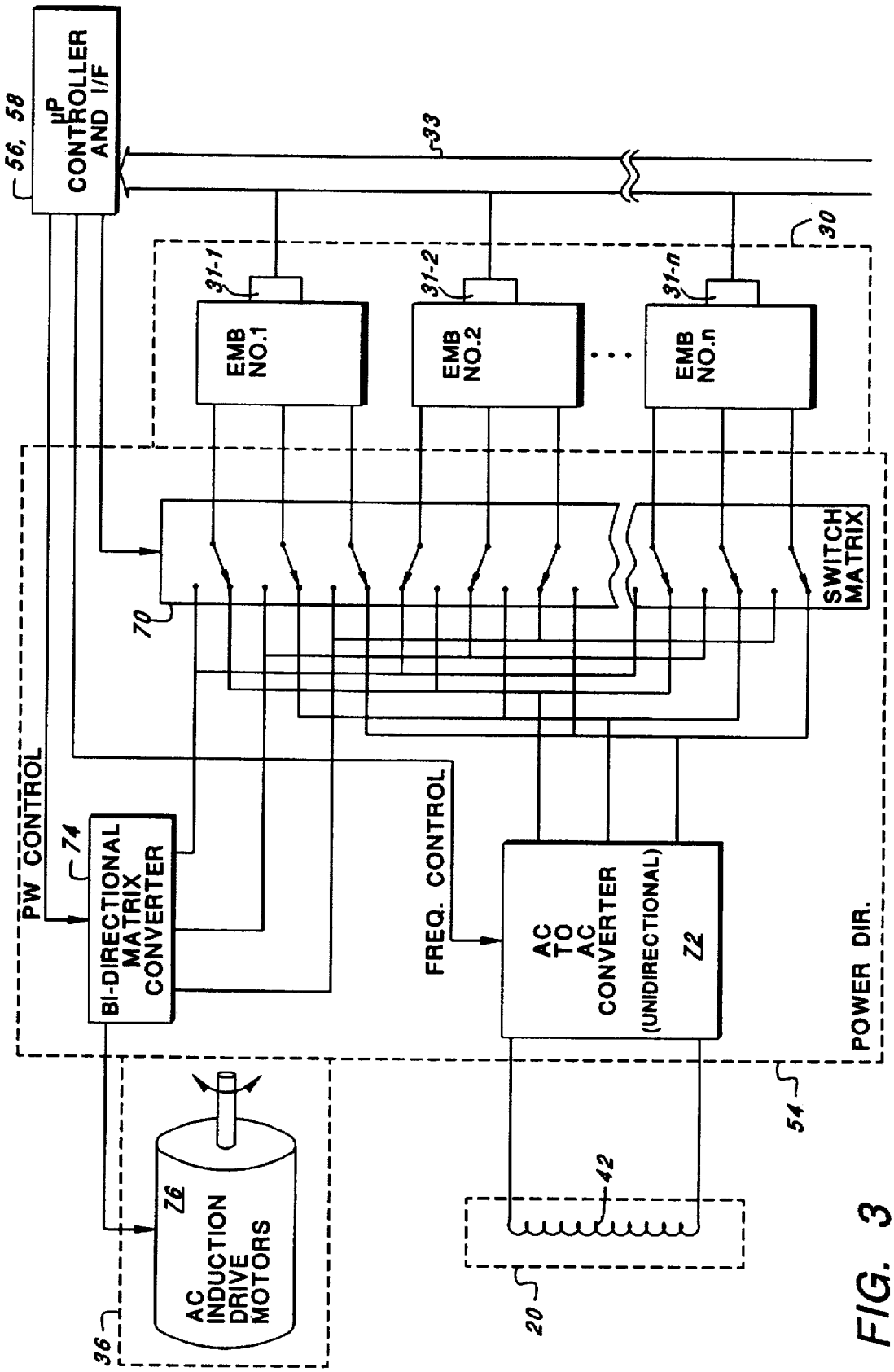
μP CONTROLLER AND I/F
56, 58
33
30
31-1
31-2
31-n
EMB NO.1
EMB NO.2
EMB NO.n
SWITCH MATRIX
70
PW CONTROL
74
BI-DIRECTIONAL MATRIX CONVERTER
FREQ. CONTROL
AC TO AC CONVERTER (UNIDIRECTIONAL)
Z2
POWER DIR.
54
Z6
AC INDUCTION DRIVE MOTORS
36
42
20

FIG. 3

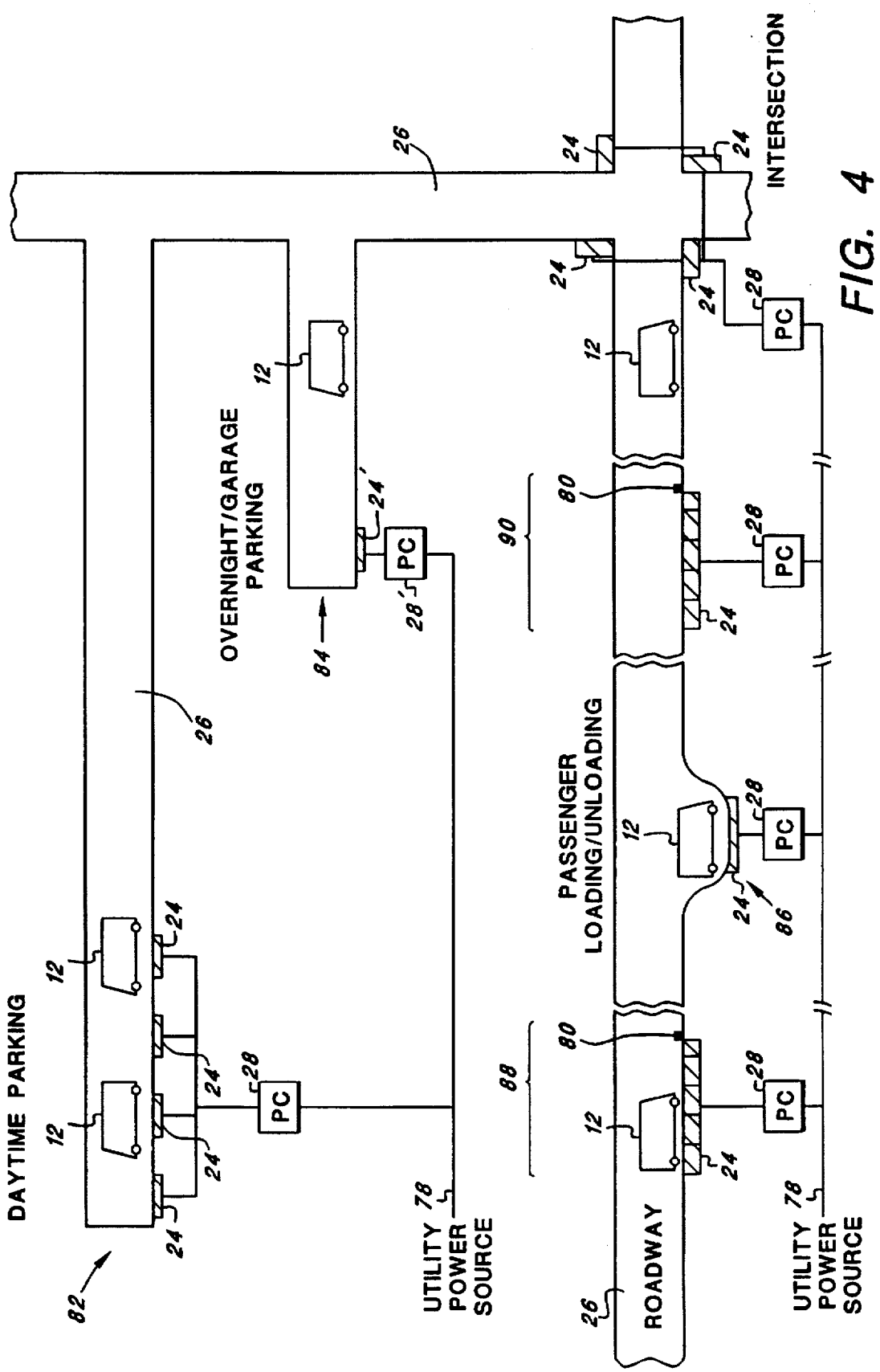
DAYTIME PARKING
OVERNIGHT/GARAGE PARKING
PASSENGER LOADING/UNLOADING
INTERSECTION
ROADWAY
UTILITY POWER SOURCE
UTILITY POWER SOURCE
PC
12
24
24'
26
28
28'
80
82
84
86
88
90

FIG. 4

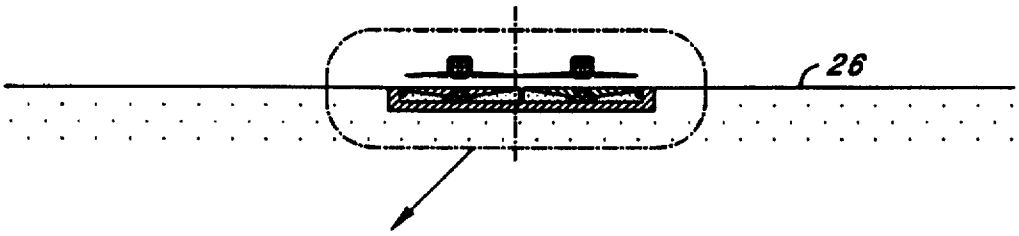

FIG. 5A

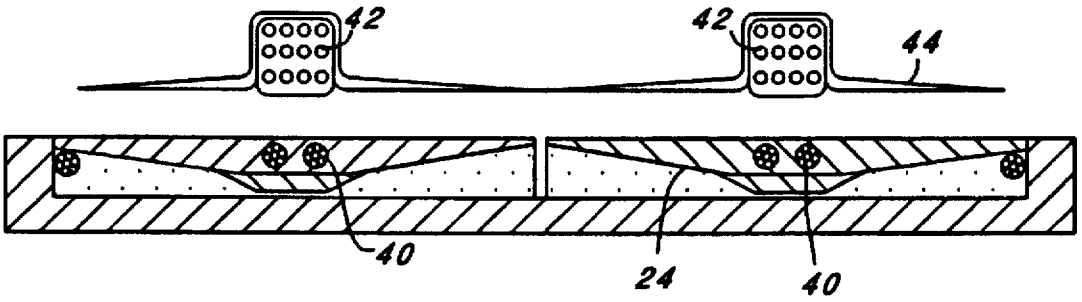

FIG. 5B

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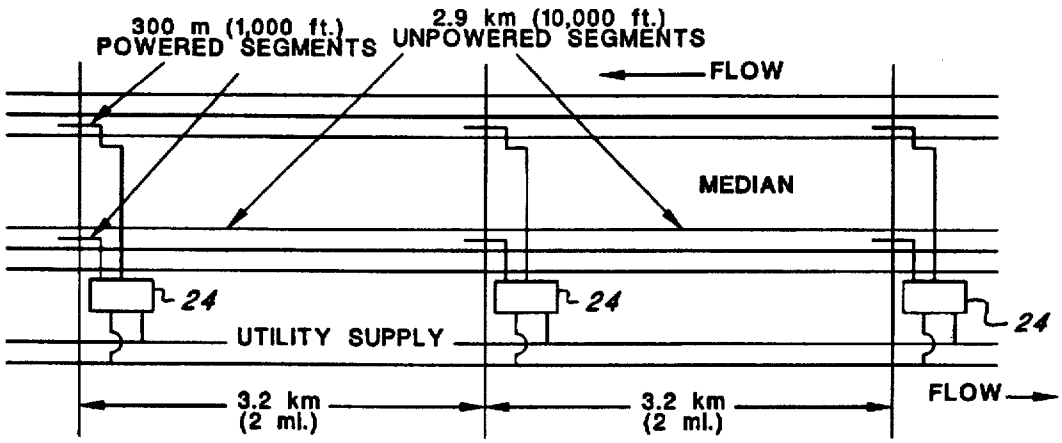

300 m (1,000 ft.)
POWERED SEGMENTS
2.9 km (10,000 ft.)
UNPOWERED SEGMENTS
FLOW
MEDIAN
24
24
24
UTILITY SUPPLY
3.2 km
(2 mi.)
3.2 km
(2 mi.)
FLOW

