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(54) **VOLTAGE SOURCE ISOLATION IN WIRELESS POWER TRANSFER SYSTEMS**

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See application file for complete search history.

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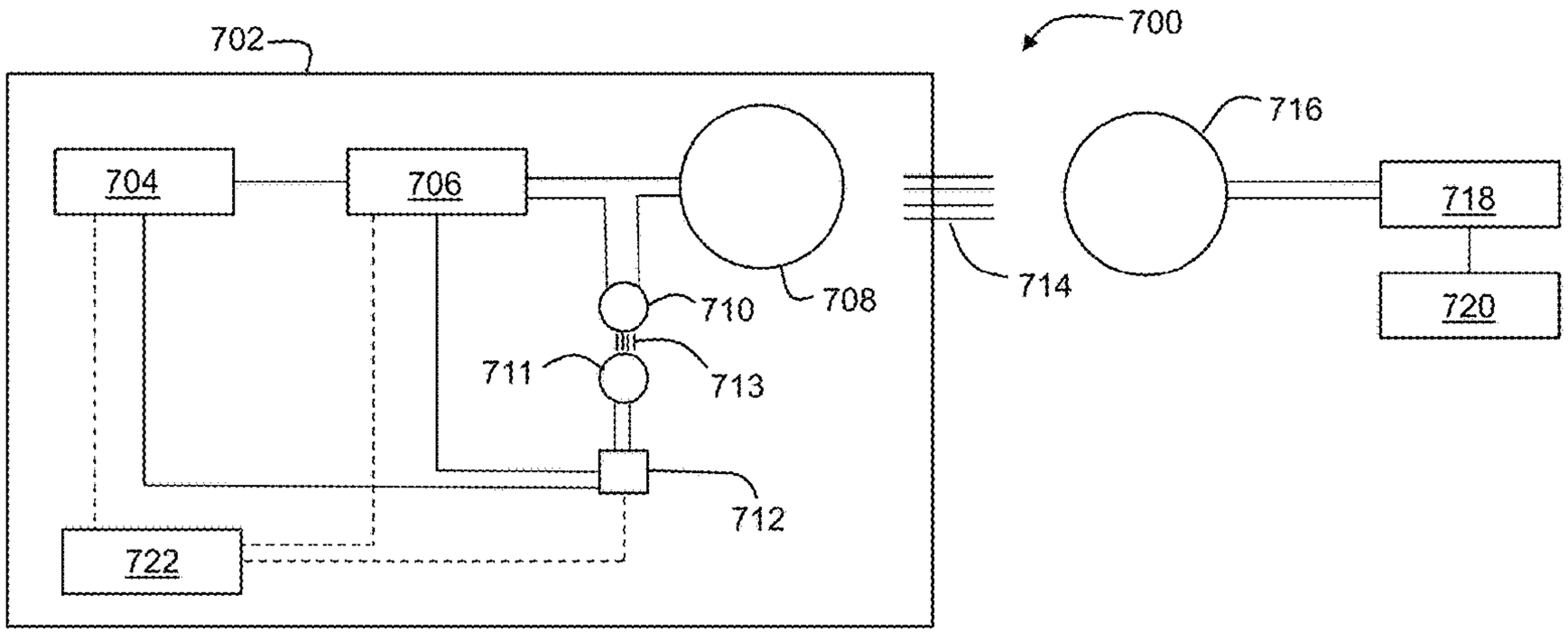
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(57) **ABSTRACT**

The disclosure features wireless power transmitters that include a power source, a first coil connected to the power source, a second coil connected in series to the first coil, and a third coil positioned in proximity to the second coil, where during operation of the wireless power transmitters, the power source applies a driving voltage to the first and second coils, the first coil generates a first magnetic field that transfers power to a receiver resonator, the second coil generates a second magnetic field that induces a voltage across the third coil, and the induced voltage across the third coil is applied to a component of the wireless power transmitters.

9 Claims, 9 Drawing Sheets



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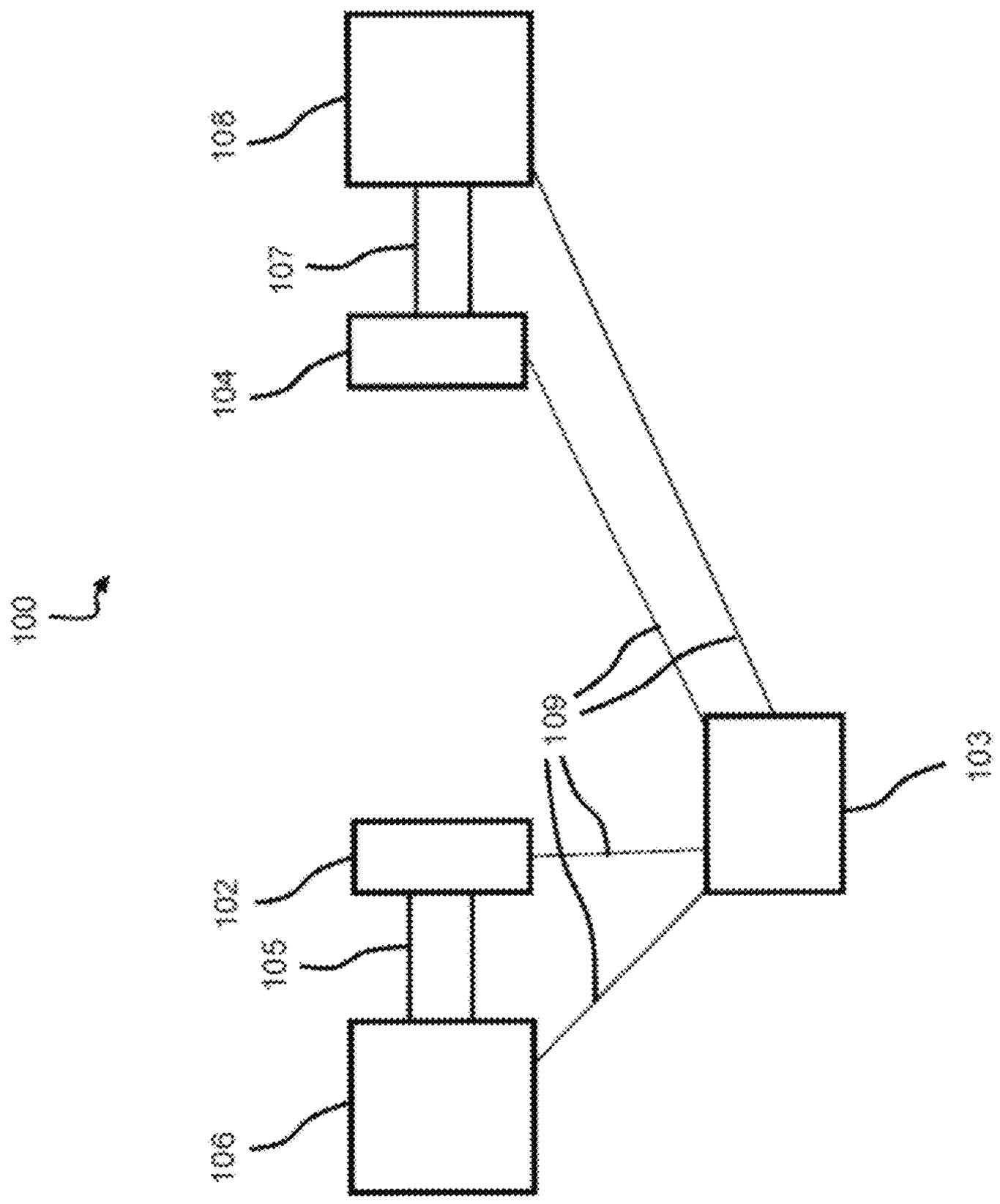
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FIG. 1



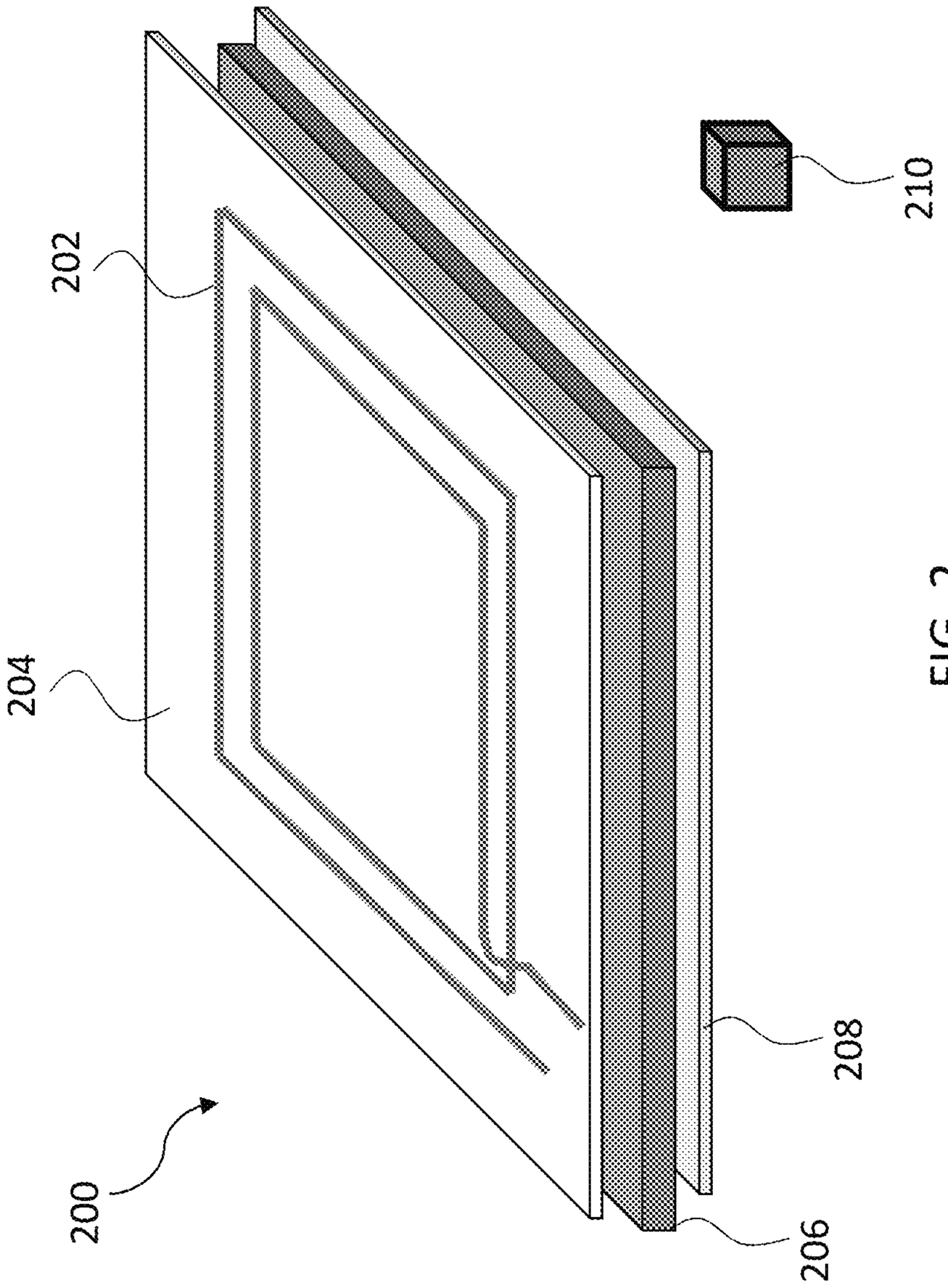


FIG. 2

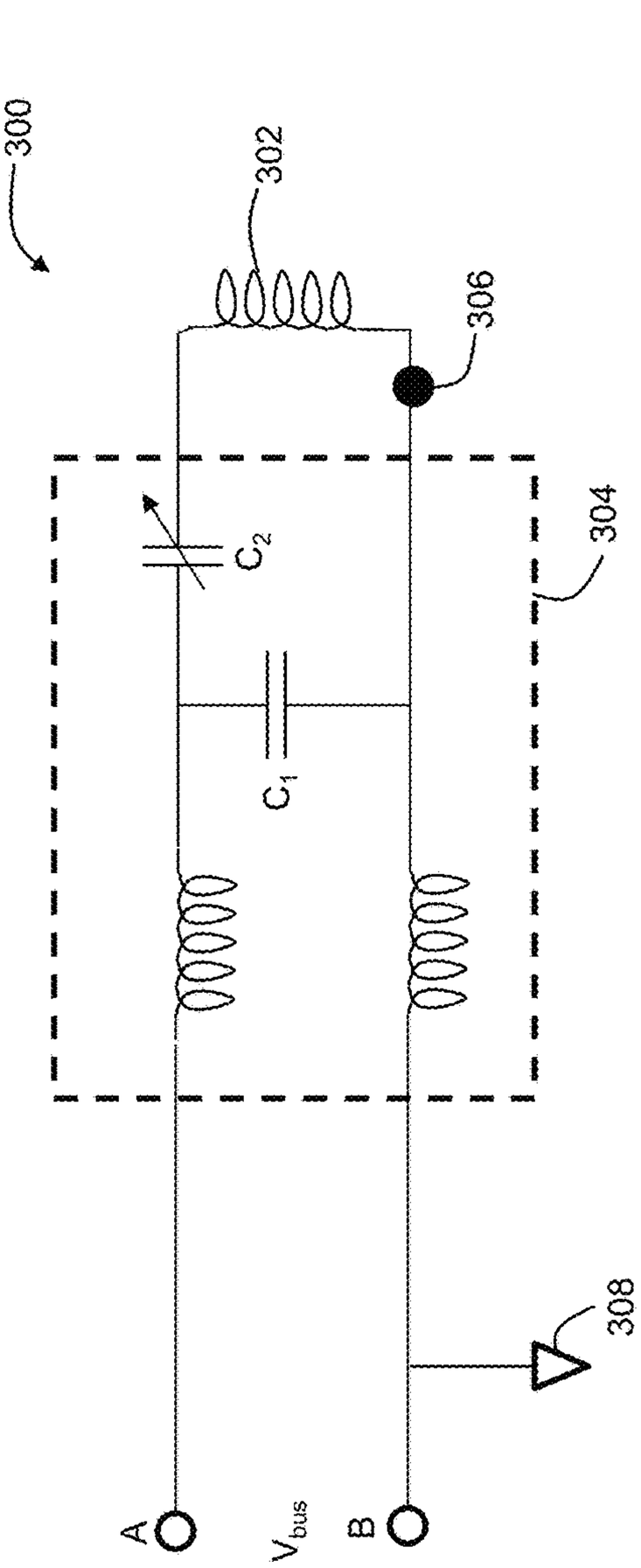


FIG. 3

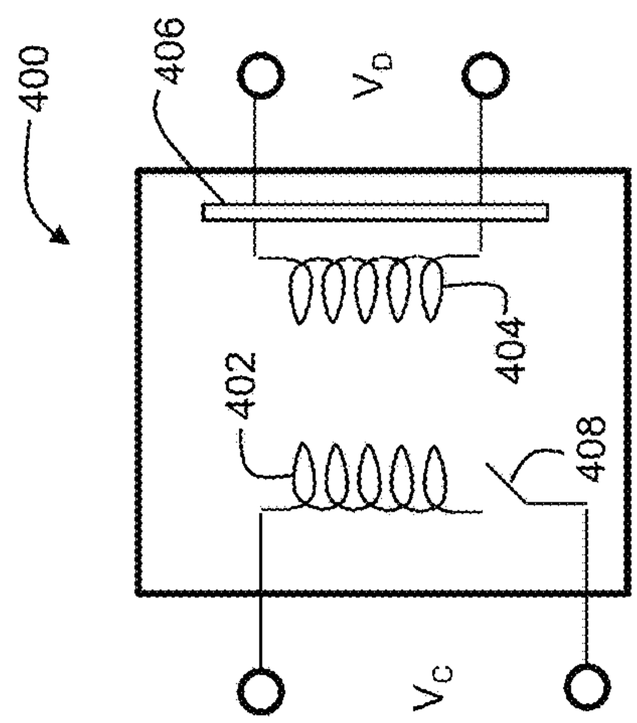


FIG. 4

FIG. 5

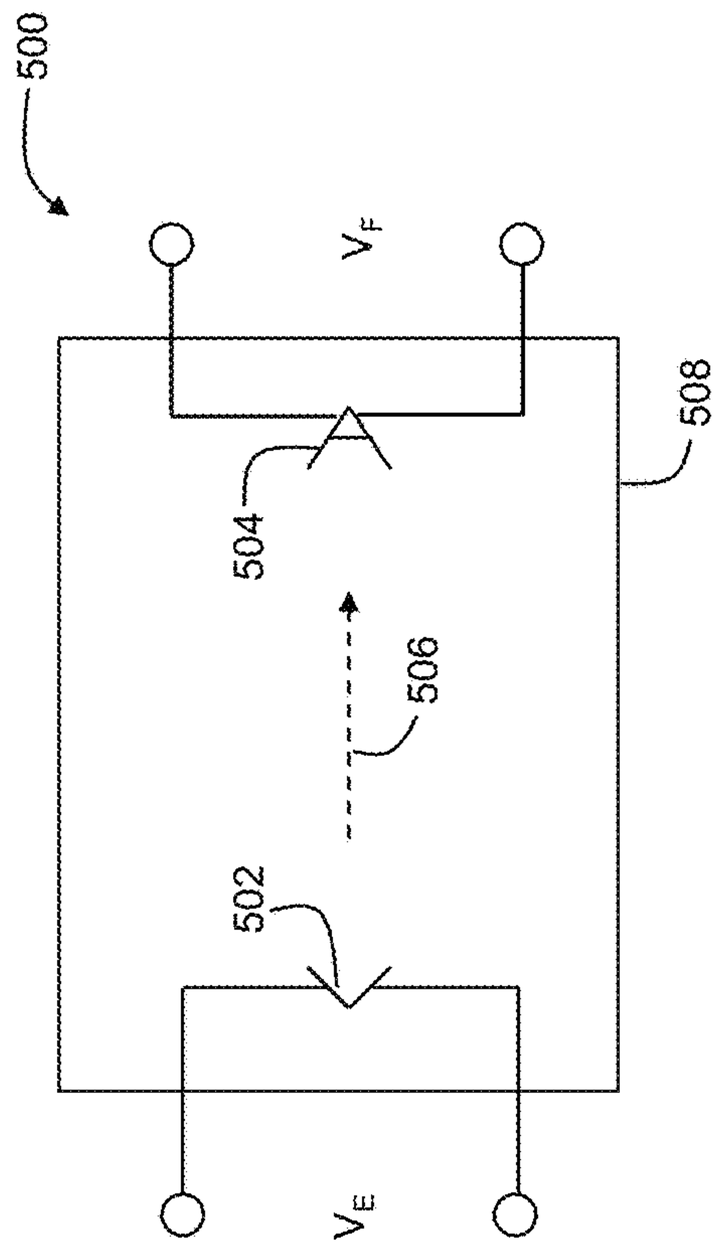
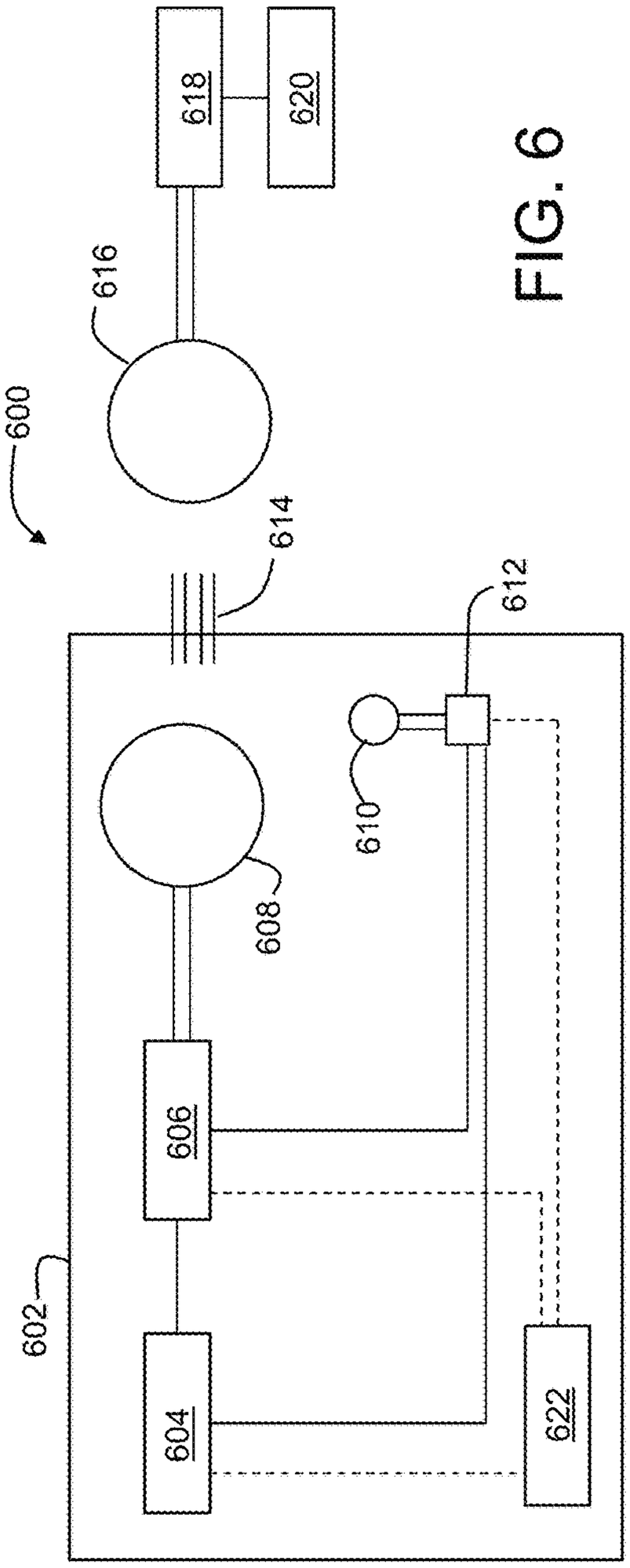