FIG. 6A

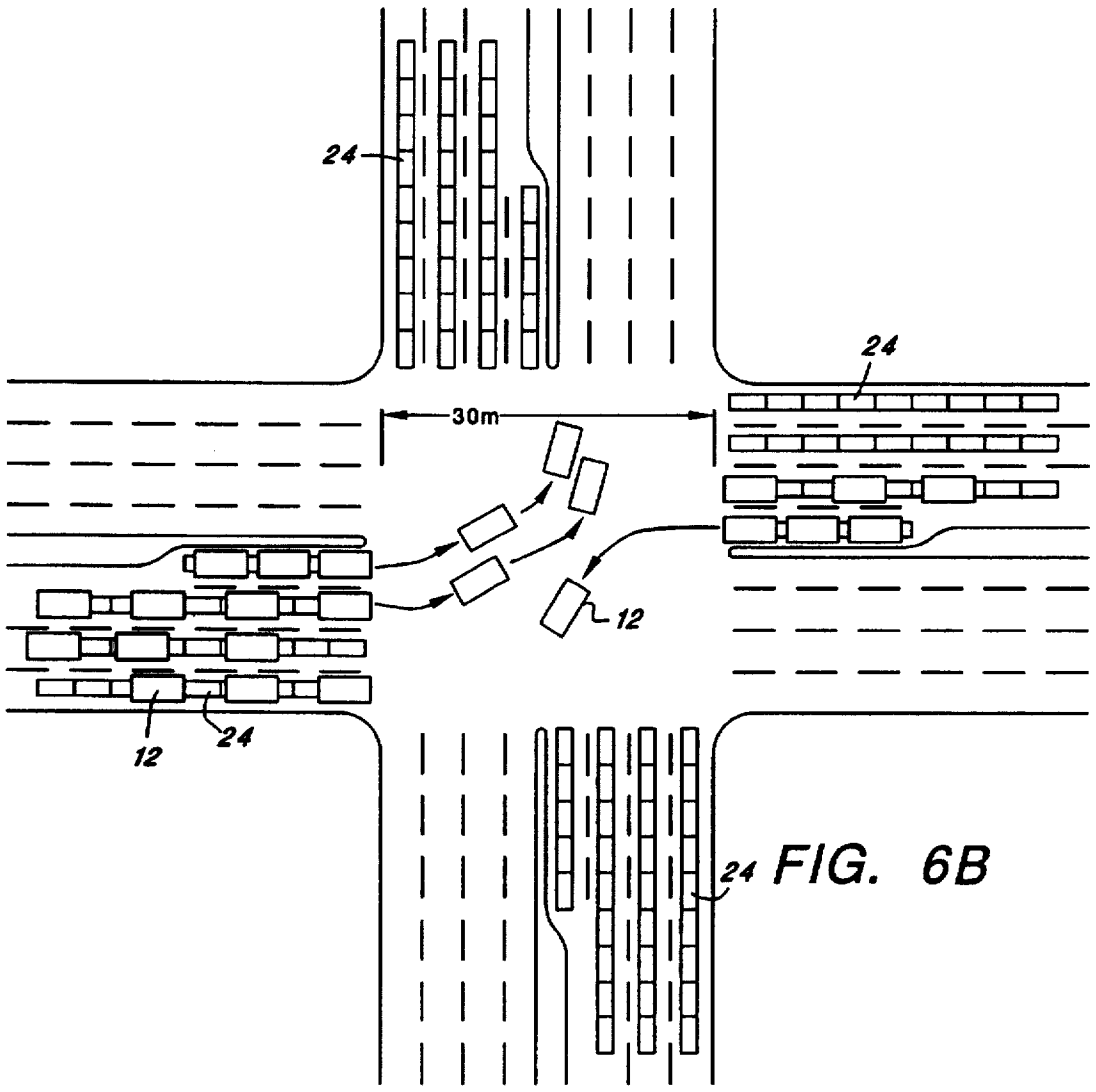
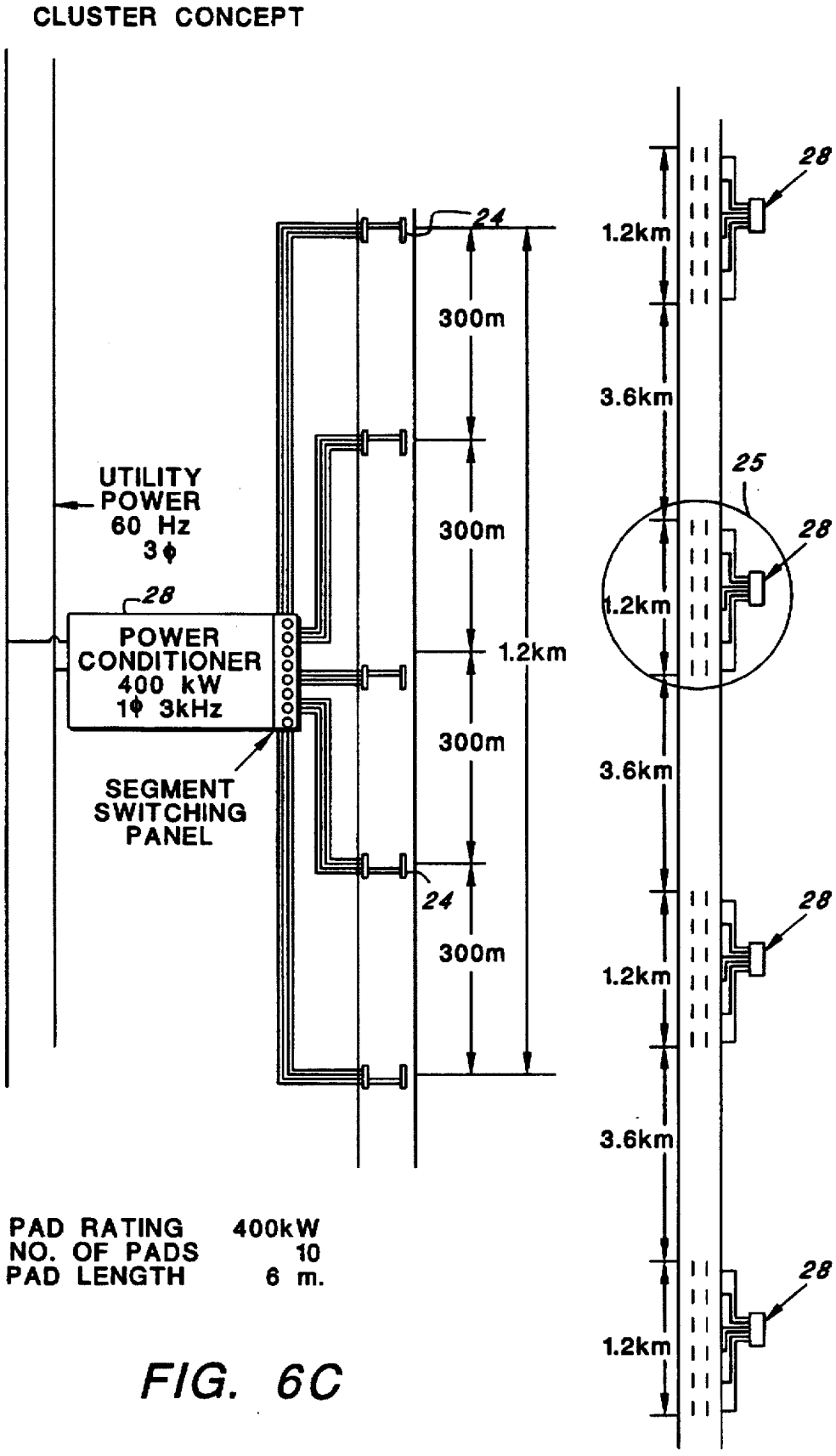
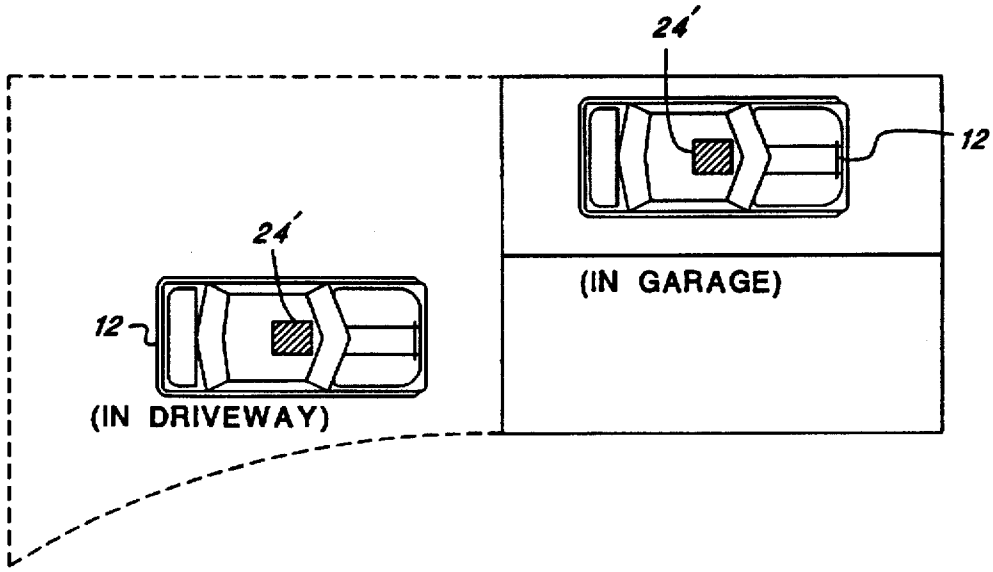

24
24
30m
12
12
24
24

FIG. 6B



PAD RATING	400kW
NO. OF PADS	10
PAD LENGTH	6 m.

FIG. 6C


24'
12
(IN GARAGE)
24'
12
(IN DRIVEWAY)

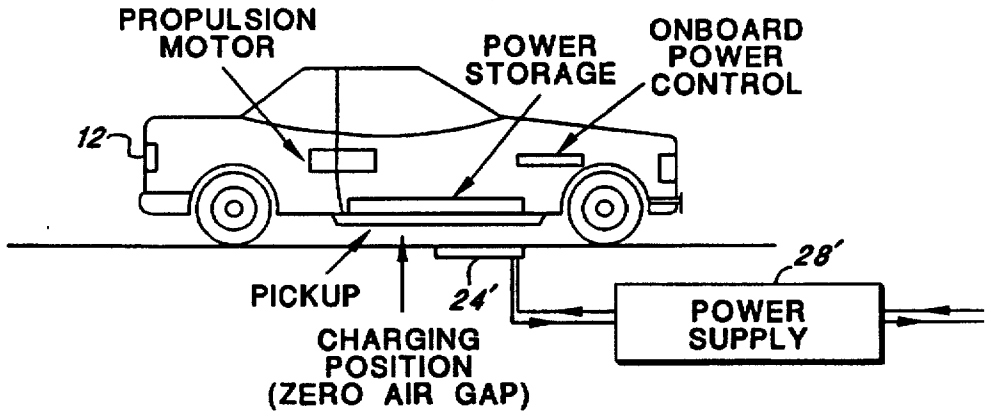

PROPULSION MOTOR
POWER STORAGE
ONBOARD POWER CONTROL
12
28'
PICKUP
24'
POWER SUPPLY
CHARGING POSITION (ZERO AIR GAP)