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FIG. 6


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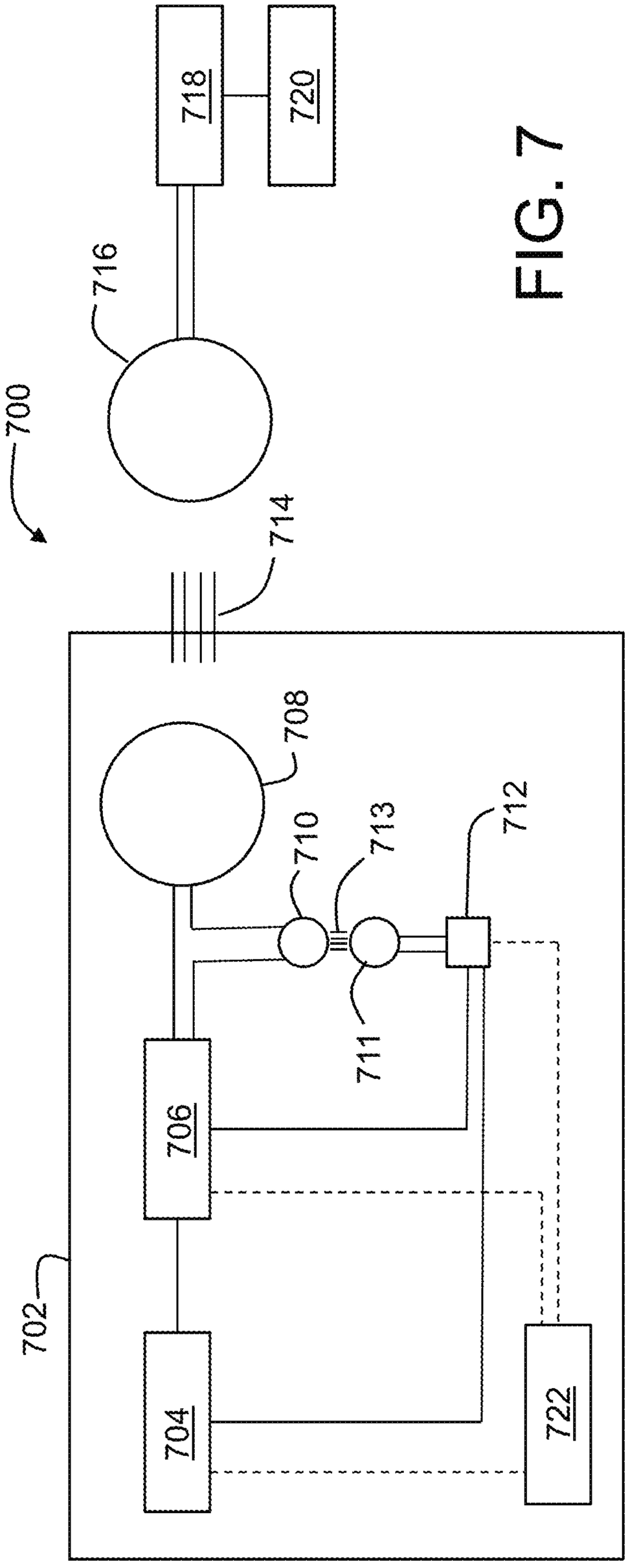


FIG. 7

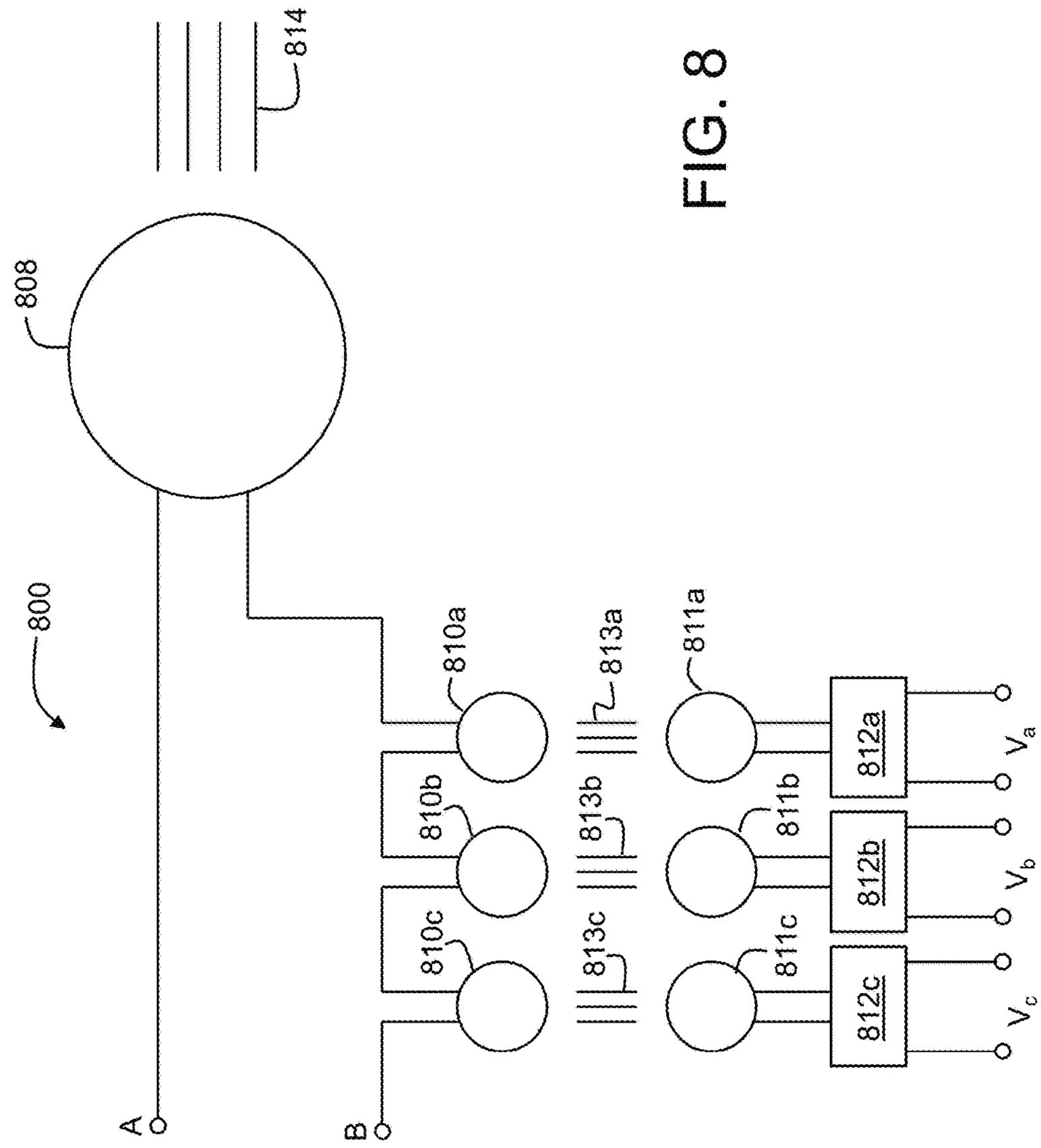

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FIG. 8

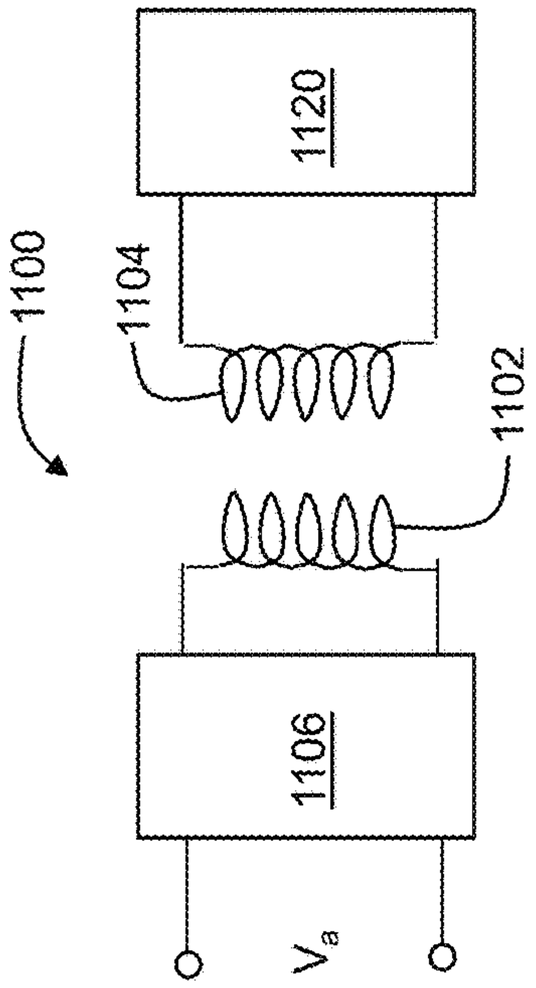


FIG. 11

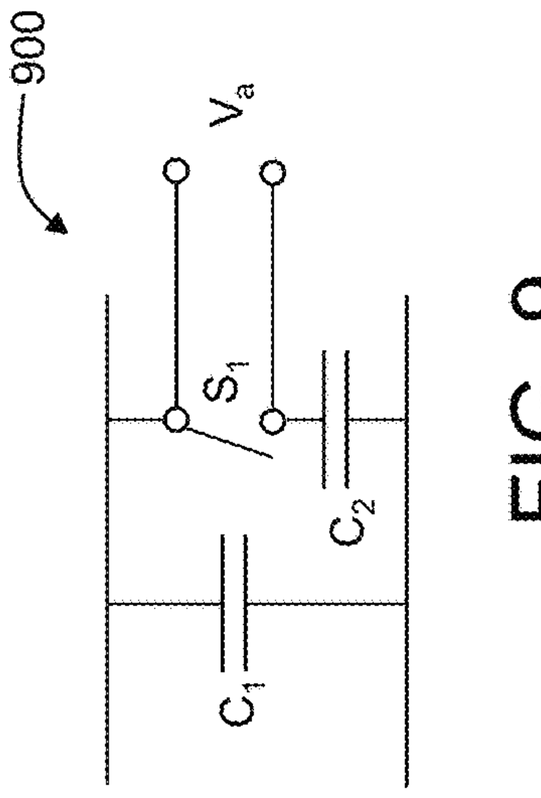


FIG. 9

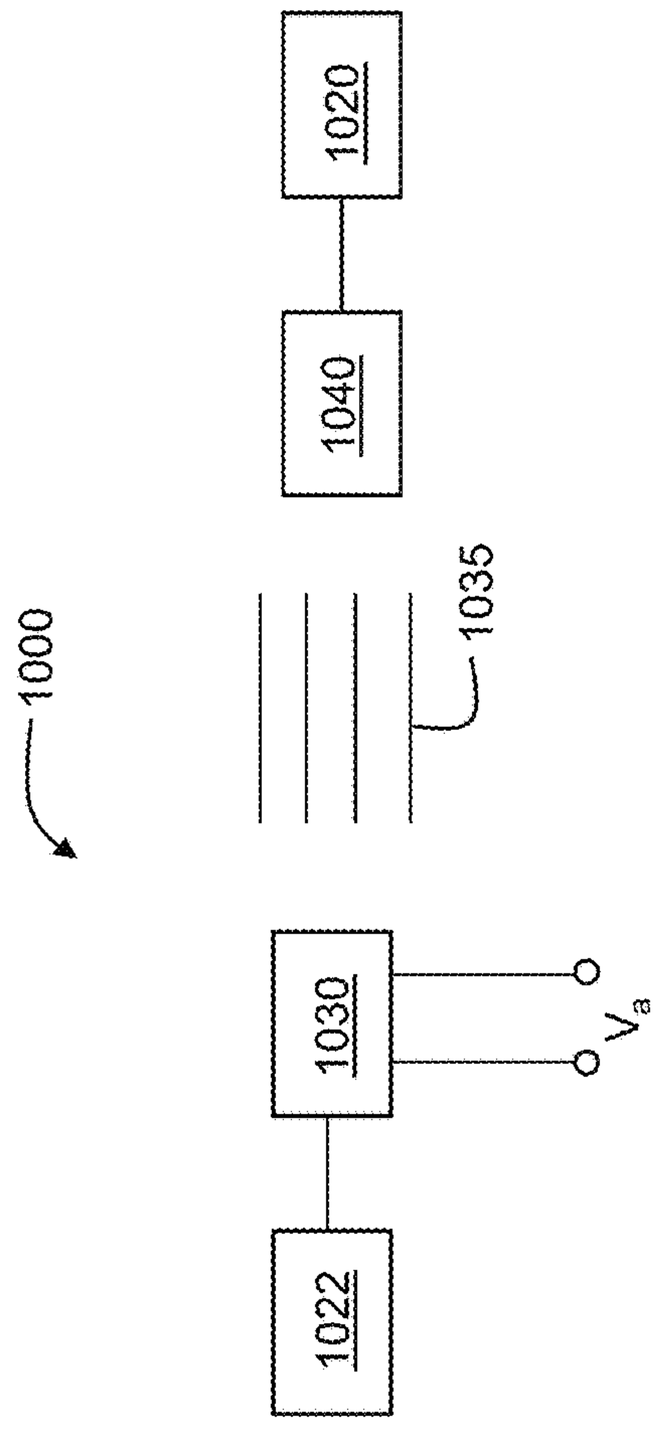


FIG. 10

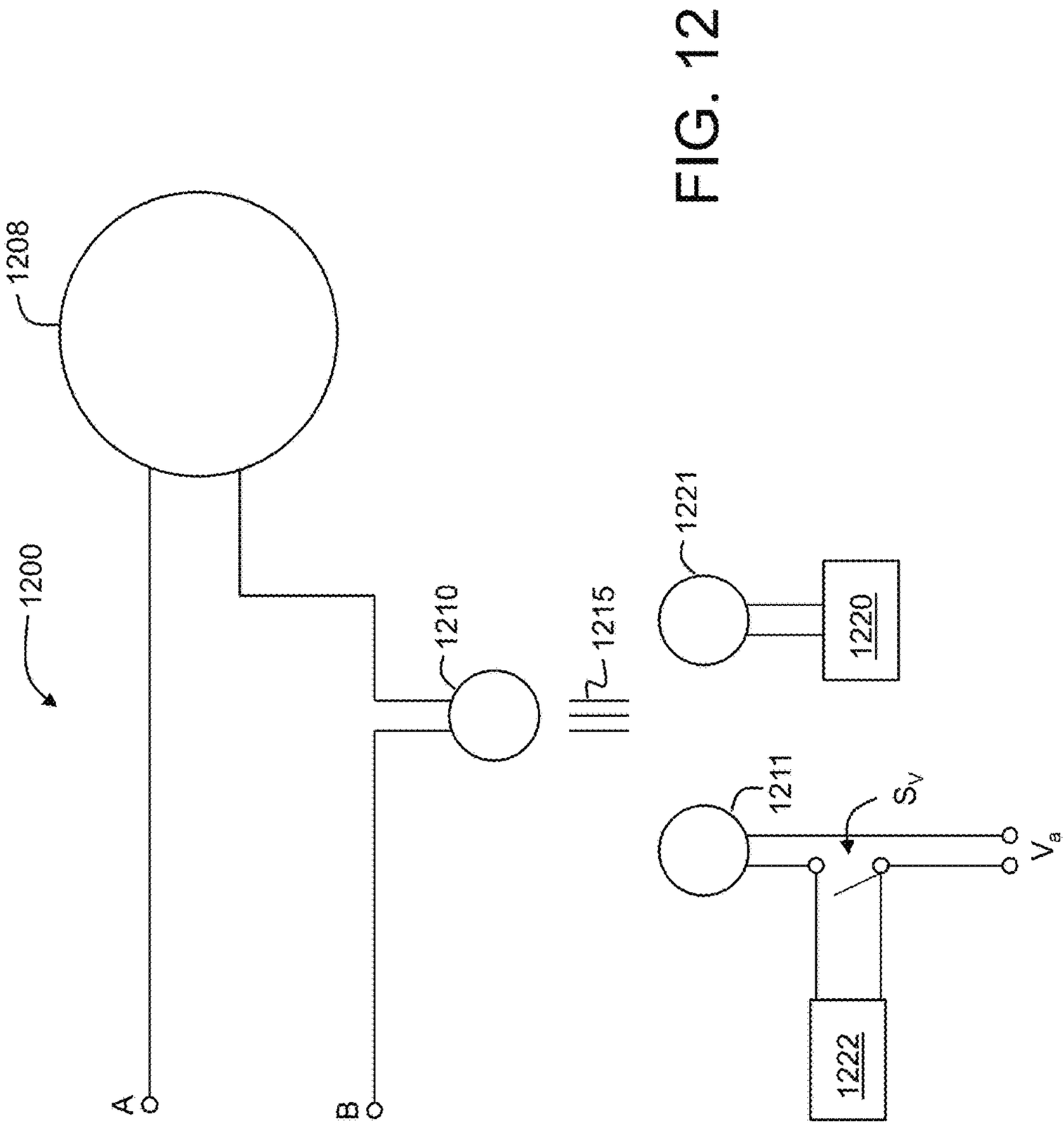


FIG. 12

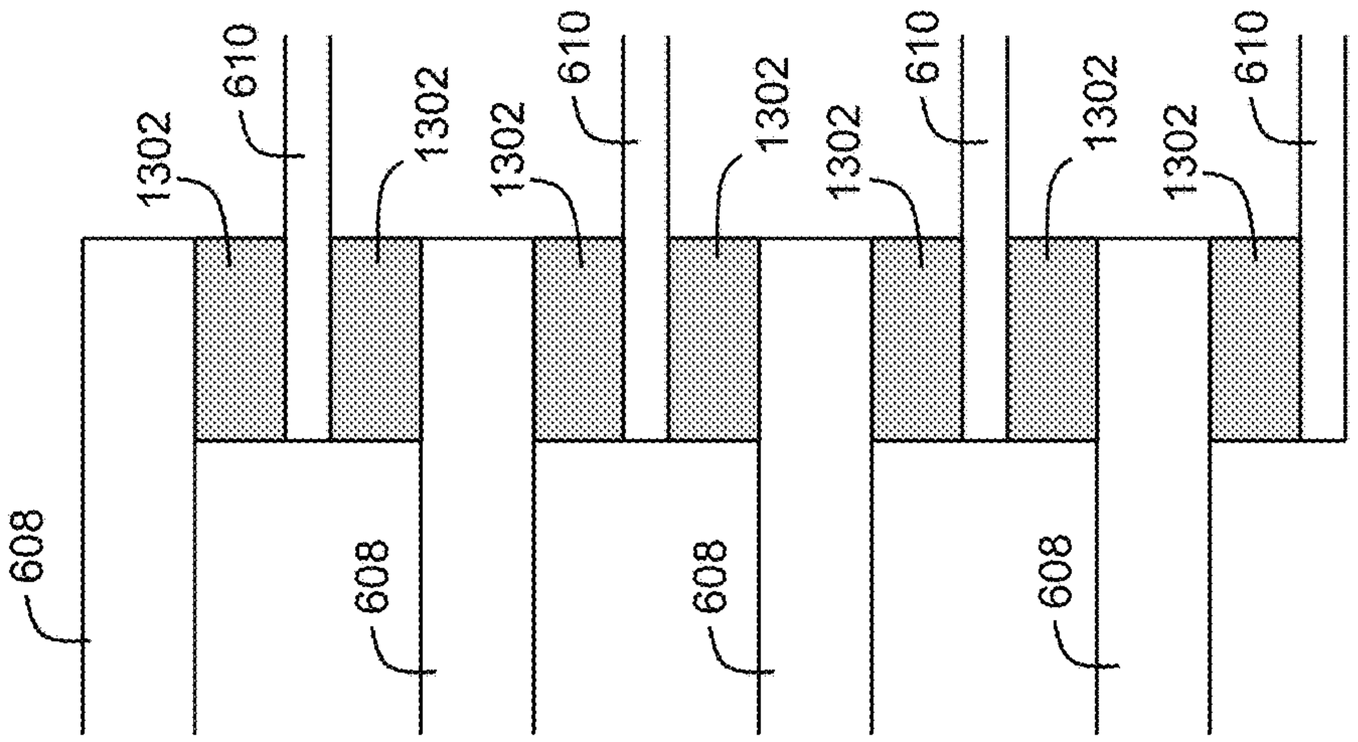


FIG. 13B

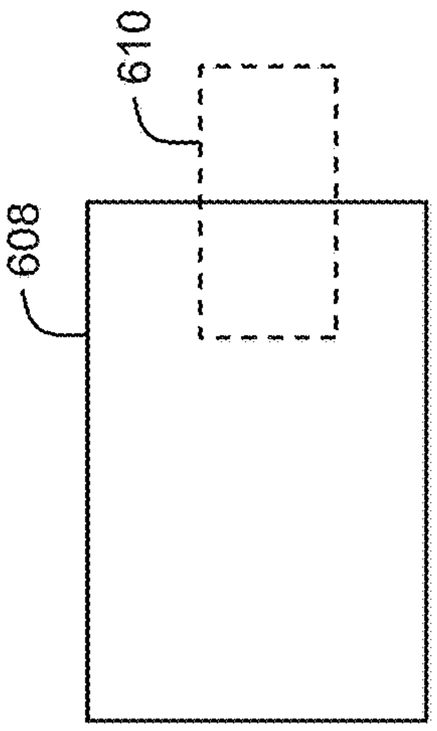


FIG. 13A

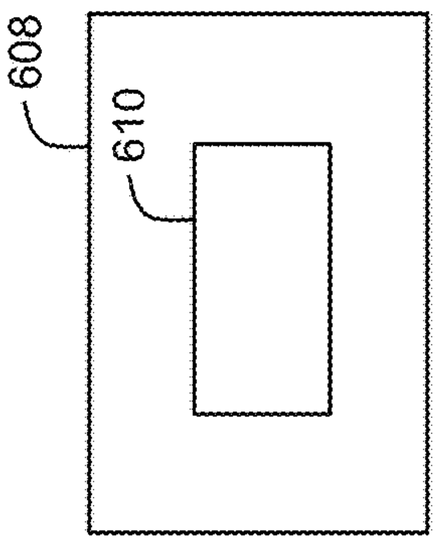


FIG. 13C

VOLTAGE SOURCE ISOLATION IN WIRELESS POWER TRANSFER SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application No. 62/258,144, filed on Nov. 20, 2015, the entire contents of which are incorporated herein by reference.

TECHNICAL FIELD

This disclosure relates to wireless power transfer systems, and in particular, to isolating voltage sources from reference ground in such systems.

BACKGROUND

Energy can be transferred from a power source to a receiving device using a variety of known techniques such as radiative (far-field) techniques. For example, radiative techniques using low-directionality antennas can transfer a small portion of the supplied radiated power, namely, that portion in the direction of, and overlapping with, the receiving device used for pick up. In such methods, much—even most—of the energy is radiated away in directions other than the direction of the receiving device, and typically the transferred energy is insufficient to power or charge the receiving device. In another example of radiative techniques, directional antennas are used to confine and preferentially direct the radiated energy towards the receiving device. In this case, an uninterruptible line-of-sight and potentially complicated tracking and steering mechanisms are used.

Another approach to energy transfer is to use non-radiative (near-field) techniques. For example, techniques known as traditional induction schemes do not (intentionally) radiate power, but use an oscillating current passing through a primary coil, to generate an oscillating magnetic near-field that induces currents in a nearby receiving or secondary coil. Traditional induction schemes can transfer modest to large amounts of power over very short distances. In these schemes, the offset tolerances between the power source and the receiving device are very small. Electric transformers and proximity chargers, for example, typically use traditional induction schemes.