FIG. 7

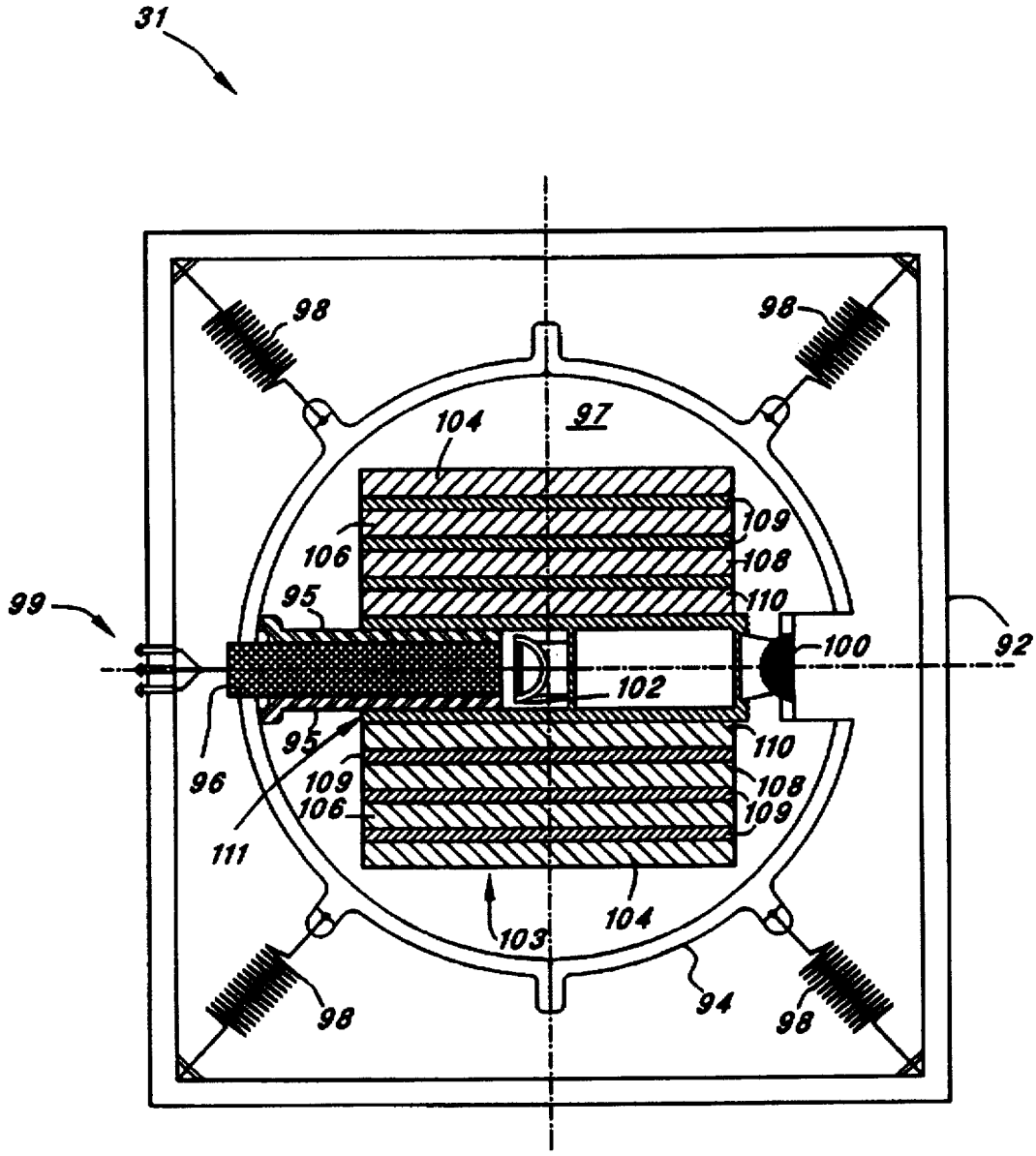

31
98
98
104
97
109
106
108
95
110
99
100
92
102
95
110
96
109
108
106
109
111
103
104
94
98
98

FIG. 8

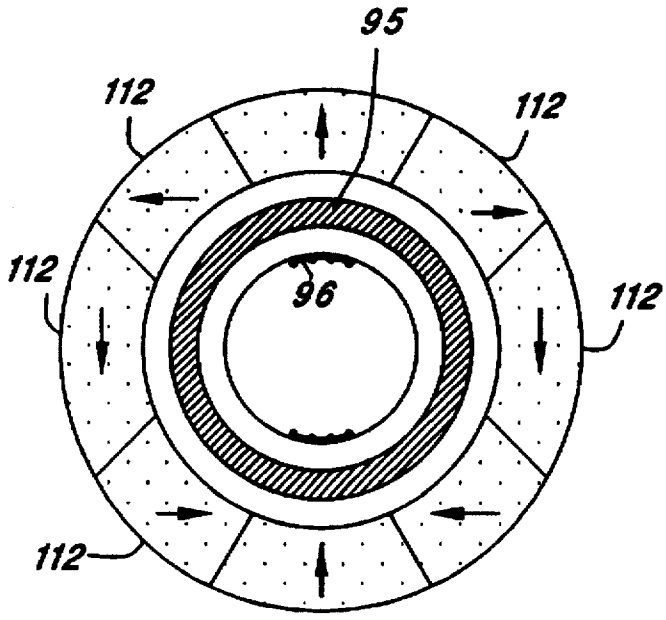


FIG. 9A

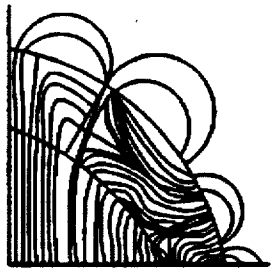


FIG. 9B

InductEV, Inc.
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ROADWAY-POWERED ELECTRIC VEHICLE SYSTEM

BACKGROUND OF THE INVENTION

The present invention relates to electric vehicles, and more particularly to an all-electric vehicle system that utilizes an electromechanical battery (EMB), or equivalent high specific power device, as its energy storage element, and that further receives operating power inductively through coils strategically embedded in the roadway over which the vehicle travels in order to recharge the EMB.

In recent years, there has been an increasing emphasis on the development of an all electric vehicle (EV). The goal, as mandated by many governmental jurisdictions, is to have a certain percentage of all vehicles be zero-emission vehicles. Advantageously, zero-emission vehicles do not directly emit any exhaust or other gases into the air, and thus do no pollute the atmosphere. In contrast, vehicles that rely upon an internal combustion engine (ICE), in whole or in part, for their power source are continually fouling the air with their exhaust emissions. Such fouling is readily seen by the visible "smog" that hangs over heavily populated urban areas. Zero-emission vehicles are thus viewed as one way to significantly improve the cleanliness of the atmosphere.

In the State of California, for example, the California Air Resources Board (CARB) has mandated that by 1998 two percent of the vehicles lighter than 1700 kg sold by each manufacturer in the state be zero-emission vehicles. This percentage must increase to five percent by the year 2001, and ten percent by the year 2003.

A zero-emission vehicle, given the known, viable technologies for vehicle propulsion, effectively means that such vehicles must be all electric, or EV's. Hence, if existing (and future) governmental mandates are to be met, there is an urgent need in the art for a viable EV that can operate efficiently and safely.

EV's are not new. They have existed in one form or another since the discovery of electrical batteries and electric motors. In general, EV's of the prior art are of one of two types: (1) those that—through rail or overhead wire—are in constant contact with an external source of electrical power (hereafter "externally-powered EV's"); or (2) those that store electrical energy in a battery and then replenish the stored energy when needed (hereafter "rechargeable battery-driven EV's").

Externally-powered EV's require their own power delivery system, e.g., electrified rails or electrified overhead wires, that forms an integral part of their own roadway or route network. Examples of externally powered EV's are subways, overhead trolley systems, and electric rails (trains). Such externally-powered EV systems are in widespread use today as public transportation systems in most large metropolitan areas. However, such systems typically require their own roadway, or right-of-way, system, as well as the need for a continuously electrified rail or overhead wire with which the EV remains in constant contact. These requirements make such systems extremely expensive to acquire, build and maintain. Moreover, such externally-powered EV systems are not able to provide the convenience and range of the ICE automobile (which effectively allows its operator to drive anywhere there is a reasonable road on which the ICE vehicle can travel). Hence, while externally-powered EV systems, such as subway, trolley, and electric rail systems, have provided (and will continue to provide) a viable public transportation system, there is still a need in the art for a zero-emission vehicle system that offers the flexibility and convenience of the ICE vehicle, and that is able to take advantage of the vast highway and roadway network already in existence used by ICE vehicles.

Rechargeable battery-driven EV's are characterized by having an electrical energy storage device onboard, e.g., one or more electrochemical batteries, from which electrical energy is withdrawn to provide the power to drive the vehicle. When the energy stored in the batteries is depleted, then the batteries are recharged with new energy. Electrochemical batteries offer the advantage o being easily charged (using an appropriate electrical charging circuit) and readily discharged when powering the vehicle (also using appropriate electrical circuity) without the need for complex mechanical drive trains and gearing systems. Unfortunately, however, such rechargeable battery-driven EV's have not yet proven to be economically viable nor practical. For most vehicle applications, such rechargeable battery-driven EV's have not been able to store sufficient electrical energy to provide the vehicle with adequate range before needing to be recharged, and/or to allow the vehicle to travel at safe highway speeds for a sufficiently long period of time. Disadvantageously, the energy density (the amount of energy that can be stored per unit volume) of currently-existing electrochemical batteries has been inadequate. That is, when sufficient electrical storage capacity is provided on board the vehicle to provide adequate range, the number of batteries required to provide such storage capacity is prohibitively large, both in volume and weight. Moreover, when the battery needs to be recharged, the time required to fully recharge the batteries usually takes hours, not "minutes" as most vehicle operators are accustomed to when they stop to refill their ICE vehicles with fuel. Further, most electrochemical batteries currently used in the art are not suited for numerous, repeated recharges. Hence, such batteries, after a nominal number of recharges, must be replaced with new batteries, thereby significantly adding to the expense of operating the rechargeable battery-driven EV. It is thus evident that what is needed is a rechargeable battery-driven EV that has sufficient energy storage capacity to drive the distances and speeds commonly achieved with ICE vehicles, as well as the ability to be rapidly recharged within a matter of minutes, not hours.

EV systems are known in the art that attempt to combine the best features of the externally-powered EV systems and the rechargeable battery-driven EV systems. For example, rather than use a battery as the energy storage element, it is known in the art to use a mechanical flywheel that is rapidly charged up to a fast speed at select locations along a designated route. See, e.g., U.S. Pat. No. 2,589,453 issued to Storsand, where there is illustrated an EV that includes a mechanical flywheel that is recharged via an electrical connection at a charging station.

Further, in U.S. Pat. No. 4,331,225, issued to Bolger, there is shown an EV that has an electrochemical battery as the preferred storage means, and that receives power from a roadway power supply via inductive coupling. An onboard power control system then provides the power to the storage means, and the storage means then supplies power as needed to an electric motor providing motive power for the vehicle. Bolger also indicates that the storage means could be a mechanical flywheel.

In U.S. Pat. No. 4,388,977, issued to Bader, an electric drive mechanism for vehicles is disclosed that uses a pair of electric motors as motive power for the vehicle. A mechanical flywheel is mechanically connected to the drive shaft of one of the electric motors. The vehicle receives power from an overhead power supply, e.g., trolley lines, and the motor

then spools up the flywheel. The flywheel is then used to supply power to the motor at locations where there is not an overhead power supply.

In U.S. Pat. No. 5,224,054, issued to Parry, there is shown a bus-type vehicle having a continuously variable gear mechanism that uses a flywheel as a power source. The flywheel is periodically charged by an overhead connection to an electrical supply. The flywheel is mechanically linked to the drive shaft of the vehicle.

In the above systems, a mechanical flywheel is used as the energy-storage element because it can be charged, i.e., spooled up, relatively quickly to a sufficiently fast speed. Disadvantageously, however, the use of such mechanical flywheel significantly complicates the drive system of the vehicle, and also significantly adds to the weight of the vehicle, thereby limiting its useful range between charges. Further, a mechanical flywheel operating at fast speeds may present a safety hazard. What is needed, therefore, is an EV that avoids the use of flywheels that are mechanically coupled to the vehicle's drive system. Further, what is needed is an EV that can receive electrical energy from an external source to rapidly recharge, within a matter of minutes, an onboard energy storage element. Moreover, what is needed is such an EV wherein the onboard energy storage element, once charged or recharged, stores sufficient energy to provide the motive force needed to safely drive the vehicle at conventional driving speeds and distances.

SUMMARY OF THE INVENTION

The present invention addresses the above and other needs by providing a roadway-powered electric vehicle system that includes: (1) an all-electric vehicle; and (2) a roadway network over which the vehicle travels. The all-electric vehicle includes one or more onboard energy storage elements or devices that can be rapidly charged or energized with energy obtained from an electrical current. The vehicle further includes an onboard controller that extracts energy from the energy storage elements, as needed, and converts such extracted energy to electrical energy used to propel the electric vehicle. Advantageously, the energy storage elements of the vehicle may be charged while the vehicle is in operation. Such charging occurs, e.g., through a network of power coupling elements embedded in the roadway. As the vehicle passes over such power coupling elements, as it traverses the roadway network, electrical current is coupled to the electric vehicle, which electrical current is then used to charge the energy storage devices. Advantageously, such power coupling elements may be embedded at strategic locations in existing roadways and highways at a very modest cost.

In a preferred embodiment, the power coupling elements embedded in the roadway comprise a network of coils connected to a conventional primary power source, e.g., three-phase 50 or 60 Hz electrical power as is readily available from public utility power companies or cooperatives. Advantageously, such coils need not be distributed along the entire length of the roadway, but need only be located at selected locations along the length of the roadway., e.g., 10% or less of the roadway. An alternating electrical current (ac current) is inductively coupled from the coils embedded in the roadway to coils carried on the vehicle as the vehicle passes over the embedded coils. Such ac current, when received on the vehicle, is then used to charge or energize the storage elements carried by the vehicle.