Wireless power transfer systems can be used to transfer significant quantities of power between a source resonator and a receiving resonator. To generate a large amplitude magnetic field using a magnetic source resonator, one or more source resonator coils are typically driven with a large amplitude AC voltage that is referenced to a common ground in the source.

SUMMARY

With components referenced in a common ground in a wireless power transmitter, the components in the source each should be capable of withstanding the large AC voltage that is applied to the resonator coil(s). For example, switches that are used in capacitor banks as part of impedance matching networks, components that are used for communication, and other circuit elements that are used to generate low power driving voltages, to detect low power signals, and/or to switch or adjust other elements, should all be capable of withstanding the large AC driving voltages.

Components that can withstand such voltages are expensive and can therefore significantly increase the cost of wireless power transfer systems.

An alternative to common ground-referenced components would be to implement floating sources, switches, and other elements that are not referenced to the common wireless source ground. However, transformers that are typically used to implement floating elements are themselves expensive and bulky, and therefore also increase the cost and size of wireless power transfer systems.

Disclosed herein are systems and methods for wireless power transfer that implement floating components (e.g., voltage sources, switches, detectors, communication transmitters and receivers) by taking advantage of the large AC voltages that are used to drive source resonator coils. The systems include one or more auxiliary coils that transmit and/or receive small quantities of power, which can then be conditioned and used for a variety of applications. In effect, the auxiliary coils can be used to construct one or more floating "batteries" within a wireless power source. The floating batteries are then available for a wide variety of uses within the source.

In general, in a first aspect, the disclosure features wireless power transmitters that include a power source, a first coil connected to the power source, a second coil connected in series to the first coil, and a third coil positioned in proximity to the second coil, where during operation of the wireless power transmitter: the power source applies a driving voltage to the first and second coils; the first coil generates a first magnetic field that transfers power to a receiver resonator; the second coil generates a second magnetic field that induces a voltage across the third coil; and the induced voltage across the third coil is applied to a component of the wireless power transmitter.

Embodiments of the transmitters can include any one or more of the following features.

Each of the first, second, and third coils can include one or more loops of conductive material. The sources can include a housing that encloses the power source and the first, second, and third coils.

The component can include at least one of a resistive element, a capacitive element, and an inductive element of the wireless power transmitters. The component can include a switch of the wireless power transmitters. The component can include a component of an impedance matching network of the wireless power transmitters, e.g., an adjustable capacitor of the impedance matching network. The component can include a transceiver or transmitter configured to generate an information carrying signal.

The component can include a fourth coil configured to generate an information carrying magnetic field that, during operation, is received by a fifth coil connected to the receiver resonator. The sources can include a modulator configured to modulate the induced voltage to generate the information carrying magnetic field. The induced voltage can correspond to an oscillating voltage signal, and the modulator can be configured to modulate at least one of an amplitude and a frequency of the oscillating voltage signal to generate the information carrying magnetic field.

The sources can include a conditioning circuit connected to the third coil, where during operation, the conditioning circuit can be configured to at least one of rectify the induced voltage, adjust an amplitude of the induced voltage, and adjust a frequency of the induced voltage.

A magnitude of the induced voltage can be 1% or less (e.g., 0.01% or less) of a magnitude of a voltage induced in

the receiver resonator. The induced voltage may not be referenced to a ground voltage of the wireless power transmitter.

The transmitters can include a fourth coil connected in series to the first and second coils, and a fifth coil positioned in proximity to the fourth coil, where during operation of the wireless power transmitters: the power source applies the driving voltage to the first, second, and fourth coils; the fourth coil generates a third magnetic field that induces a voltage across the fifth coil; and the induced voltage across the fifth coil is applied to a second component of the wireless power transmitters. The second component can include at least one of a resistive element, a capacitive element, an inductive element, a switch, and a component of an impedance matching network. The second component can include a transceiver configured to generate an information carrying signal. The second component can include a sixth coil configured to generate an information carrying magnetic field that, during operation, is received by a seventh coil connected to the receiver resonator.

Embodiments of the transmitters can also include any of the other features disclosed herein, including combinations of features disclosed in connection with different embodiments, except as expressly stated otherwise.

In another aspect, the disclosure features wireless power transmitters that include a power source, a first coil connected to the power source, and a second coil positioned in proximity to the first coil, where during operation of the wireless power transmitters: the power source applies a driving voltage to the first coil; the first coil generates a magnetic field that transfers power to a receiver resonator; the magnetic field induces a voltage across the second coil; and the induced voltage across the second coil is applied to a component of the wireless power transmitters.

Embodiments of the transmitters can include any one or more of the following features.

Each of the first and second coils can include one or more loops of conductive material. The transmitters can include a housing that encloses the power source and the first and second coils.

The component can include at least one of a resistive element, a capacitive element, and an inductive element of the wireless power transmitters. The component can include a switch of the wireless power transmitters. The component can include a component of an impedance matching network of the wireless power transmitters. The component can include an adjustable capacitor of the impedance matching network. The component can include a transceiver or transmitter configured to generate an information carrying signal.

The component can include a third coil configured to generate an information carrying magnetic field that, during operation, is received by a fourth coil connected to the receiver resonator. The sources can include a modulator configured to modulate the induced voltage to generate the information carrying magnetic field. The induced voltage can correspond to an oscillating voltage signal, and the modulator can be configured to modulate at least one of an amplitude and a frequency of the oscillating voltage signal to generate the information carrying magnetic field.

The sources can include a conditioning circuit connected to the second coil, where during operation, the conditioning circuit is configured to at least one of rectify the induced voltage, adjust an amplitude of the induced voltage, and adjust a frequency of the induced voltage.

A magnitude of the induced voltage can be 1% or less (e.g., 0.01% or less) of a magnitude of a voltage induced in the receiver resonator. The induced voltage may not be referenced to a ground voltage of the wireless power transmitters.

The sources can include a third coil positioned in proximity to the first coil, where during operation of the wireless power transmitters, the magnetic field induces a voltage across the third coil, and the induced voltage across the third coil is applied to a second component of the wireless power transmitters. The second component can include at least one of a resistive element, a capacitive element, an inductive element, a switch, and a component of an impedance matching network. The second component can include a transceiver or transmitter configured to generate an information carrying signal. The second component can include a fourth coil configured to generate an information carrying magnetic field that, during operation, is received by a fifth coil connected to the receiver resonator.

Embodiments of the transmitters can also include any of the other features disclosed herein, including combinations of features disclosed in connection with different embodiments, except as expressly stated otherwise.

In a further aspect, the disclosure features wireless power systems that include a power source, a first coil connected to the power source, a second coil connected in series to the first coil, a third coil positioned in proximity to the second coil, a controller connected to the third coil and configured to selectively modulate coupling between the second and third coils, a power receiving device, a receiver resonator connected to the power receiving device, and a fourth coil connected to the power receiving device and positioned in proximity to the second coil, where during operation of the wireless power transfer systems: the power source applies a driving voltage to the first and second coils; the first coil generates a first magnetic field that transfers power to the receiver resonator; the second coil generates a second magnetic field that induces voltages across the third and fourth coils; and the controller modulates the coupling between the second and third coils to adjust a magnitude of the induced voltage across the fourth coil.

Embodiments of the systems can include any one or more of the features disclosed herein, including combinations of features disclosed in connection with different embodiments, except as expressly stated otherwise.

In another aspect, the disclosure features methods that include applying a driving voltage across first and second coils connected in series in a wireless power transmitter to generate a first magnetic field and a second magnetic field, where the first magnetic field transfers power wirelessly to a receiver resonator, and where the second magnetic field induces a voltage across a third coil positioned in proximity to the second coil in the wireless power transmitter, and applying the induced voltage to a component of the wireless power transmitter.

Embodiments of the methods can include any one or more of the features disclosed herein, including combinations of features disclosed in connection with different embodiments, except as expressly stated otherwise.

In a further aspect, the disclosure features methods that include applying a driving voltage across a source coil in a wireless power transmitter to generate a magnetic field to transfer power wirelessly to a receiver resonator, inducing a voltage in an auxiliary coil positioned in proximity to the source coil in the wireless power transmitter, and applying the induced voltage to a component of the wireless power transmitter.

Embodiments of the methods can include any one or more of the features disclosed herein, including combinations of

features disclosed in connection with different embodiments, except as expressly stated otherwise.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the subject matter herein, suitable methods and materials are described below. All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

The details of one or more embodiments are set forth in the accompanying drawings and the description below. Other features and advantages will be apparent from the description, drawings, and claims.

DESCRIPTION OF DRAWINGS

FIG. **1** is a schematic diagram of a wireless power system.

FIG. **2** is a perspective view of a wireless power transmitting apparatus.

FIG. **3** is a schematic diagram of a wireless power source.

FIG. **4** is a schematic diagram of a flyback transformer.

FIG. **5** is a schematic diagram of an opto-coupler.

FIG. **6** is a schematic diagram of a wireless power transfer system that includes one or more auxiliary coils.

FIG. **7** is a schematic diagram of a wireless power transfer system that includes two auxiliary coils.

FIG. **8** is a schematic diagram of a wireless power transfer system that includes multiple floating auxiliary power sources.

FIG. **9** is a schematic diagram of a portion of a wireless power transfer system that uses an auxiliary coil to adjust a variable capacitance.

FIG. **10** is a schematic diagram of a portion of a wireless power transfer system that uses an auxiliary coil for wireless communication.

FIG. **11** is a schematic diagram of a portion of a wireless power transfer system that uses an auxiliary coil to modulate an analog communication signal.

FIG. **12** is a schematic diagram of a portion of a wireless power transfer system that uses an auxiliary coil to generate a digital signal.

FIGS. **13**A-**13**C are schematic diagrams showing a portion of a source resonator coil in proximity to a portion of an auxiliary coil.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Introduction

A wireless power transfer system can include a power transmitting apparatus which is configured to wirelessly transmit power to a power receiving apparatus. In some embodiments, the power transmitting apparatus can include a source coil which generates oscillating fields (e.g., electric fields, magnetic fields) due to currents oscillating within the source coil. The generated oscillating fields can couple to the power receiving apparatus and provide power to the power receiving apparatus through the coupling. To achieve coupling, the power receiving apparatus typically includes a receiver coil. The oscillating fields generated by the source coil can induce oscillating currents within the receiver coil. In some embodiments, either or both of the source and receiver coils can be resonant. In some other embodiments, either or both of the source and receiver coils can be non-resonant so that power transfer is achieved through non-resonant coupling.

In some embodiments, a wireless power transfer system can utilize a source resonator to wirelessly transmit power to a receiver resonator. For example, a power transmitting apparatus of the system can include the source resonator, which has a source coil, and a power receiving apparatus of the system can include the receiver resonator, which has a receiver coil. Power can be wirelessly transferred between the source resonator and the receiver resonator. In certain embodiments, the wireless power transfer can be extended by multiple source resonators and/or multiple device resonators and/or multiple intermediate (also referred as "repeater" or "repeating") resonators.

FIG. **1** is a schematic diagram of a wireless power transfer system **100**. System **100** includes a power transmitting apparatus **102** and a power receiving apparatus **104**. Power transmitting apparatus **102** is coupled to power source **106** through a coupling **105**. In some embodiments, coupling **105** is a direct electrical connection. In certain embodiments, coupling **105** is a non-contact inductive coupling. In some embodiments, coupling **105** can include an impedance matching network (not shown in FIG. **1**). Impedance matching networks and methods for impedance matching are disclosed, for example, in commonly owned U.S. patent application Ser. No. 13/283,822, published as US Patent Application Publication No. 2012/0242225, the entire contents of which are incorporated herein by reference.

In similar fashion, power receiving apparatus **104** is coupled to a device **108** through a coupling **107**. Coupling **107** can be a direct electrical connection or a non-contact inductive coupling. In some embodiments, coupling **107** can include an impedance matching network, as described above.

In general, device **108** receives power from power receiving apparatus **104**. Device **108** then uses the power to do useful work. In some embodiments, for example, device **108** is a battery charger that charges depleted batteries (e.g., car batteries). In certain embodiments, device **108** is a lighting device and uses the power to illuminate one or more light sources. In some embodiments, device **108** is an electronic device such as a communication device (e.g., a mobile telephone) or a display. In some embodiments, device **108** is a medical device which can be implanted in a patient.

During operation, power transmitting apparatus **102** is configured to wirelessly transmit power to power receiving apparatus **104**. In some embodiments, power transmitting apparatus **102** can include a source coil, which can generate oscillating fields (e.g., electric, magnetic fields) when electrical currents oscillate within the source resonator. The generated oscillating fields can couple to power receiving apparatus **104** and provide power to the power receiving apparatus through the coupling. To achieve coupling between power transmitting apparatus **102** and power receiving apparatus **104**, the power receiving apparatus can include a receiver resonator. The oscillating fields can induce oscillating currents within the receiver resonator.

In certain embodiments, the system **100** can include a power repeating apparatus (not shown in FIG. **1**). The power repeating apparatus can be configured to wirelessly receive power from the power transmitting apparatus **102** and wirelessly transmit the power to the power receiving apparatus **104**. The power repeating apparatus can include similar

elements described in relation to the power transmitting apparatus **102** and the power receiving apparatus **104** above.

System **100** can include an electronic controller **103** configured to control the power transfer in the system **100**, for example, by directing electrical currents through coils of the system **100**. In some embodiments, the electronic controller **103** can tune resonant frequencies of resonators included in the system **100**, through coupling **109**. In some embodiments, the electronic controller **103** can tune impedance matching elements in either impedance matching network. The electronic controller **103** can be coupled to one or more elements of the system **100** in various configurations. For example, the electronic controller **103** can be only coupled to power source **106**. The electronic controller **103** can be coupled to power source **106** and power transmitting apparatus **102**. The electronic controller **103** can be only coupled to power transmitting apparatus **102**. In some embodiments, coupling **109** is a wireless communication (e.g., radio-frequency, Bluetooth communication). The coupling **109** between the electronic controller **103** and the various components of system **100** can depend, respectively, on the components. For example, the electronic controller **103** can be directly connected to power source **106** while wirelessly communicating with power receiving apparatus **104**.

In some embodiments, the electronic controller **103** can configure the power source **106** to provide power to the power transmitting apparatus **102**. For example, the electronic controller **103** can increase the power output of the power source **106** by sending a higher drive current to a coil in the power transmitting apparatus **102**. The power output can be at an operating frequency, which is used to generate oscillating fields by the power transmitting apparatus **102**.

In certain embodiments, the electronic controller **103** can tune a resonant frequency of a resonator in the power transmitting apparatus **102** and/or a resonant frequency of a resonator in the power receiving apparatus **104**. By tuning resonant frequencies of resonators relative to the operating frequency of the power output of the power source **106**, the efficiency of power transfer from the power source **106** to the device **108** can be controlled. For example, the electronic controller **103** can tune the resonant frequencies to be substantially the same (e.g., within 0.5%, within 1%, within 2%) to the operating frequency to increase the efficiency of power transfer. The electronic controller **103** can tune the resonant frequencies by adjusting capacitance values of respective resonators. To achieve this, for example, the electronic controller **103** can adjust a capacitance of a capacitor connected to a coil in a resonator. The adjustment can be based on the electronic controller **103**'s measurement of the resonant frequency or based on wireless communication signal from the apparatuses **102** and **104**. In certain embodiments, the electronic controller **103** can tune the operating frequency to be substantially the same (e.g., within 0.5%, within 1%, within 2%) to the resonant frequencies of the resonators. In some embodiments, the electronic controller **103** can tune the operating frequency.

In some embodiments, the electronic controller **103** can control an impedance matching network in the system **100** to optimize or de-tune impedance matching conditions in the system **100**, and thereby control the efficiency of power transfer. For example, the electronic controller **103** can tune capacitance of capacitors or networks of capacitors included in the impedance matching network connected between power transmitting apparatus **102** and power source **106**. The optimum impedance conditions can be calculated internally by the electronic controller **103** or can be received from an external device.

FIG. **2** is a schematic diagram of a power transmitting apparatus **200** that includes a resonator coil **202** having a plurality of loops. The resonator coil **202** can be printed on substrate **204** in the form of, for example, a printed circuit board. In some embodiments, a layer of magnetic material **206** can guide the magnetic field from one side of the resonator coil **210**. In certain embodiments, the power transmitting apparatus **200** can include a shield **208** (e.g., a sheet of conductive material) positioned between coil **202** and a lossy object **210**. Shield **208**, which is typically formed of a conductive material (such as copper, aluminum, and/or other metallic materials), shields magnetic fields generated by coil **202** from lossy object **210** (e.g., lossy steel object). For example, the shield **208** can reduce aberrant coupling of magnetic fields to lossy object **210** by guiding magnetic field lines away from the lossy object **210**.

FIG. **3** is a schematic diagram of a portion of a wireless power transmitter **300**. Source **300** includes a resonator coil **302** used to generate an oscillating magnetic field for wireless power transfer. Coil **302** is coupled through an impedance matching network (IMN) **304** to a power source represented by terminals A and B. Impedance matching network **304** includes a fixed capacitance C_1 and a variable capacitance C_2, although an impedance matching network **304** can be implemented in a wide variety of ways. Various aspects of impedance matching networks are disclosed, for example, in U.S. Patent Application Publication No. 2015/0270719, the entire contents of which are incorporated herein by reference.

The power source applies a driving voltage between terminals A and B to drive coil **302** to generate the magnetic field. The power source is referenced to common ground **308**, as are the other components of source **300**. During operation, the voltage at each of the terminals A and B can range from 0 (i.e., the ground voltage) to a maximum voltage V_{max}, which can be 1 V to 50 V or more.

A voltage difference $V_A - V_B$ is applied across coil **302** to drive the coil and generate the magnetic field used for wireless power transfer to a receiving coil. However, because V_A and V_B can each range in magnitude from V_{max} to 0 (the common ground voltage), each of the other components in source **300**—including the capacitors, inductors, switches, and other components of IMN **304**—should be capable of withstanding any voltage up to V_{max} to ensure that failure does not occur during operation of source **300**. If source **300** is tapped at point **306**, for example, to apply a voltage to a switch, a resistive element, a capacitive element, an inductive element, or any other circuit component, that component should also be capable of withstanding any voltage up to V_{max} to ensure failure does not occur, since that component will also be referenced to ground **308**.

Since V_{max} in wireless power transfer systems can be high, implementing such systems with hundreds or thousands of elements, all of which are capable of withstanding high voltages, adds significant expense to the systems. Moreover, for certain components designed to operate only at low voltages, designing high voltage-capable counterparts may be quite difficult.

Decoupling certain components of source **300** from common ground **308** creates "floating" components, i.e., components that are not ground referenced. During operation, components that are not ground referenced need only be capable of withstanding the voltage difference that is applied across their terminals, not the difference between the voltage

at one terminal and a ground reference, as discussed above. Such components are said to be "isolated" from other components in the system.

In general electrical circuits, isolation can conventionally be performed using DC-DC flyback transformers. FIG. **4** is a schematic diagram of a flyback transformer **400** that includes a primary winding **402** and a secondary winding **404**. During operation, a voltage V_C is applied across primary winding **402**, which is spaced from secondary winding **404**. The current flowing in primary winding **402** generates a magnetic field which in turn induces a voltage V_D across the terminals of secondary winding **404**.

In general, voltage V_D across the terminals of secondary winding **404** is only induced when the magnetic field generated by primary winding **402** is time-varying. However, V_C is typically a DC voltage. Accordingly, to produce a time-varying magnetic field from primary winding **402** (which approximates the field that would be produced from an AC driving voltage), V_C can be "chopped" using switch **408**, which alternately opens and closes to replicate a time-varying driving voltage.

The voltage that is thus induced across secondary coil **404** is a time-varying voltage also. Typically, however, flyback transformers are used for DC-DC voltage conversion. Accordingly, the induced voltage can be conditioned by voltage conditioner **406** (which can be, for example, a rectifier) to produce a DC output voltage V_D, which differs from the input DC voltage V_C.

Isolation can also be achieved using opto-couplers, particularly for low power signals such as those used for communication. FIG. **5** is a schematic diagram of an opto-coupler **500** that includes a radiation source **502** and a radiation receiver **504** enclosed in a housing **508**. During operation, a voltage V_E is applied across the terminals of source **502**, causing source **502** to emit radiation **506**. The emitted radiation is detected by receiver **504**, which generates a voltage V_F across its terminals. As the conversions from electrical energy to radiation and then from radiation back to electrical energy are lossy processes, V_F is less than V_E. Moreover, conventional sources **502** are not capable of generating sufficient quantities of radiation **506** such that large quantities of power can be transferred between source **502** and receiver **504**. As a result, opto-couplers are best suited for isolation in circumstances where only weak signals are involved, such as in communication.

Isolation with Auxiliary Coils

The benefits of achieving isolation of circuit elements are significant. For circuit elements that are isolated from large potentials relative to ground, the elements need only be capable of withstanding smaller voltages. As low-voltage circuit components are typically much cheaper than corresponding high-voltage components, portions of wireless power sources can be implemented at significant cost savings.

In addition, systems that implement isolation among components are typically safer, as portions of such systems are not exposed to high voltages. Isolation is important in medical applications, for example, where a wireless power source may be located in close proximity to a human or animal patient. Isolating certain components of the source ensures that the human or animal is not exposed to potentially lethal voltages that are generated within the source.

Further, isolation helps to eliminate electromagnetic interference (EMI) that can arise when energy couples back into the common ground, giving rise to ground loops. When this occurs, electrical noise from the ground-coupled energy can propagate into other components of the system that are also connected to the common ground, and can particularly disrupt low power signals such as those used for communication and low amplitude measurements.

But while these advantages of isolation in wireless power transfer systems are significant, the use of conventional isolation technologies in such systems is difficult, and obviates some of the advantages. Transformers that operate at high voltages are large and expensive, and inclusion of such devices in wireless power source can both increase the physical size of the source and increase the cost of the source. If multiple groups of isolated components are desired, multiple transformers may be required, further emphasizing these drawbacks. Opto-couplers are generally also expensive and only suitable for isolation of components that handle very low-power signals such as communication signals.

The systems and methods disclosed herein implement isolation in a different manner, using one or more auxiliary coils (i.e., coils that are different from one or more source resonator coils that are used to transfer power wirelessly to a receiver resonator by generating magnetic fields). In particular, the systems and methods exploit the AC driving voltage that is generated within a source resonator and used to drive one or more source resonator coils, using the driving voltage to generate auxiliary magnetic fields (or capturing a small portion of the magnetic field that is generated by the source resonator coil(s)) to transfer small quantities of power wirelessly to additional components within the source. As the additional components are not connected through conductors to the electronics that generate the AC driving voltage, the additional components are isolated from the source's common ground. The additional components therefore are effectively driven by floating batteries or power sources, and are not subject to, or expected to withstand, the large ground-referenced voltages that are generated in the source.