A power meter, carried onboard the vehicle, monitors how much power is coupled to or used by the vehicle. Hence, the public utility (or other power company) that provides the primary power to the power coupling elements embedded in the roadway (or otherwise located to couple power to the vehicle) is able to charge the vehicle owner an appropriate amount for such power, thereby recouping the cost and expense and generating and delivering such electrical power.

In the preferred embodiment, the rapid charge energy storage elements or devices carried onboard the electric vehicle comprise an electromechanical battery (EMB), or a group or network of EMB modules. An EMB is a special type of energy-storage device having a rotor, mounted for rapid rotation on magnetic bearings in a vacuum-sealed housing. Because magnetic bearings are used, the shaft of the rotor does not physically contact any other components. Hence, there is no friction loss in the bearings. Because the rotor is housed in a sealed, evacuated, chamber, there are no loses due to windage. As a result, the rotor—made from high-strength graphite-fiber/epoxy composite—is able to rotate at extremely high speeds, e.g., 200,000 RPM. At such speeds, high amounts of energy can be stored in a very compact or small volume. Hence, the EMB represents a significant improvement in energy density relative to conventional electrochemical batteries.

In order to store energy in the EMB, and in order to extract energy therefrom, a special dipolar array of high-field permanent magnet material is mounted on the rotor. The resulting magnetic field from such array, extends outside of the sealed housing to cut through stationary, external coils, wound external to the housing. By applying an appropriate ac current to the external coils, the rotor is forced to spin. Because of the compactness and special design of the rotor, it is able to achieve high rotational speeds very rapidly (within minutes). Hence, the EMB may be charged to store a high amount of energy in a very short time, commensurate with the same time it takes to fill the gas tank of existing ICE vehicles.

Advantageously, the rapid charging of the EMB does not require any direct mechanical linkages with the rotor. Rather, the EMB is charged by simply applying an appropriate ac electrical signal to its terminals. Similarly, the EMB is discharged (energy is withdrawn therefrom) by simply using it as a generator, i.e., connecting its electrical terminals to a suitable load through which an electrical current may flow. Thus, the complexity of the charging components and the discharging components is greatly simplified, and the EMB appears, from an electrical point-of-view, as a "battery", having an electrical input and an electrical output.

In actuality, the input ac voltage applied to the terminals of the EMB spools up the rotor of the EMB to a rate proportional to the frequency of the applied ac voltage, just as if the EMB were an ac motor. The energy stored in the EMB is in the form of kinetic energy associated with the rapid rotation of the rotor. When extracting energy, the rapid rotating magnetic field, created by the rapid rotation of the magnetic array on the rotor, cuts through the stationary windings, inducing an ac voltage, just as though the EMB were an ac generator. Such induced voltage thus represents the extracted energy. The extracted voltage, in turn, is then used, as needed, to drive the electrical motors that propel the vehicle. Thus, the EMB functions as a motor/generator depending upon whether electrical energy is being applied thereto as an input (motor), or withdrawn therefrom as an output (generator). Unlike a conventional motor/generator, however, the extremely high rotational speeds of the EMB rotor allow great amounts of energy to be stored therein—sufficient energy to provide the motive force for the EV over substantial distances and at conventional speeds.

Hence, without any direct mechanical linkage, the EMB is electrically charged (i.e., its rotor is spun-up to rapid rotational velocities) using electrical current that is inductively coupled to the vehicle through the roadway over which the vehicle travels. Similarly, without any direct mechanical linkage, the EMB is electrically discharged (i.e., energy is withdrawn from the rapidly spinning rotor) by having the rotating magnetic field induce a voltage on the stationary windings, which induced voltage powers the electrical drive system of the vehicle.

Advantageously, an EMB may be manufactured as a standardized EMB module, and several EMB modules may then be connected in parallel, as required, in order to customize the available energy that can be stored for use by the EV to the particular application at hand. For example, a relatively small EV, equivalent in size and weight to a "sub-compact" or "compact" vehicle as is commonly used in the ICE art, may require only two to six EMB modules. A larger or more powerful EV, equivalent in size to a passenger van or high performance vehicle, may utilize 6 to 10 or more EMB modules. A still larger and more powerful EV, equivalent, e.g., to a large bus or truck, may utilize 12–20 or more EMB modules.

Standardizing the EMB module results in significant savings. EMB manufacturing costs, for example, are greatly reduced. Further, maintenance of the EV is greatly simplified, and the cost of replacing an EMB within the EV when such replacement is needed is low.

Additionally, a high operating efficiency is advantageously achieved when an EMB is used as the energy storage element. For example, in an EMB, the entire generator/motor assembly is ironless. Hence, there are low standby losses (no hysteresis effects). In combination with the frictionless magnetic bearings and windless evacuated chamber wherein the rotor spins, this means that the overall efficiency of EMB exceeds 90%, and may be as high as 95% or 96%. Such high efficiencies result in significantly reduced operating costs of the EV.

When inductive coupling is used to transfer power from the embedded roadway coupling elements (coils) to the EV, the preferred coupling frequency of the ac current is in the 1–10 KHz range (typically around 2–3 KHz). The use of such frequency, significantly higher than the conventional 60 Hz or 400 Hz ac signals that are commonly used in the prior art for power coupling purposes, advantageously optimizes the coupling efficiency of the power signal and operation of the EV system. Moreover, by using an ac signal within this frequency range (1–10 KHz), the magnitude or intensity of any stray magnetic fields that might otherwise penetrate into the vehicle or surrounding areas (as electrical current is inductively coupled into the vehicle) is significantly reduced. Having the magnetic fields that penetrate into the vehicle or surrounding areas be of low intensity is an important safety issue, at least from a public perception point-of-view, as there has been much debate in recent years concerning the possible harmful effects of over-exposure to magnetic field radiation. See, e.g., U.S. Pat. No. 5,068,543.

It is thus feature of the present invention to provide an efficient, viable, safe, roadway-powered all electric vehicle.

It is an additional feature of the invention to provide such an EV that uses, with only minor modification, the existing network of highways, roadways, and/or garaging/parking facilitates that are already in place to serve ICE vehicles.

It is yet another feature of the invention to provide an EV system herein the EV's of the system may be recharged while such EV's are in operation within the system. Hence, the EV's need not be taken out of service from the system in order to be recharged, as is common with prior art battery-storage type EV's.

It is an additional feature of the invention to provide an EV, or EV system, wherein the EV uses a high energy, efficient, electromechanical battery (EMB), or a group of EMB's, as an onboard energy storage element. The EMB, due to the use of magnetic bearings and enclosing the rotor in a sealed vacuum chamber, is able to run at extremely high speeds (e.g., exceeding 100K–200K RPM), and thereby provides a large amount of power in a relatively small space.

It is a further feature of the invention to provide an EV system that powers a fleet of electrically-powered buses, or other mass transit electric vehicles, using a demand responsive charging system or scheme. In accordance with such scheme, existing highways and roadways over which the EV's travel are electrified only at select locations, such as: (1) at designated "stops" of the vehicle, e.g., at designated passenger loading/unloading zones, parking garages, or the like; (2) at locations where the vehicle regularly passes, such as roadway intersections; and/or (3) along selected portions of the route,. e.g., 50–100 meters of every kilometer over which the vehicle travels.

It is still another feature of the invention to provide an EV system that uses inductive coupling to couple electrical power between embedded coils in the roadway and coils carried onboard the EV. Such coupled electrical power is stored onboard the EV and is thereafter used to provide the motive force of the EV. In accordance with a related feature of the invention, onboard systems and methods are provided that laterally and vertically position the relative spacing and alignment between the onboard coil and the coils selectively embedded in the roadway in order to minimize the air gap between the coils and maximize the alignment between the coils, thereby making the power transfer from the roadway to the vehicle more efficient. Moreover, using such onboard systems and methods, when the EV is stopped, the air gap may advantageously be minimized to zero.

It is an additional feature of the invention to provide an EV that utilizes an on-board control module to perform and coordinate the functions of: (i) receiving the inductive power from the embedded coils in the roadway, (ii) storing the received power as energy in the onboard storage elements, e.g., EMB's, and (iii) selectively extracting the stored energy to power the vehicle.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other aspects, features and advantages of the present invention will be more apparent from the following more particular description thereof, presented in conjunction with the following drawings wherein:

FIG. **1** is a block diagram of a roadway-powered electric vehicle made in accordance with the present invention;

FIG. **2** is a more detailed block diagram of the roadway-powered EV of the present invention;

FIG. **3** is a block diagram of the on-board power director of FIG. **2**, and illustrates how the on-board energy storage system of FIG. **2** is preferably realized using a plurality of electromechanical battery (EMB) modules;

FIG. **4** schematically illustrates a roadway-powered EV system made in accordance with the present invention;

FIGS. **5A** and **5B** respectively show a cross section, and an enlarged cross section, of a roadway having a coil embedded therein that serves as the roadway power module of the roadway-powered EV system;

FIG. 6A depicts one manner in which only a portion of the roadways over which the roadway-powered EV travels need be energized with roadway power modules;

FIG. 6B depicts the electrification of the roadway at a multi-lane, signalled intersection, where vehicles must often come to a complete stop as they wait their turn to go through the intersection;

FIG. 6C illustrates electrification of the roadway in clusters, with clusters being distributed over the length of the roadway;

FIG. 7 shows one manner in which electronic garaging or overnight charging may be realized within a roadway-powered EV system made in accordance with the invention;

FIG. 8 depicts a schematic cutaway view of a modular EMB of a type that may be used with the present invention;

FIG. 9A illustrates an end view of a Halbach array of a type that may be used with the EMB module of FIG. 8; and

FIG. 9B depicts the calculated field lines for a quadrant of the Halbach array of FIG. 9A.

Corresponding reference characters indicate corresponding components throughout the several views of the drawings.

DETAILED DESCRIPTION OF THE INVENTION

The following description is of the best mode presently contemplated for carrying out the invention. This description is not to be taken in a limiting sense, but is made merely for the purpose of describing the general principles of the invention. The scope of the invention should be determined with reference to the claims.

Broadly stated, the present invention is directed to a roadway-powered electric vehicle system that includes a network of highways and roadways that have been electrified at select locations, and a fleet of roadway-powered electric vehicles (RPEV's) that traverse the network of highways and roadways and receive their electrical operating power from the electrified highways and roadways. Many of the components that make up the RPEV system of the present invention are components that already exist and have been used for other types of EV systems, or other applications. Such components may be found, for example, and are described in the following documents, all of which are incorporated herein by reference: U.S. Pat. Nos. 4,629,947 (Hammerslag et al.); 4,800,328 (Bolger et al.); 4,836,344 (Bolger); 5,207,304 (Lechner et al.); Ziogas, et al., "Analysis and Design of Forced Commutated Cycloconverter Structures with Improved Transfer Characteristics," *IEEE Trans. Ind. Elec.*, Vol. IE-33, No. 3, p. 271 et seq. (August 1986); Riezenman, Special Report, "Electric Vehicles," *IEEE Spectrum* (November 1992, pp. 18–101; Post, et al., "A High-Efficiency Electromechanical Battery", *Proceedings of the IEEE*, Vol. 81, No. 3, pp. 462–474 (March 1993).

Referring first to FIG. 1, there is shown a block diagram of a roadway-powered electric vehicle (RPEV) **12** made in accordance with the present invention. The RPEV **12** includes a vehicle frame **14** supported by a front suspension system **16**, including front wheels **17**, and a rear suspension system **18**, including rear wheels **19**. The frame **14** and suspension systems may be of conventional design. Mounted on the underneath side of the RPEV **14** is an onboard power receiving module **20**. The module **20** receives electrical power, symbolically represented by the wavy arrows **22**, from a roadway power transmitting module **24** embedded in a roadway **26** over which the RPEV travels. The roadway power transmitting module **24** receives power from a power conditioner circuit **28**, which in turn is connected to a utility power distribution system, such as is provided by a public utility company. Typically, the utility company provides electrical power to most customers as 3-phase, 60 Hz power, at 220 vac. Higher voltages may be made available to some customers, as required, such as 480 volts ac (vac). The function of the power converter circuit **28** is to convert the 3-phase, 60 Hz power (at whatever voltage is provided) to an appropriate frequency and voltage for driving the roadway power module **24**, as described in more detail below.