FIG. **6** is a schematic diagram showing one embodiment of a wireless power transfer system **600** that includes one or more auxiliary coils for ground-isolation of components. In FIG. **6**, a housing **602** encloses the components of a source, which include a power source **604**, switching and impedance matching circuitry **606**, a source resonator coil **608**, an auxiliary coil **610**, and conditioning circuit **612**. During operation of system **600**, power source **604** generates an AC driving voltage that is conveyed to coil **608** through switching and impedance matching circuitry **606**. Coil **608** generates a magnetic field (represented by field lines **614**), a portion of which is captured by receiver resonator coil **616**, inducing a current within the coil. Switching and impedance matching circuitry **618** (along with switching and impedance matching circuitry **606**) is configured to ensure that power is transferred efficiently between source coil **608** and receiver coil **616**. The current induced in receiver coil **616** is delivered to device **620**, where it performs useful work.

During operation of system **600**, auxiliary coil **610**—which can be positioned outside of a principal region of power transfer between source and receiver coils **608** and **616**—captures a small fraction of the magnetic field generated by source coil **608**, inducing a small voltage across auxiliary coil **610**. The induced voltage is optionally conditioned by conditioning circuit **612**, before being used to drive one or more elements in switching and impedance matching circuitry **606** and/or power source **604**. Conditioning can include, but is not limited to, rectification of the AC voltage induced in auxiliary coil **610** to generate a DC

voltage, attenuation of the voltage induced in auxiliary coil **610**, and changing the frequency of the voltage induced in auxiliary coil **610**.

Typically, auxiliary coil **610** captures only a very small portion of the magnetic field that is generated by source coil **608**, and therefore the voltage generated across the terminals of auxiliary coil **610** is small relative to the driving voltage applied to source coil **608**. By capturing only a small fraction of the field that is generated, the perturbing effect of the auxiliary coil on the transfer of power between source coil **608** and receiver coil **616** is relatively insignificant. In some embodiments, for example, the voltage across auxiliary coil **610**, V_{aux} can be 1% or less of the driving voltage V_{src} applied across source coil **608** (e.g., 0.5% or less, 0.1% or less, 0.05% or less, 0.01% or less, 0.001% or less, 0.0001% or less).

In FIG. **6**, a single auxiliary coil is used in system **600** to function effectively as a floating voltage source. More generally, however, system **600** can include more than one auxiliary coil configured in the same manner, each of which functions as an independent, floating voltage source. In some embodiments, for example, system **600** can include 2 or more auxiliary coils (e.g., 3 or more auxiliary coils, 4 or more auxiliary coils, 5 or more auxiliary coils, 7 or more auxiliary coils, or even more).

In general, the auxiliary coil **610** can be positioned on or near the source resonator coil **608**, and the spatial location and orientation of auxiliary coil **610** relative to source resonator coil **608** can be adjusted to control the amount of flux captured by auxiliary coil **610** from source coil **608**, and the coupling between the coils. In some embodiments, for example, auxiliary coil **610** and source coil **608** overlap in the x-y (i.e., coil) plane, but are relatively displaced in a direction perpendicular to the plane. FIG. **13**A is a schematic diagram showing an embodiment of a wireless power transfer system in which auxiliary coil **610** overlaps with, and is displaced vertically from, source resonator coil **608**. To indicate that coil **610** is in a different plane from coil **608**, coil **610** is shown in dashed lines.

In certain embodiments, auxiliary coil **610** and source resonator coil **608** can be interleaved. FIG. **13**B is a schematic diagram showing an embodiment of a wireless power transfer system in which individual loops of source coil **608** are interleaved with loops of auxiliary coil **610**. Insulating material **1302** is positioned between adjacent interleaved loops.

In some embodiments, auxiliary coil **610** can be positioned within source resonator coil **608**. FIG. **13**C is a schematic diagram of a wireless power transfer system in which auxiliary coil **610**, which is coplanar with source resonator coil **608**, is positioned within a central region of source coil **608**, surrounded by the loops of source coil **608**.

In general, the action of conditioning circuit **612**, as well as power source **604** and switching and matching circuitry **606**, is controlled by controller **622**, which is connected to conditioning circuit **612**, power source **604**, and switching and matching circuitry **606** via one or more communication lines (shown as dashed lines in FIG. **6**). In addition to regulating modulation (amplitude and/or frequency) and rectification by conditioning circuit **612**, controller **622** also adjusts the driving voltage and frequency generated by power source **604**, impedance adjustment by circuitry **606**, and also regulates other functions such as communication between components of the source, and between the source and device **620**.

In FIG. **6**, auxiliary coil **610** is positioned inside housing **602**. Housing **602** can be formed from or lined with a material (e.g., a conductive material) that effectively prevents stray fields other than those used for wireless power transfer from escaping. By positioning auxiliary coil **610** inside housing **602**, the portion of the magnetic field that is captured by auxiliary coil **610** does not affect other field-sensitive devices or elements that may be positioned outside housing **602**, which reduces electrical interference and noise that might otherwise occur during operation of the system. More generally, however, in certain embodiments, auxiliary coil **610** can be positioned either inside housing **602** or external to housing **602**. By positioning auxiliary coil **610** external to housing **602**, the auxiliary coil may be able to capture a larger fraction of the field generated by source coil **608**. Such a configuration can be useful for certain applications, particularly where shielding and/or containment of the magnetic field is not as significant a concern.

In certain embodiments, multiple auxiliary coils can be used to create an isolated, floating voltage source. FIG. **7** is a schematic diagram of a wireless power transfer system **700** that includes a power source **704**, switching and matching circuitry **706**, source resonator coil **708**, and a controller **722** enclosed within a housing **702**. During operation, source resonator coil **708** generates a magnetic field (represented by field lines **714**) that is captured by receiver resonator coil **716**, which is coupled to switching and matching circuitry **718**. The current induced in receiver resonator coil **716** is coupled to load **720** and provides electrical power for the load. The foregoing components of system **700** function in a manner similar to their counterparts in system **600**.

System **700** includes two auxiliary coils **710** and **711**. Coil **710** is connected in series with source resonator coil **708**, such that the driving voltage applied to source resonator coil **708** is also applied across auxiliary coil **710**. Coil **711** is coupled to conditioning circuit **712**. During operation of system **700**, when the driving voltage is applied across source resonator coil **708** and auxiliary coil **710**, auxiliary coil **710** generates a magnetic field (represented by field lines **713**). Auxiliary coil **711** captures the field generated by coil **710**, which induces a voltage across the terminals of coil **711**. Conditioning circuit **712** is configured to perform functions similar to the functions of conditioning circuit **612**, i.e., rectifying the induced voltage across coil **711** and/or modulating the amplitude and/or frequency of the induced voltage, for example. The conditioned voltage then functions as an auxiliary floating power source, which is coupled to one or more elements of power source **704** and/or switching and matching circuitry **706** within the wireless power source.

As shown in FIG. **7**, auxiliary coils **710** and **711** can be fully enclosed within housing **702** to ensure that magnetic fields used to creating floating power sources do not perturb other components of the system (i.e., components that are not part of the wireless power source). More generally, auxiliary coils **710** and/or **711** can be positioned either interior to housing **702** or exterior to housing **702**, depending upon the particular wireless power transfer application.

The use of two auxiliary coils—one of which is connected in series with source resonator coil **708**—to realize a floating power source internal to the wireless power source that is isolated from the wireless power source's common ground reference has certain advantages relative to one-auxiliary-coil implementations, as shown in FIG. **6**. By using a first auxiliary coil (i.e., coil **710**) to generate a small amplitude magnetic field, and a second auxiliary coil (i.e., coil **711**) to capture the small amplitude field, the auxiliary coil that receives the field does not have to be positioned anywhere near the magnetic field that is generated by source coil **708**

for wireless power transfer. As such, the use of auxiliary coils does not perturb the spatial field distribution (represented by magnetic field lines **714**) used for wireless power transfer, and the auxiliary coil that receives the magnetic field does not capture too large a fraction (or even any fraction) of the wireless power transfer field. Furthermore, the use of two auxiliary coils allows for greater flexibility in the layout and design of wireless power transfer systems; pairs of auxiliary coils can be positioned at nearly any desired location within the wireless power source to realize a floating auxiliary power source.

In general, auxiliary coil **710** can be positioned in series with source coil **708** on either side of source coil **708** (i.e., in terms of current flow, either upstream or downstream relative to source coil **708**). Further, while a single pair of auxiliary coils are used to implement a single auxiliary floating power source in FIG. **7**, more generally a wireless power source can include multiple pairs of auxiliary coils, each of which is used to implement an independent auxiliary floating power source.

FIG. **8** is a schematic diagram showing a portion of a wireless power system **800** that is similar to system **700** of FIG. **7**, but includes multiple floating auxiliary power sources. More specifically, in system **800**, a source resonator coil **808** is connected at points A and B to switching and matching circuitry and a power source (not shown in FIG. **8**), and during operation, generates a magnetic field **814** for wireless power transfer to a receiving resonator. Connected in series with source coil **808** are three auxiliary coils **810***a*, **810***b*, and **810***c*, which generate magnetic fields **813***a*, **813***b*, and **813***c*, respectively, when the driving voltage is applied across terminals A and B. Fields **813***a-c* are captured by auxiliary coils **811***a*, **811***b*, and **811***c*, respectively, inducing voltages across each of coils **811***a-c*. The induced voltages are conditioned, respectively, by conditioning circuits **812***a*, **812***b*, and **812***c*. As a result, auxiliary coils **810***a-c* and **811***a-c* yield three floating, independent auxiliary voltage sources V_a, V_b, and V_c, each of which can be connected to one or more components within the wireless power source to drive the components and/or perform other useful work.

While system **800** includes three auxiliary floating power sources, in general any number of auxiliary power sources can be included in a wireless power source. For example, a wireless power source can include two or more auxiliary floating power sources (e.g., three or more sources, four or more sources, five or more sources, or even more sources). Each of the multiple sources can be implemented using a single auxiliary coil, as discussed above in connection with FIG. **6**, or using two auxiliary coils, as discussed in connection with FIGS. **7** and **8**. In some embodiments, these implementations can be mixed: one or more auxiliary floating power sources can be implemented using a single auxiliary coil, and one or more auxiliary floating power sources can be implemented using pairs of auxiliary coils. Typically, the area and strength of the magnetic field generated by source resonator **808** are considerations in determining the number of auxiliary power sources that are implemented.

Whether auxiliary floating power sources are implemented using a single auxiliary coil or a pair of auxiliary coils, the sizes of the coils (e.g., the number of turns, the diameter of the turns, the size and composition of the core material) determine the magnitudes of the voltages of each auxiliary source. In general, the sizes of the coils are chosen such that perturbations of the wireless power transfer process between the source coil and the receiver resonator are relatively insignificant, and so that the voltage of each floating source is nonetheless sufficient for its intended purpose. Where a wireless power source includes multiple auxiliary floating sources, the sources are independent and therefore can have the same or different output voltages. For example, in system **800**, V_a, V_b, and V_c can be the same, any two of these can be the same, or they can each be different voltages.

Applications

The floating (i.e., ground isolated) auxiliary sources disclosed herein can be used for a variety of applications in wireless power transfer systems. In general, each of the auxiliary sources is coupled to one or more low voltage components within the wireless power source and is used to drive the coupled components. Because the auxiliary sources are decoupled from the wireless power source's common ground, the components to which they are coupled are not subjected to the large, ground-referenced voltages that are generated by the wireless power source's electronics. To the contrary, the components to which the auxiliary sources are coupled are subjected only to the much lower floating voltages (i.e., V_a, V_b, and V_c in system **800**), and are therefore significantly cheaper to implement than their corresponding high voltage counterparts would be.

Floating auxiliary power sources can generally be used for functions that fall within one of two categories in a wireless power source: power-related functions and communication-related functions. Power-related functions include driving adjustable components such as inductors, capacitors, resistors, switches, detectors, and other electronic devices. FIG. **9** illustrates an example of such an application. In FIG. **9**, the output voltage V_a from a floating auxiliary source (such as the corresponding source shown in FIG. **8**) is connected across switch S_1, which is connected in series with capacitance C_2 of an adjustable capacitor. The adjustable capacitor also includes a fixed capacitance C_1. When voltage V_a is applied across switch S_1, the switch closes, coupling C_2 into the circuit. When the voltage is not applied across S_1, C_2 is decoupled from the circuit. Thus, the auxiliary floating source can be used to implement an adjustable capacitor (e.g., in an impedance matching circuit) by selectively closing or opening S_1 to switch C_2 in or out of the total capacitance.

As mentioned above, auxiliary floating power sources are also well suited for communications-related applications. Such applications can include communications between components internal to the wireless power source, and communications between the wireless power source and the wireless power receiver that receives wirelessly transmitted power. A variety of different types of communications systems can be implemented. In some embodiments, for example, an auxiliary floating power source can be used to drive a transmitter located in a wireless power source to generate a communications signal that is received by the receiver connected to the receiving resonator.

FIG. **10** is a schematic diagram showing a portion of a wireless power transfer system **1000**, including a controller **1022** connected to a transceiver **1030** in a wireless power source, and a transceiver **1040** connected to a load **1020** that receives power from the wireless power source. A voltage V_a is applied to transceiver **1030**, which also receives an information signal from controller **1022**. Transceiver **1030**, energized by voltage V_a, generates a communications signal **1035** that carries the information from controller **1022**. The communications signal is received by transceiver **1040** and delivered to device **1020**, and the information encoded in the signal is extracted. Communications signals that correspond to a wide variety of different protocols and implementations

can be transmitted in the foregoing manner, including Bluetooth® signals, wireless 802.11a/b/g/n signals, IrDA signals, and signals corresponding to other open and/or proprietary specifications.

In the above discussion, wireless power transfer system **1000** includes transceivers **1030** and **1040**. In general, transceivers are devices that both transmit and receive communication signals. However, the system shown in FIG. **10**, as well as the other systems disclosed herein, are not limited to the use of transceivers and/or two-way communication. It should be understood that any of the transceivers disclosed in connection with embodiments herein can be replaced with a transmitter or a receiver alone, or separate transmitters and receivers, for purposes of one-way communication. Thus, the term "transceiver" should be understood to include functional devices that can transmit only, receive only, or both transmit and receive communication signals.

In some embodiments, floating auxiliary voltage sources can be used to drive magnetic resonators that generate communications signals. FIG. **11** is a schematic diagram showing a portion of a wireless power transfer system **1100** that includes a source resonator coil **1102** in a wireless power source and a receiving resonator coil **1104** connected to a load **1120** that receives power wirelessly from the wireless power source. To generate a communications signal, voltage V_a generated by a floating auxiliary source is applied to a modulator **1106**. Voltage V_a typically corresponds to an oscillating AC voltage signal at a frequency corresponding approximately to the frequency of the voltage applied to the source resonator coil in the wireless power source to generate the power transmitting magnetic field.

Modulator **1106** modulates voltage signal V_a to encode information into the voltage signal. In some embodiments, for example, modulator **1106** generates an amplitude modulated voltage signal, where the information is encoded as variations in an amplitude envelope function that modulates the underlying sinusoidal AC voltage signal V_a. In certain embodiments, modulator **1106** generates a frequency modulated voltage signal, where the information is encoded as variations in the nominal frequency of the oscillating AC voltage signal V_a. Modulator **1106** can also implement other modulation or encoding schemes as well.

The modulated voltage signal is then delivered to source resonator coil **1102**, where it generates a magnetic field that is modulated in a manner that corresponds to the modulation of the voltage signal. The modulated magnetic field is captured by receiving resonator coil **1104**, and induces a voltage signal across the receiving resonator coil that is modulated in the same manner as V_a. Load **1120** (or circuits connected to load **1120**) demodulates the induced voltage signal to extract the information encoded in it.

Amplitude and frequency modulation of a sinusoidal or other oscillating/periodic carrier wave signal are methods for implementing analog communication between a wireless power source and receiver. However, floating auxiliary voltage sources can also be used to implement digital communication between a source and receiver. FIG. **12** is a schematic diagram showing a portion of a wireless power transfer system **1200**. In system **1200**, a source resonator coil **1208** and an auxiliary coil **1210** are connected in series. When a driving voltage is applied across terminal points A and B, source resonator coil **1208** generates a magnetic field that transfers power to a receiver resonator (not shown in FIG. **12**), and auxiliary coil **1210** generates an auxiliary magnetic field **1215**.

System **1200** includes two additional auxiliary coils **1211** and **1221**. Auxiliary coil **1211** is a component of the wireless power source, and auxiliary coil **1221** is connected to a device **1220** that receives power from the wireless power source. Auxiliary coil **1211** is connected in series with a switch S_v, which is controlled by controller **1222**. Auxiliary coils **1211** and **1221** are positioned so that each coil captures a portion of magnetic field **1215**. Accordingly, voltages are induced across each of coils **1211** and **1221** when coil **1210** generates field **1215**.

Because both auxiliary coils **1211** and **1221** couple to coil **1210** through the same magnetic field **1215**, a change in the coupling between coils **1211** and **1210** changes the coupling between coils **1221** and **1210**, and vice versa. Put another way, the coupling between auxiliary coils **1210** and **1221**—and therefore the voltage induced across auxiliary coil **1221**—can be changed by adjusting the coupling between coils **1210** and **1211**. System **1200** exploits this property by using switch S_v to adjust the coupling between coils **1210** and **1211**. When controller **1222** closes switch S_v, coil **1211** is connected or shorted within the wireless power source. Power is transferred from coil **1210** to coil **1211**, and power transfer between coils **1210** and **1221** is therefore reduced or otherwise modulated. Conversely, when controller **1222** opens switch S_v thereby decoupling or open-circuiting coil **1211** within the wireless power source, power transfer between coils **1210** and **1211** is reduced, and power transfer between coils **1210** and **1221** is increased or otherwise modulated.

Device **1220** connected to auxiliary coil **1221** senses the changes in induced voltage across coil **1221** as switch S_v is opened and closed. As a result, controller **1222** can implement a digital (or bitwise) communication protocol that transmits information to device **1220** by opening and closing switch S_v to alternately switch coil **1221** between high and low voltage states. In this method, controller **1222** does not directly generate a communication signal that is broadcast. Instead, controller **1222**—through auxiliary coil **1211**—effectively functions as a digital modulator that perturbs power transfer between two different coils (i.e., coils **1210** and **1221**).

This method for generating an "on/off" signal can also be used to switch devices such as power supplies on and off. Using a method similar to the one described above, signals corresponding to high and low voltage states can be used to activate and de-activate, respectively, device **1220**. Device **1220** can correspond to a power supply or to any one or more of various switchable electronic devices.

FIG. **12** shows communication of information from a wireless power source to a receiving device by modulating power transfer between an auxiliary coil connected in series with a source resonator coil and an auxiliary coil connected to the receiving device. Similar methods can be used to generate a digital communication signal that is received by auxiliary coil **1211** and controller **1222**, i.e., coil **1221** can be alternately connected and disconnected by closing and opening a switch connected in series with coil **1221** by device **1220**, thereby modulating coupling and the induced voltage across coil **1211** between high and low voltage states.

Two-way communication between the wireless power source and device **1220** can be implemented in various ways. In some embodiments, for example, coils **1211** and **1221** can be used both to effectively "transmit" and "receive" signals by interleaving these functions in time. For example, for a first period of time, coil **1211** can be alternately coupled and decoupled by controller **1222** to induce voltage changes across coil **1221**, thereby communicating

information to device **1220**. Then, for a second period of time, coil **1221** can be alternately coupled and decoupled by device **1220** to induce voltage changes across coil **1211**, thereby communicating information to the wireless power source. The alternating of functionalities defines a duty cycle for coils **1211** and **1221** that enables two-way communication.

In certain embodiments, system **1200** includes additional auxiliary coils to enable simultaneous two-way communication. For example, system **1200** can include a second auxiliary coil connected in series with source coil **1208** that generates a second auxiliary magnetic field, analogous to field **1215**. Two additional auxiliary coils, one implemented as part of the wireless power source and the other connected to device **1220**, are positioned so that each captures a portion of the second auxiliary magnetic field, analogous to auxiliary coils **1211** and **1221**.

The generation of two magnetic fields by two different auxiliary coils connected in series with source resonator coil **1208** allows the wireless power source to transmit information to, and receive information from, device **1220** at the same time. In particular, one of the auxiliary magnetic fields can be used to induce an information-carrying voltage signal that is received by device **1220**, while the other auxiliary magnetic field can be used to induce an information-carrying voltage signal that is received by the wireless power source, as disclosed above. In this manner, digitally encoded information can be transmitted bi-directionally between the wireless power source and device **1220**.

Other applications can also take advantage of the auxiliary coils disclosed herein. For example, auxiliary coils can be used to isolate sensitive analog circuitry from noisy power ground connections, thereby ensuring that such circuitry operates at high sensitivity. Auxiliary coils can also be used to implement feedback systems in which power from one or more auxiliary coils is used to adjust coupling to provide a regulated source (i.e., perform auxiliary coil-mediated voltage regulation).

Other Embodiments

A number of embodiments have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the disclosure. Accordingly, other embodiments are within the scope of the following claims.

What is claimed is:

1. A wireless power transmitter, comprising:
a power source;
a first coil connected to the power source;
a second coil connected in series to the first coil; and
a third coil positioned in proximity to the second coil,
wherein during operation of the wireless power transmitter:
the power source applies a driving voltage to the first and second coils;
the first coil generates a first magnetic field that transfers power to a receiver resonator;
the second coil generates a second magnetic field that induces a voltage across the third coil; and
the induced voltage across the third coil is applied to a component of the wireless power transmitter.

2. The transmitter of claim **1**, wherein each one of the first, second, and third coils comprises one or more loops of conductive material.

3. The transmitter of claim **1**, wherein the component comprises at least one of a resistive element, a capacitive element, an inductive element, and a switch of the wireless power transmitter.

4. The transmitter of claim **1**, wherein the component comprises a component of an impedance matching network of the wireless power transmitter.

5. The transmitter of claim **1**, wherein the component comprises a transceiver configured to generate an information carrying signal.

6. The transmitter of claim **1**, wherein the component comprises a fourth coil configured to generate an information carrying magnetic field that, during operation, is received by a fifth coil connected to the receiver resonator, the transmitter further comprising a modulator configured to modulate the induced voltage to generate the information carrying magnetic field, wherein the induced voltage corresponds to an oscillating voltage signal, and wherein the modulator is configured to modulate at least one of an amplitude and a frequency of the oscillating voltage signal to generate the information carrying magnetic field.

7. The transmitter of claim **1**, wherein a magnitude of the induced voltage is 1% or less of a magnitude of a voltage induced in the receiver resonator.

8. The transmitter of claim **1**, wherein the induced voltage is not referenced to a ground voltage of the wireless power transmitter.

9. A method, comprising:
applying a driving voltage across first and second coils connected in series in a wireless power transmitter to generate a first magnetic field and a second magnetic field, wherein the first magnetic field transfers power wirelessly to a receiver resonator, and wherein the second magnetic field induces a voltage across a third coil positioned in proximity to the second coil in the wireless power transmitter; and
applying the induced voltage to a component of the wireless power transmitter.

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