Electrical power received from the electrified roadway **26** (the term "electrified" is used herein to describe a roadway wherein a roadway power module **24** has been embedded) via the onboard power receiving module **20** is stored in an onboard energy storage system **30**. The power is directed to such energy storage system **30** through an onboard power control unit **32**. A power meter **34** monitors all electrical power received by the onboard power module **20**. A key feature of the invention is performance achieved from the onboard energy storage system **30**, described more fully below. Such storage system exhibits a very high energy storage capacity, on the order of 10–15 kw-h. Further, such energy storage capacity is provided in a very small volume, e.g., on the order of 0.5–1 m^3, at an extremely low weight, thereby providing a very attractive energy density, on the order 20–30 kW-h/m^3; a high specific energy, on the order of 150 W-h/kg; and a high specific power, on the order of 5–10 kW/kg. (Note that a conventional electrochemical battery, at best, can only provide a specific power of about 0.2–0.4 kW/kg; and an internal combustion engine only provides about 0.6–0.8 kW/kg.)

As described more fully below, the preferred element of the energy storage system **30** is an electromechanical battery (EMB) because it offers a specific power of up to 10 kW/kg, and offers a very high efficiency (power out/power in) on the order of 95% or higher. It is to be understood, however, that the present invention is not limited to the use of an EMB as the energy storage element. Any storage element which offers the specific power, efficiency, specific energy and other criteria set forth herein, may be used with the RPEV system of the present invention. At present, of the available energy storage devices, the EMB appears to best meet the stated criteria, and therefore it is the preferred energy storage element. However, as other alternate energy storage elements are made or developed or otherwise discovered or made available, whether such elements comprise dramatically improved electrochemical batteries, or ultracapacitors, or other devices, such alternate energy storage elements may be used in lieu of, or in combination with, the EMB's described herein.

The RPEV **12** also includes an electric drive **36** that provides the motive force for propelling the front and/or rear suspension systems. The onboard power control unit **32**, which is controlled by onboard operator controls **38** and/or automatic control features programmed into the power control unit **32**, selectively directs electrical power from the energy storage system **30** to the electric drive **36**. The electric drive **36**, and operator controls **38**, may incorporate designs and features as are commonly used in existing EV's, e.g., battery-powered EV's, or other EV's, as are known in the art. One such feature common to most EV's, and also applicable to the RPEV of the present invention, is that of regenerative braking. Regenerative breaking takes kinetic energy associated with the motion of the vehicle and redi-

rects it back to the energy storage system **30** rather than having such energy be dissipated as heat, or in some other form, whenever it is necessary to brake the vehicle.

Thus, as seen in FIG. **1**, the RPEV receives its operating power through the electrified roadway **26**, i.e., through the roadway power module **24**; stores such power in a highly efficient energy storage system **30**; and then uses such stored energy, as required, to drive the RPEV's electric drive **36**. Advantageously, the RPEV **12** is all electric and has zero emissions.

Referring next to FIG. **2**, an electrical block diagram of the RPEV **12** and roadway power module **24** is shown. As seen in FIG. **2**, the onboard power control unit **32** of the RPEV includes a power director **54**, a microprocessor controller **56** and various vehicle control units **58**. As further seen in FIG. **2**, the preferred roadway power transmitting module **24** is simply a coil **40**. Such coil **40** is connected to the power conditioner **28**. The preferred power conditioner **28** is a 3-phase/60 Hz to 1-phase/f1 KHz converter, where f1 is a desired coupling frequency. Similarly, the preferred onboard power receiving module **20** is also a coil **42**. When a suitable ac electrical current flows through the coil **40** at frequency f1, such current generates a magnetic field that varies at frequency f1. Such varying magnetic field cuts through the coil **42** and induces a voltage therein according to Faraday's law of induction. When the coil **42** is connected to a suitable load, an ac current is thus established in the coil **42** and power is effectively coupled from the coil **40** to the coil **42**.

The coupling between the coils **40** and **42** is referred to as inductive coupling. It is the same type of coupling that occurs in a transformer, except that in a transformer the two coupled coils are closely physically coupled and are usually on the same magnetic core so that the coupling efficiency between the two coils is very high (i.e., all of the magnetic flux generated by the current in one coil cuts through the other coil). Where the coupled coils have an air gap between them, as occurs for this invention (with the coil **40** being embedded in the roadway, and the coil **42** being carried on the underneath side of the RPEV **12**), the coupling efficiency is a function of the distance, or air gap, between the two coils **40** and **42**, as well as the relative alignment between the coils.

In order to improve the coupling efficiency between the embedded coil **40** and the onboard coil **42**, the present invention mounts the coil **42** on a movable assembly **44**. The horizontal position of the movable assembly **44** is controlled by a horizontal coil position unit **46**. Similarly, the vertical position of the assembly **44** is controlled by a vertical (air gap) coil position unit **48**. The positioning units **46** and **48**, in combination with the steering of the RPEV **12**, thus combine to allow the onboard coil **42** to be optimally aligned with the embedded coil **40** so as to provide the maximum possible coupling efficiency between the two coils. Advantageously, when the RPEV **12** is stopped, for example, e.g., at a passenger loading/unloading zone, or at a signaled intersection, or when parked in a parking zone or garage, the air gap between the onboard coil **42** and the embedded coil **40** may be reduced to zero, or near zero, by lowering the movable assembly **44** until it contacts the surface of the roadway **26** where the roadway power transmitting module **24** is embedded. Such reduction in the air gap, coupled with optimum lateral alignment of the assembly **44** relative to the embedded coil **40**, allows a maximum amount of power to be coupled from the embedded coil **40** to the onboard coil **42**. Even when the air gap between the two coils is not zero, however, as when the RPEV **12** is simply driving over the electrified roadway, some power is still coupled from the embedded coil **40** to the onboard coil **42**. Thus, the RPEV **12** is capable of receiving some power from the electrified roadway **12** simply by having the RPEV **12** drive over or on the electrified roadway.

Two ways of coupling power from the embedded coil **40** to the onboard coil **42** may be used. First, the embedded coil **40** may be continuously energized with an appropriate power signal generated by the power converter **28**. Only when the onboard coil **42** comes near the embedded coil **40**, however, is significant power transferred through the inductive coupling link. This is because the RPEV **12** represents the electrical load that receives the coupled electrical power. When the load is not present, as when the RPEV is not over the electrified roadway, then there is nowhere for the electrical power to go, and no power transfer (or very little power transfer occurs). This is analogous to having a load, or not having a load, attached to the secondary winding of a transformer. When the load is attached, power is transferred to the load through the transformer. When the load is not attached, no power is transferred to the secondary winding, and no power (other than the power associated with magnetic field losses) is transferred.

A second way of coupling power from the embedded coil **40** to the onboard coil **42** is to incorporate a vehicle sensor **50** into the roadway power module **24**. The sensor **50** senses the presence of the RPEV **12**, and in response to such sensing, activates the power converter **28** to energize the embedded coil **40**. If the RPEV is not sensed, then the power converter **28** is not turned on. Thus, using such sensor **50**, only when an RPEV **12** is present on the roadway **26** is the roadway **26** electrified. The sensor **50** may be a conventional vehicle sensor that senses the presence of any vehicle driving on the roadway, e.g., a pressure switch sensitive to weight, an inductive strip or loop, or a magnetic or an optical sensor, as are commonly used in the art to sense vehicles and other large objects. Alternatively, the sensor **50** may be a "smart" sensor that senses only RPEV's and not other types of vehicles. A smart sensor is realized, for example, by incorporating a conventional rf or optical receiver in the sensor **50** that receives a particular type of identifying signal (rf or optical) that is broadcast by a small transmitter **52** carried onboard the RPEV **12**, or by employing an optical scanner as part of the roadway sensor **50** that senses or "reads" a bar code placed on an underneath side of the vehicle as the vehicle passes thereover.

Regardless of the manner in which power is inductively coupled to the RPEV **12** through the coils **40** and **42**, an important consideration for such inductive power transfer is the frequency (referred to as "f1" above). Such electric power frequency is the dominant system parameter in the RPEV since the alternating current is fundamental to the inductive coupling energy transfer principle, and it affects the size, weight, cost, acoustic noise, flux density and efficiency of the various energy handling systems. Further, the frequency interacts with all of the other system variables in relationships that are generally complex and non-linear. Frequency is thus a basic parameter that appears in the specification for every piece of electrical and electronic apparatus.

The importance of frequency can be further appreciated by recognizing that heretofore only two standard power frequencies have existed for several decades, one at 50/60 Hz, which is the universal industrial and household standard, and the other at 400 Hz, which is an aircraft standard adopted to reduce size and weight. Neither frequency, however, is optimum for the RPEV system of the present invention.

The above "standard" frequencies of 50/60 Hz or 400 Hz, termed for purposes of this application to be relatively "low" frequencies, offer some advantages, particularly in the transmission of power over transmission lines of substantial length. For purposes of the RPEV of the present invention however, it has been determined that a "higher" frequency, in the KHz range, e.g., between 1 and 10 KHz, and preferably between 2 KHz and 3.5 KHz, is the most optimum frequency to use for transferring power through the inductive coupling link and within the RPEV to power the RPEV and to minimize losses. The EMB, for example, while operating at variable frequencies, operates at a nominal frequency of around 3000 Hz. (Note, if the rotor of the EMB is synchronized with a 3000 Hz driving signal, then it is rotating at 180,000 RPM.) Further, on the utility side of the energy transfer, i.e., at the power converter **28**, converting the input power from the utility (typically 3-phase, 480 vac, at 60 Hz) to a single phase signal at 3000 Hz can be achieved in a commercially-available power converter.

Another important consideration for using an inductive coupling frequency of around 3000 Hz is the strength or intensity of the stray magnetic fields that might otherwise penetrate into the RPEV as a result of the electromagnetic fields associated with the inductive coupling. As indicated above, there are some safety concerns at present regarding whether exposure to such electromagnetic field poses a health risk. While there exists no direct evidence confirming such health risk, many who have studied the issue have concluded that the prudent thing to do is to avoid exposure to strong electromagnetic fields. See, e.g., "Electromagnetic Fields", *Consumer Reports*, pp. 354–359 (May 1994). Advantageously, by using a coupling frequency of around 3000 Hz, the strength of the magnetic fields within the RPEV is generally less than 1 mG (milligauss), which is no greater than the background magnetic fields that are present in a typical U.S. home.

Still referring to FIG. **2**, it is seen that the power received through the onboard coil **42** is coupled through a power director **54** to the onboard energy storage system **30**. Also coupled to the power director **54** is the electric drive **36**. It is the function of the power director **54**, as its name implies, to direct power to and from the onboard energy storage system **30** and the electric drive train **36**. Power is initially directed, for example, from the onboard coil **42** to the energy storage system **30**. Power is also directed, as required, from the energy storage system **30** to the electric drive train **36**. Regenerative power may also be directed, when available, from the electric drive train **36** back to the onboard energy storage system **30**.

The power director **54** is controlled by the microprocessor controller **56**. The microprocessor controller **56**, which is realized using a conventional processor-based system, such as the Motorola 68000 series, or the Intel 386/486 series of processors, both of which are well documented in the art, has appropriate RAM/ROM memory associated therewith wherein there are stored numerous operating routines, or programs, that define various tasks carried out by the controller **56**. Many such tasks are the same as are carried out with the operation of any EV. For purposes of the present invention, the most significant tasks carried out under control of the controller **56** relate to directing the power to and from the energy storage system (explained below in conjunction with FIG. **3**), controlling the lateral and vertical position of the assembly **44** on which the onboard coil **42** is mounted, receiving appropriate commands from the operator control devices **38**, and monitoring onboard vehicle sensors **60**.

The operator control devices **38** include both operator control input devices **62** and vehicle displays **64**. The input control devices include, e.g., manual switches or controls that determine speed, direction, braking, and other controls, associated with the manual operation or driving of the RPEV. Such devices are of conventional design and operation. The displays **64** are also of conventional function and design, indicating to the operator such parameters as vehicle speed and the status of the energy storage system **30**.

The operator input control devices **62** generate input signals to the microprocessor controller **56**. The microprocessor controller **56**, in turn, responds to such input signals by generating appropriate output signals that are directed to a set of vehicle control units **58**. The vehicle control units **58** perform the function of interface (I/F) units that convert the signals output from the controller **56**, which are digital signals, to the requisite signals for actually effectuating the desired control. Thus, for example, a braking signal may be sent from the operator control **62** to the processor controller **56**. The processor controller **56** would process the braking control signal in an appropriate manner relative to the current status of the RPEV, e.g., speed, direction, etc., as determined by the vehicle sensors **60**, and would determine the appropriate amount of braking needed. It would then send its output signal to a braking control unit (one of the control units **58**), which would convert it to an appropriate analog signal. The analog braking signal is then directed to a conventional braking mechanism, i.e., a hydraulic control pump, that would apply the appropriate hydraulic pressure to the vehicle's braking system. Similar processes are carried out for driving the vehicle at a desired speed, steering the vehicle, and the like.

Some Of the RPEV "driving" functions of the RPEV, although normally under manual control of the operator through the operator control devices **38**, may also be automated, or controlled by the controller **56** in accordance with a prescribed or preprogrammed regime. For example, a key feature of the RPEV of the present invention is to incorporate lateral, as well as vertical (air gap) positioning of the assembly **44** on which the coil **42** is mounted. Thus, as the operator of the RPEV approaches, e.g., a passenger loading/unloading zone, he or she activates an auto-positioning control that effectively "takes over" the driving of the vehicle for the final 10–15 feet. Once the auto-positioning function is activated, the vehicle sensors **60** sense the position of the RPEV **12** relative to the roadway power transmitting module **24** embedded in the roadway. The steering of the vehicle is then controlled by the microprocessor controller **56** so that the vehicle is laterally positioned, to within a rough tolerance, e.g., ±5–10 cm, of the optimum lateral position when the vehicle comes to its designed stopped location. Once stopped, the horizontal coil positioning unit **46**, typically realized, e.g., using conventional hydraulic and/or electronic positioning devices, further controls the lateral position of the coil **42** so that it is more closely aligned, e.g., to within ±1–2 cm, of the optimum lateral position. Once the assembly **44** has been aligned laterally, or concurrent with the lateral alignment of the assembly **44**, the vertical (air gap) positioning unit **48**, also typically realized, e.g., using conventional hydraulic and/or electronic positioning devices, lowers the assembly **44** so as to reduce the air gap to near zero.

With the air gap near zero, the onboard energy storage system **30** is charged with additional power obtained from the power converter **28** through the inductive coupling link (which operates at maximum efficiency with a near zero air gap). Before the RPEV is allowed to move, i.e., before the

RPEV can be driven away from the passenger loading/unloading zone, the vertical positioning unit **48** raises the assembly **44** back to its normal position on the underneath side of the RPEV frame.

The vehicle sensors **60** comprise a variety of different types of sensors that sense all of the parameters needed for proper operation of the RPEV. Such sensors sense, e.g., temperature, lane position, distance from nearest vehicle or object, and the like. For purposes of laterally positioning the assembly **44**, such sensors are typically optical sensors that look for markers placed on the roadway power transmitting module **24** embedded in the roadway. Other types of sensors may also be used for this purpose, including acoustic, mechanical, and electromagnetic sensors.

When the RPEV is traveling (being driven) on an electrified portion of a highway or roadway, the lateral (horizontal) positioning device **46** is also activated so that the coil **42** can maintain, to within a rough tolerance, an optimum lateral position relative to the coil **40** that is embedded in the roadway. In such instances, and even when the vehicle is stopped, instead of using the sensors **60**, or in combination with using the sensors **60**, to sense the relative lateral location of the coil **42** to the coil **40**, the approximate lateral position may be determined by monitoring the change in the amplitude of the inductively received power signal as the coil **42** is laterally moved in one direction or the other. The processor controller **56** then laterally positions the coil **42**, using the horizontal coil positioning unit **46** and/or the steering of the RPEV, to maintain the coil **42** at a lateral position that keeps the induced power signal at a peak or maximum level.

Turning next to FIG. **3**, a block diagram of the onboard power director **54** and the onboard energy storage system **30** is shown. As seen in FIG. **3**, the preferred onboard energy storage system **30** comprises a plurality of electromechanical battery (EMB) modules, labeled EMB-**1**, EMB-**2**, . . . EMB-n. Each EMB module is constructed as described below in conjunction with FIGS. **8** and **9**A and **9**B. The power director includes a switch matrix **70**, a unidirectional ac-to-ac converter **72**, and a bidirectional matrix converter **74**. The bidirectional matrix converter **74** is connected to the electric drive train **36**, which includes one or more ac induction drive motors **76**. The ac-to-ac converter **72** is connected to the onboard receiving coil **42** through which inductively coupled electrical power is received.

Each EMB includes three power terminals, representing the 3-phase signals that are applied thereto (when the EMB is being charged), or extracted therefrom (when the EMB is acting as an ac generator). A set of switches, one set for each EMB, connects each power terminal of each EMB to either the ac-to-ac converter **72** (when electrical power is being applied to the EMB to charge it) or the matrix converter **74** (when electrical power is being extracted from the EMB and applied to the induction drive motors **76** that form part of the electric drive train **36**; or when regenerative electrical power is being applied back t the EMB from the motors **76**).

The unidirectional ac-to-ac converter **72** is of conventional design. The power signal received through the coil **42** comprises a single phase, e.g., 3000 Hz signal. This signal is rectified, and then chopped with an appropriate frequency control signal(s), provided by the microprocessor controller **58**, to create a 3-phase signal of varying frequency. Each phase of the 3-phase signal thus generated is applied to the switch matrix **70** so that each phase may, in turn, be selectively applied to the respective input terminal of each EMB of the energy storage system. Each EMB is charged (energy is stored therein) by applying a 3-phase signal thereto that causes the rotor of the EMB to spin at the frequency of the applied signal. By applying a 3000 Hz, 3-phase signal, for example, to the terminals of the EMB, a rotating magnetic field is established within the EMB that rotates at a rate of 3000 revolutions per second, or 180,000 revolutions per minute (RPM). If the rotor is stopped when such a signal is applied, then it spools up to the speed corresponding to the applied frequency, representing the storage of energy. If the rotor is rotating at a speed less than the speed corresponding to the applied frequency, then the rotor speed increases to match the speed dictated by the applied frequency, representing the storage of additional energy. If the rotor is rotating at a speed greater than the speed corresponding to the applied frequency, then the rotor speed decreases to match the speed dictated by the applied frequency, representing a decrease in the energy stored in the EMB. Thus, the key to spooling up, or charging, a given EMB to increase the energy stored therein is to apply a signal thereto having a frequency corresponding to a rotor speed that is greater than the present rotor speed.

In view of the above, one of the main functions of the microprocessor controller **56** is to monitor the rotor speeds of each EMB within the energy storage system **30** so that when an input signal is received through the onboard coil **42**, it can be converted to a 3-phase signal having an appropriate frequency sufficiently high so that it will increase the present EMB rotor speed, thereby storing additional energy in the EMB. To this end, each EMB includes a means **31** for determining its rotor speed, shown functionally in FIG. **3** as the speed sensors **31**-**1**, **31**-**2**, . . . **31**-n. Each of the speed sensors **31**-**1**, **31**-**2**, . . . **31**-n is coupled to the controller **56** through a suitable bus **33**. In practice, a separate rotor speed sensor is not needed, as the rotor speed of each EMB may be determined by simply sampling the ac signal generated by the EMB when operating in a generator mode. However, in order to emphasize the importance of sensing the EMB rotor speed (which provides a measure of the energy stored therein), separate functional speed sensors are shown in FIG. **3**.

The bi-directional matrix converter **74** performs the function of taking the 3-phase signals generated by each EMB (when functioning as an energy source, or generator) and converts such signals as required in order to drive the ac induction motors **76** included in the electric drive train **36**. When the RPEV is braking, or coasting (e.g., going down hill), the matrix converter **74** also performs the function of taking any energy generated by the motors (which, when the RPEV is braking or coasting, are really functioning as generators) and reapplying such energy to the EMB's of the energy storage system **30**. The matrix converter **74** may be as described, e.g., in Ziogas, et al., "Analysis and Design of Forced Commutated Cycloconverter Structures with Improved Transfer Characteristics", *IEEE Trans. Ind Elec.* Vol. IE-33, No. 3, 271 (August 1986).

The switch matrix **70** performs the function of a plurality of switches that connect the set of power terminals of each EMB to either the matrix converter **74** or the ac-to-ac converter **72**. Such switch matrix may take various forms, including electrical relays, solid state switches, SCR's, diodes, and the like.

One of the advantages of using the EMB as the basic building block of the energy storage system **30** is that each individual EMB may be of a standard size and design. A conventional EMB, for example, is designed to provide an energy capacity of 1 kW-h. By using fifteen such EMB modules in parallel, as shown in FIG. **3**, the overall energy

capacity thus increases to 15 kW-h. For smaller, lighter, RPEV's, only a few EMB's are needed to power the vehicle, e.g., 2–6. For larger, heavier RPEV's, such as trucks and vans, more EMB's are needed, e.g., 6–10, or more. For even larger RPEV's, such as buses, further EMB's are added as required, e.g., 12–20, or more.

The specifications of a typical RPEV made in accordance with the present invention are as shown in Table 1.

TABLE 1

Specifications of Typical Roadway-Powered Multiple Occupancy All Electric Vehicle

Item	Description
UTILITY POWER	480 vac, 60 Hz, 3-phase
POWER CONDITIONER	Input: 480 vac, 60 Hz, 3-phase Output: 225 kW, 3 KHz, 1-phase
ROADWAY POWER	3 KHz, 300 amps, 200 kW.
TRANSMITTER MODULE	Module Length: 3 meters
ONBOARD POWER	3 KHz, 200 kW;
RECEIVING MODULE	Mounted on movable assembly to provide multiple pickup positions
ONBOARD POWER CONTROLLER	Functions; Motor Controller; Regeneration Management; Pickup Power Control; Onboard Energy Storage Control; Monitoring State of Change; Metering Energy Consumption
ONBOARD ENERGY STORAGE	15 kW-h (15 1 kW-h modules @ 10 kW each, 3 KHz (nominal)
ELECTRIC DRIVE TRAIN	Two 35 kW AC Motors
MULTIPLE OCCUPANCY VEHICLE (MOV) DESIGN FEATURES	10–15 seated passengers; 110 km/h max speed; low floor; platform loading; electric propulsion; electronic guidance; electronic coupling.
ONBOARD CONTROL SYSTEM	Functions: electronic steering; lateral guidance control; electronic coupling and platform control; vehicle diagnostics; vehicle ID; "throttle" control; brake control; speed profile control; route control; vehicle "flight recorder".
ROADWAY CONTROL ELEMENTS	Functions: roadway-vehicle communication; lateral guidance signal; speed markers; vehicle ID interrogation; roadway surface condition sensors.

Turning next to FIG. **4**, there is shown a schematic illustration of a roadway-powered electric vehicle (RPEV) system made in accordance with the present invention. The RPEV system includes a network of roadways and highways **26**, selected portions of which have been electrified with a roadway power transmitting module **24**, over which a fleet of RPEV's **12** may travel. Each power transmitting module **24** is connected to a utility power source over suitable power lines **78**, as previously described.

As indicated above in Table 1, the roadway power transmitting modules **24** are typically about 3 meters in length. For many locations of the roadway/highway network, a single module **24** is all that is required in order to efficiently couple to an RPEV that is above it. At other locations, e.g., along a section where there is no planned stopping of the RPEV's, such as areas **88** and **90**, several modules **24**, laid end-to-end, will be needed. Thus, at parking locations **82**, or in an overnight parking garage area **84**, or even at a passenger loading/unloading zone **86**, and other locations where it is anticipated that the RPEV will be stopped for a sufficient charging time, a single power transmitting module of 3 meter length is all that should be needed. In fact, for a garage/parking situation, a shortened (e.g., 1–2 meters) power transmitting module **24'** can normally be employed and still provide adequate coupling with the parked RPEV. Further, at strategic locations throughout the network of roadways/highways **26**, various sensors **80** may be positioned to provide an indication of roadway surface conditions. Such information may be transmitted to the RPEV's **12** through conventional means, e.g., rf transmission; or through modulation of the power signal transmitted over the primary power line **78** and inductive coupling link with each vehicle.

A cross-sectional view of the roadway power transmitting module **24** is illustrated in FIGS. **5A** and **5B**, with FIG. **5B** showing an enlarged view of the section of the roadway that is circled in FIG. **5A**. The preferred width of the coils **40** and **42** is about 65 cm, as seen in FIG. **5B**, with the coil being centered in a typical lane of about 3.65 meters in width, as seen in FIG. **5A**. Both the embedded coil **40** and the onboard coil **42** may be characterized as "flat" or "pancake" coils that lie in respective planes that are parallel to the surface of the road **26**.

With reference to the RPEV system of the present invention, it is noted that a conventional battery-driven electric vehicle is normally charged overnight for several hours in one's garage, and then the vehicle starts off the day with a full charge on the batteries. The rate of charge is inherently constrained by limitations of power available in the typical household, since 200 KW, if installed, would be prohibitively expensive. The rate of charge in the home is thus limited to about 6 KW to 10 KW, which means that a typical recharge takes several hours.

The term "opportunity charging" has been used in the prior art to signify other times when a stopped vehicle can receive a charge, for example at curbside or in a parking garage, where it is stationary and can be plugged in.

Advantageously, with the RPEV system of the present invention, the idea of opportunity charging takes on a whole new meaning. In fact, since opportunity charging is so different for the RPEV system, a new term has been coined, "demand charging" or "demand responsive charging," to signify the difference. Demand responsive charging is, as previously explained, made possible by two technologies: (1) the non-contacting inductive coupling energy transfer system, and (2) an energy storage system that allows a very high rate of charge to take place. The combination of these two technologies and the associated onboard power control unit **32** make it possible to replenish the stored energy of an RPEV in minutes, not hours.

At least four types of demand responsive charging are possible with the RPEV system, described below.

A first type of demand responsive charging is of electric buses, using inductive coupling about 25 percent of its stops. Such charging transfers enough energy for the bus to run continuously for 24 hours a day, if necessary, since the energy storage system is being constantly replenished. This means that for a bus system less than 1 percent of the route would need to be electrified, contrasted with the trolley bus, which has 100 percent electrified. From a cost standpoint, this means that a bus line can be electrified for less than 4 percent of the cost of overhead wires. It makes a practical electric bus possible for the first time.

For the bus, the energy transfer takes place for a 20 second to 30 second period when the vehicle is fully stopped, thus the air gap can be zero, or nearly zero, thereby greatly improving the efficiency as well as the rate of power

collection. A representative electrification of a bus stop along a highway route is shown at area **86** in FIG. **4**. Advantageously, using such demand responsive charging system for a bus line as described above makes possible an all-electric bus system that is competitive with a diesel bus in life cycle costs.

It should also be noted that in many cases, a bus has assigned layover points where it must wait for a few minutes in order to synchronize its route with an advertised schedule. In such instances, a charging pad **24** may be installed at the layover point, and the RPEV bus could get enough energy replenishment in 3 to 5 minutes to run much of its assigned loop or route without the need for further energy transfer.

A second type of demand responsive charging for use with the RPEV system of the present invention is that of automobile and highway, and depicted in FIG. **6**A. Heretofore, it has been assumed that an effective electrification system would require the heavily traveled freeway lanes to be fully electrified, i.e., at least one lane in each direction for even a thin network in a region. In the San Diego region, for example, this would mean about 500 lane-kilometers (312 lane miles) would need to be electrified if one established an electrification network on the freeways. However, with the RPEV system of the present invention, only about 10 percent of the powered lane actually needs power, with the remaining 90 percent being unpowered, as shown schematically in FIG. **6**A. Hence, when the RPEV travels over the 10% of the lane that is electrified, it is charged, which charge provides sufficient energy for it to travel the remaining 90% to the next electrified location. In practice, of course, a large safety factor is designed into the RPEV so that it has the capacity, when fully charged, to travel much further than the 90% distance to the next charging location. However, the point is that the RPEV receives a charge as it is traveling over electrified portions of the roadway. From a system specification standpoint, minimum power transfer rates of 100 to 140 kW in motion, or roughly 30 to 50 KW/m, are desirable. The onboard energy storage system **30**, when realized using a network of EMB's, advantageously permits this rate of power collection to take place.

A variation of the demand responsive charging system shown in FIG. **6**A is depicted in FIG. **6**C. In FIG. **6**C, the roadway power transmitting modules **24** (charging pads) are spaced about every 300 m over a distance of, e.g., 1.2 km, and are thus grouped in clusters **25** of five modules **24** each, with each cluster **25** being powered from the same power conditioner **28**. The clusters **25** are then selectively spaced along the length of the roadway, e.g., with a non-electrified section of roadway of about 3.6 km separating the clustered sections. Thus, for the cluster configuration shown in FIG. **6**C, a new cluster of power transmitting modules **24** is found about every 4.8 km of the roadway.

A third type of demand responsive charging for use with the RPEV system is that of selective electrification of a signalized arterial intersection, as shown in FIG. **6**B. In FIG. **6**B, which shows an aerial view of a typical intersection, the electrified portions of the intersections, i.e., those that have the roadway power transmitting modules **24** embedded therein, are shaded. All RPEV's **12** passing through the signalized arterial intersection are able to take advantage of demand responsive charging. The typical transit time through the intersection is about 45 seconds to 60 seconds. During this time, the RPEV receives as much energy from the roadway module **24** as it could in a mile of a powered lane on the highway. Thus by electrifying the last 30 meters of a signalized intersection lane, or lanes, 2% of the arterial lane being electrified has the same effect as fully electrifying the lane.

A fourth type of demand responsive charging that may be used with the RPEV system is that of electric garaging. In electric garaging, a charging pad **24'**, approximately 1 meter square and 3 cm thick, is installed on the surface of a driveway or garage floor, as shown in FIG. **7**. The pad **24'** is used for an overnight recharging of the energy storage system **30** of the RPEV **12**. The power flow levels are between 6 KW and 10 KW (comparable to an electric clothes dryer in a residence), and the time for recharge ranges from 1 hour to 2 hours.

Preferably, the electronic garaging operates in a demand responsive mode, and is fully automated and hands-off for the driver. The RPEV generates an enabling signal to carry out the charging at times of day when utility rates are lowest, e.g., at 2:00 a.m., turning it off when the energy storage is replenished.

The RPEV, as previously described, may issue an enabling signal from the vehicle to command the energy transfer to take place, depending on the energy storage requirements at that moment. A high rate of energy transfer for a short period is preferred, if possible. But regardless of whether the transfer is for a short period of time, as at an intersection or bus stop, or for a longer period of time, as at a parking stall or garage, the system is charged only as needed and as requested or demanded, hence the term "demand responsive charging" accurately describes the charging action that takes place.

Referring next to FIG. **8**, a schematic cutaway view of a modular EMB **31** of a type that may be used with the present invention is illustrated. An EMB module **31** of the type shown in FIG. **8** is described more thoroughly in Post et al., "A High-Efficiency Electromechanical Battery,", *Proceedings of the IEEE*, Vol. 81, No. 3, pp. 462–474 (March 1993). Basically, the EMB module **31** includes a rotor **103** mounted for rotation on magnetic bearings **100** and **102** within a sealed vacuum chamber **97**. The sealed vacuum chamber **97** is defined by thin stainless steel walls **94**, reinforced with fiber composite, and a glass ceramic sleeve **95**. The entire vacuum chamber **97** is then mounted inside of a containment vessel **92** made of highly impact-resistant material, such as three-dimensional fiber composite. Appropriate gimbal mounts **98** (represented as springs) are used to mount the vacuum chamber **97** within the vessel **92**. Three-phase, stationary, generator windings **96** are mounted outside of the vacuum chamber **97**, between the thin walls **95** that define a narrow neck portion of the vacuum chamber. Each winding terminates at one of three terminals **99**.

The rotor **103** is made from concentric rotating cylinders **104**, **106**, **108** and **110**. The concentric cylinders are made from thin walls (10% of the radius) to prevent delamination, and are separated by an elastic material **109**. A magnet array **111** is placed on the inside of the inner concentric rotor cylinder **110** to create a rotating dipole magnetic field. The rotor **103** rotates at a velocity of the order to 10,000 rads/s, and allows each EMB module to produce about 1 kW-h of energy.

Advantageously, the EMB module **31** stores more energy per unit mass or per unit volume than other known energy devices. This is because stored energy increases only linearly with the mass of the rotor (for a given geometry), but goes up as the square of its rotation speed. Since the rotor **103** is made of a light, strong material, it can be spun much faster than heavy strong material (commonly used in conventional mechanical flywheels) before centrifugal forces threaten to break it up. The result is that the EMB can store much more energy, and more safely, than has previously been possible.

Composite materials based on graphite make it possible to build the EMB with a specific energy of about 150 W-h/kg, and a specific power that is orders of magnitude greater than anything achievable by an electrochemical battery or even an internal combustion engine. As indicated previously, the EMB can deliver a specific power 5,000 to 10,000 W/kg.

To keep the EMB from running down, the rotor **103**, as indicated, runs on magnetic bearings **100** and **102** in the vacuum chamber **97**, realized using, e.g., permanent magnetic materials such as Nd-Fe-B. Such bearings offer the added advantage of extending the EMB's life since there is no mechanical contact, and hence no wear, with this mode of suspension. As a result, the sealed EMB, has an extremely long lifetime, and should outlast the vehicle in which it is carried.

The vacuum chamber **97** is evacuated to a pressure of 10^{-3} to 10^{-4} pascals. To achieve and maintain a vacuum of that pressure, it is important that the rotor materials minimize vacuum outgassing, and that other materials employ modern getter alloys.

In order to assure safety, which is always a concern any time a great deal of energy is stored in a small volume, the rotor materials are selected and designed to fail by disintegrating into a mass of fairly benign fluff, or "cotton candy". In contrast, massive steel rotors, such as are used in mechanical flywheels, may fail in spectacular fashion, throwing off large chunks of shrapnel. The vessel **92**, also made of a three-dimensional composite, is able to readily contain any such disintegrating mass by incorporating into its design high-strength fibers that run in all three directions. With such construction, any cracks that get started in the housing are not able to propagate.

Advantageously, the EMB is ironless. This feature not only keeps the weight low, but prevents hysteresis losses common in iron systems. Moreover, since inductances of the multi-phase windings are extremely low (with no iron present), and since rotation speeds are high, unusually high peak power outputs are achievable, with stator copper losses that can readily be handled by conventional means (air or liquid cooling).

A central feature of the EMB is the generator/motor design. A special array of permanent magnet bars **112** is mounted on the rotor at **109** (FIG. **8**). An end view of such array, known as the Halbach array, is shown in FIG. **9A**, with the arrows indicating the relative polarity of the bar magnets **112**. The magnetic lines of force associated with one quadrant of such array are shown in FIG. **9B**. Of significance is the uniformity of the interior field, and its near cancellation outside of the array. Using Nd-Fe-B magnets, having a B_r equal to 1.25 Tesla, dipole fields of the order 0.5 T can be readily obtained.

A typical EMB module of the type shown in FIGS. **8**, **9A** and **9B**, provides the following operating parameters:

Rotation speed:	200,000 RPM
Magnetic field of Halbach Array:	0.5 T
Length & Width of windings:	0.8 m × .04 m
Number of turns:	10
Output voltage (3-phase):	240 V rms

As described above, it is thus seen that the present invention provides an efficient, viable, safe, roadway-powered all electric vehicle that uses, with only minor modification, the existing network of highways, roadways, and/or garaging/parking facilitates that are already in place to service ICE vehicles.

Further, it is seen that the RPEV system disclosed provides a zero-emission electric vehicle system wherein the RPEV's of the system may be recharged while such EV's are in operation within the system. Hence, the RPEV's need not be taken out of service from the system in order to be recharged, as is common with prior art battery-storage type EV's.

Moreover, it is seen that the invention provides an RPEV system wherein a high energy, efficient, electromechanical battery (EMB), or a group of EMB's, are used as an onboard energy storage system. The EMB, due to the use of magnetic bearings and enclosing the rotor in a sealed vacuum chamber, is able to run at extremely high speeds (e.g., exceeding 100K–200K RPM), and thereby provides a large amount of power in a relatively very small space and at a small weight.

Still further, it is seen that the invention described herein may be used to provide an EV system that powers a fleet of electrically-powered buses, or other mass transit electric vehicles, using a demand responsive charging system or scheme. In accordance with such scheme, existing highways and roadways over which the EV's travel need be electrified only at select locations, such as: (1) at designated "stops" of the vehicle, e.g., at designated passenger loading/unloading zones, parking garages, or the like; (2) at locations where the vehicle regularly passes, such as roadway intersections; and/or (3) along selected portions of the route, e.g., 50–100 meters of every kilometer over which the vehicle travels.

Additionally, it is seen that the invention described herein provides a viable electric vehicle system that uses inductive coupling to couple electrical energy between embedded coils in the roadway and coils carried onboard the EV. Such coupled electrical energy is stored onboard the EV and is thereafter used to provide the motive force of the EV. Onboard systems and methods are utilized, as required, to laterally and vertically position the relative spacing (air gap) and alignment between the onboard coil and the embedded coils in order to make the energy transfer from the roadway to the vehicle more efficient, reducing the air gap to near zero when the EV is stopped.

While the invention herein disclosed has been described by means of specific embodiments and applications thereof, numerous modifications and variations could be made thereto by those skilled in the art without departing from the scope of the invention set forth in the claims.

What is claimed is:

1. A roadway-powered electric vehicle (EV) comprising:

a vehicle frame supported by front and rear suspension systems, including front and rear wheels;

an onboard power receiving module mounted on an underneath side of said vehicle frame that receives electrical power coupled thereto from a roadway power transmitting module embedded in a roadway over which the EV travels, wherein a first ac electrical current passing through the roadway power transmitting module has a frequency of from between 1 and 10 khz;

an onboard energy storage means for storing and delivering electrical energy;

an electric drive means coupled to at least one of said front or rear suspension systems for driving a least one of said front and rear wheels; and

an onboard power controller means for receiving electrical power from said onboard power receiving module and directing it to said onboard energy storage means, and for selectively delivering electrical energy from

said energy storage means to said electric drive means in order to provide operating power for said EV.

2. The roadway-powered EV as set forth in claim 1 wherein said first ac electrical current has a frequency of between 2.5 and 3.5 KHz.

3. The roadway-powered EV as set forth in claim 1 wherein said onboard energy storage means comprises an electromechanical battery (EMB) system, said electromechanical battery system being characterized by a plurality of EMB modules connected in a parallel network, each EMB module having a specific energy of at least a kW-h, each EMB module having: a sealed housing, a rotor within the sealed housing mounted on magnetic bearings, an array of magnets mounted on the rotor in a specific array so as to set up a prescribed rotor magnetic field pattern, and a set of stationary coils positioned to interact with said prescribed rotor magnetic field pattern; an alternating current applied to said set of stationary coils setting up a rotating magnetic field that interacts with the prescribed rotor magnetic field pattern so as to cause said rotor to spin, the spinning of said rotor representing the storage of energy; and the spinning of the rotor causing the prescribed rotor magnetic field pattern to interact with said set of stationary coils so as to induce an ac voltage thereon, said ac voltage representing the extraction of energy from said EMB; whereby said EMB functions as a motor/generator depending upon whether electrical energy is being applied thereto or extracted therefrom.

4. The roadway-powered EV as set forth in claim 1 wherein said roadway power transmitting module comprises a first electrical coil embedded in the roadway, and wherein said onboard power receiving module comprises a second electrical coil, and wherein the first ac electrical current passes through said first coil and sets up an alternating magnetic field that induces a second ac electrical current in the second electrical coil, said first electrical coil and said second electrical coil thereby becoming inductively coupled to each other whenever the second electrical coil passes over the first electrical coil.

5. The roadway-powered EV as set forth in claim 4 wherein said onboard power controller means includes:

microprocessor controller means for generating a set of control signals that control said EV; and

a power director circuit connected to said onboard energy storage means and controlled by said microprocessor controller means, said power director circuit comprising:

ac-to-ac converter means electrically connected to the second coil for converting the second ac current inductively coupled in the second coil to a third ac current having a variable frequency set by a frequency control signal included within said set of control signals generated by said microprocessor controller means;

bi-directional matrix converter means for converting an ac voltage generated by said onboard energy storage means to an appropriate electrical drive signal as controlled by a pulse width control signal included within said set of control signals generated by said microprocessor controller means, said electrical drive signal being coupled to the electric drive means of said EV;

a switch matrix that selectively connects each of a plurality of energy storage modules included within a parallel network of energy storage modules to either said ac-to-ac converter means or to said bi-directional matrix converter means as a function of said control signals generated by said microprocessor controller means;

said microprocessor controller means thereby controlling whether electrical energy is directed to, and hence stored within, the parallel network of energy storage modules, or whether electrical energy is withdrawn from the parallel network of energy storage modules and directed to the electric drive means.

6. The roadway-powered EV as set forth in claim 5 wherein each of said energy storage modules is an electromechanical battery, said roadway-powered EV further including sensor means coupled to said microprocessor controller means for sensing a rotational speed of a rotor of each energy storage modules module within said parallel network of energy storage modules, said rotational speed providing a measure of the energy stored within each energy storage module, said measure of the energy stored within each energy storage module being used by said microprocessor controller means to control said switch matrix in an appropriate manner so that at least one of said energy storage modules can receive energy from said ac-to-ac conversion means at the same time that another of said energy storage modules is providing a source of energy for driving said electric drive means, whereby said EV may operate at the same time that it is being recharged with electrical energy.

7. The roadway-powered EV as set forth in claim 5 wherein said electric drive means includes means for generating a regenerative electrical current whenever said EV is coasting or braking, and wherein said bi-directional matrix converter means converts said regenerative electrical current to a fourth electrical current that may be applied to at least one of the energy storage modules of said parallel network of energy storage modules through said switch matrix, whereby energy associated with said regenerative electrical current is stored within said parallel network of energy storage modules.

8. The roadway-powered EV as set forth in claim 4 wherein said second coil is mounted on a movable assembly attached to an underneath side of said EV, and wherein said onboard power controller means includes positioning means for selectively positioning said movable assembly in order to optimize inductive coupling between said second coil and said first coil.

9. The roadway-powered EV as set forth in claim 8 wherein the positioning means for selectively positioning the movable assembly to optimize inductive coupling between said second coil and said first coil includes reducing means for selectively reducing an air gap between said first coil and said second coil whenever said EV is stopped, whereby vertical distance between said movable assembly and said roadway may be selectively reduced whenever said EV stops.

10. The roadway-powered EV as set forth in claim 8 wherein said positioning means for selectively positioning said movable assembly to optimize inductive coupling between said second coil and said first coil includes guiding means for automatically laterally guiding said EV so that said second coil is properly aligned with said first coil.

11. The roadway-powered EV as set forth in claim 8 wherein said positioning means for selectively positioning said movable assembly to optimize inductive coupling between said second coil and said first coil includes reducing means for selectively reducing an air gap between said first coil and said second coil whenever said EV is stopped, and guiding means for automatically laterally guiding said EV so that said second coil is properly laterally aligned with said first coil as the air gap is reduced.

12. A roadway-powered electric vehicle (RPEV) system comprising:

a network of highways and roadways that have been electrified with a multiplicity of roadway power transmitting modules embedded in the highways and roadways at select locations, each of said roadway power transmitting modules being connected to receive power from an electrical utility; and

at least one RPEV that traverses said network of highways and roadways using electrical power coupled to said at least one RPEV from the electrified highways and roadways as said RPEV travels over the locations of the highways and roadways that have been electrified, said RPEV including:

a vehicle frame supported by front and rear suspension systems, including front and rear wheels,

an onboard power receiving module mounted on an underneath side of the vehicle frame that receives electrical power coupled thereto from a roadway power transmitting module embedded in a roadway at the select locations that have been electrified, wherein a first ac electrical current passing through the roadway power transmitting module has a frequency of from between 1 and 10 khz,

an onboard energy storage means for storing and delivering electrical energy,

an electric drive means coupled to at least one of said front or rear suspension systems for driving at least one of said front and rear wheels, and

an onboard power controller means for receiving electrical power from said onboard power receiving module and directing it to said onboard energy storage means, and for selectively delivering electrical energy from said onboard energy storage means to said electric drive means in order to provide operating power for said EV.

13. The RPEV system as set forth in claim **12** wherein the select locations of said network of highways and roadways that have been electrified include no more than approximately 10% of the linear length of said roadways and highways.

14. The RPEV system as set forth in claim **12** wherein said onboard energy storage means comprises an electromechanical battery (EMB) system, said electromechanical battery system having at least one EMB, said EMB having a specific energy of at least 1 kW-h achieved by rotating a rotor sealed in an evacuated housing at rotational speeds in excess of 100,000 RPM as driven by an electrical input power signal applied thereto, an electrical output power signal being generated as a function of the speed of the rotating rotor; said electrical output power signal representing the extraction of energy from said EMB; whereby said EMB functions as a motor/generator depending upon whether electrical power is being applied thereto as said electrical power input signal or extracted therefrom as said electrical power output signal.

15. The RPEV system as set forth in claim **12** wherein the select locations of said network of highways and roadways that have been electrified include intersections where the RPEV is likely to be stopped for a time, and passenger loading/unloading zones where the RPEV will be stopped for a time.

16. The RPEV system as set forth in claim **15** wherein the network of highways and roadways includes parking/garaging locations, and further wherein said parking/garaging locations are electrified with said roadway power transmitting modules.

17. The RPEV system as set forth in claim **12** wherein each of said roadway power transmitting modules is electrically connected to the electrical utility via a power conditioner circuit, said power conditioner circuit comprising converting means for converting the electrical power obtained from the electrical utility to a form that can be efficiently and safely transmitted to the onboard power receiving module of the RPEV.

18. The RPEV system as set forth in claim **17** wherein said roadway power transmitting module comprises a first electrical coil embedded in the roadway, and wherein said onboard power receiving module comprises a second electrical coil, and wherein said electrical power conversion means of said power conditioner circuit converts electrical power obtained from the electrical utility to said first ac electrical current, and applies said first ac electrical current to said first coil to set up an alternating magnetic field, said alternating magnetic field inducing a second ac electrical current in the second electrical coil, said first electrical coil and said second electrical coil thereby being inductively coupled to each other whenever said second electrical coil passes over said first electrical coil.

19. The RPEV system as set forth in claim **18** wherein said power converter comprises an ac converter that includes means for converting 3-phase 50/60 Hz power obtained from the electrical utility to said first ac electrical current.

20. The RPEV system as set forth in claim **19** wherein said first ac electrical current has a frequency of between 2.5 and 3.5 KHz.

21. The RPEV system as set forth in claim **18** wherein said electromechanical battery system comprises a plurality of energy storage modules connected in a parallel network, and wherein said onboard power controller means includes:

microprocessor controller means for generating a set of control signals that control said EV; and

a power director circuit connected to said onboard energy storage means and controlled by said microprocessor controller means, said power director circuit comprising:

ac-to-ac converter means electrically connected to the second coil for converting the second ac current inductively coupled in the second coil to a third ac current having a variable frequency set by a frequency control signal included within said set of control signals generated by said microprocessor controller means;

bi-directional matrix converter means for converting an ac voltage generated by said onboard energy storage means to an appropriate electrical drive signal as controlled by a pulse width control signal included within said set of control signals generated by said microprocessor controller means, said electrical drive signal being coupled to the electric drive means of said EV;

a switch matrix that selectively connects each of said plurality of energy storage modules included within said parallel network of energy storage modules to either said ac-to-ac converter means or to said bi-directional matrix converter means as a function of said control signals generated by said microprocessor controller means;

said microprocessor controller means thereby controlling whether electrical power is directed to, and hence stored within, the parallel network of energy storage modules, or whether electrical power is withdrawn from the parallel network of energy storage modules and directed to the electric drive means.

22. The RPEV system as set forth in claim **21** wherein each of said energy storage modules is an electromechanical

battery, said RPEV system further including sensor means coupled to said microprocessor controller means for sensing a rotational speed of a rotor of each energy storage module within said parallel network of energy storage modules, said rotational speed providing a measure of the energy stored within each energy storage module, said measure of the energy stored within each energy storage module being used by said microprocessor controller means to control said switch matrix in an appropriate manner so that at least one of said energy storage modules can receive energy from said ac-to-ac conversion means at the same time that another of said energy storage modules is providing a source of energy for driving said electric drive means, whereby each of said RPEV's may operate at the same time that it is being recharged with electrical energy.

23. The RPEV system as set forth in claim **18** wherein said second coil is mounted on a movable assembly attached to an underneath side of said RPEV, and wherein said onboard power controller means includes positioning means for selectively positioning said movable assembly in order to optimize inductive coupling between said second coil and said first coil.

24. The RPEV system as set forth in claim **23** wherein the positioning means for selectively positioning the movable assembly to optimize inductive coupling between said second coil and said first coil includes reducing means for selectively reducing an air gap between said first coil and said second coil whenever said RPEV is stopped, whereby a vertical distance between said movable assembly and said roadway may be selectively reduced.

25. The RPEV system as set forth in claim **23** wherein said positioning means for selectively positioning said movable assembly to optimize inductive coupling between said second coil and said first coil includes guiding means for automatically laterally guiding said RPEV so that said second coil is properly aligned with said first coil.

26. The RPEV system as set forth in claim **23** wherein said positioning means for selectively positioning said movable assembly to optimize inductive coupling between said second coil and said first coil includes reducing means for selectively reducing an air gap between said first coil and said second coil whenever said RPEV is stopped, and guiding means for automatically laterally guiding said RPEV so that said second coil is properly laterally aligned with said first coil as the air gap is reduced.

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