A current sensor (402) may include a sense element (604) disposed proximate a conductor (542). The current sensor may be configured to couple to a first magnetic field (548) generated at the conductor when current flows in the conductor. An output (48) electrically connected to the sense element can produce a signal (Vout) that is representative of the flow of current in the conductor. The sense element may be oriented in a plane parallel to magnetic field lines (546) of a second magnetic field generated by a load (544) connected to the conductor.
APPARATUS AND METHOD FOR A CURRENT SENSOR

TECHNICAL FIELD

[0001] The present disclosure generally relates to current sensors. More specifically, the disclosure is directed to devices, systems, and methods related to current sensors using magnetic induction.

BACKGROUND

[0002] Wireless power transfer is an increasingly popular capability in portable electronic devices, such as mobile phones, computer tablets, etc. because such devices typically require long battery life and low battery weight. The ability to power an electronic device without the use of wires provides a convenient solution for users of portable electronic devices. Wireless power charging systems, for example, may allow users to charge and/or power electronic devices without physical, electrical connections, thus reducing the number of components required for operation of the electronic devices and simplifying the use of the electronic device.

Wireless power transfer allows manufacturers to develop creative solutions to problems due to having limited power sources in consumer electronic devices. Wireless power transfer may reduce overall cost (for both the user and the manufacturer) because conventional charging hardware such as power adapters and charging chords can be eliminated. There is flexibility in having different sizes and shapes in the components (e.g., magnetic coil, charging plate, etc.) that make up a wireless power transmitter and/or a wireless power receiver in terms of industrial design and support for a wide range of devices, from mobile handheld devices to computer laptops.

SUMMARY

[0003] In some aspects of the present disclosure, a current sensor may include a sense element configured to couple to a first magnetic field generated at a first location that can arise due a flow of current in the conductor. The current sensor may include an output that is electrically connected to the sense element to produce a signal that is representative of the flow of current in the conductor. The sense element may be oriented in a plane parallel to magnetic field lines of a second magnetic field, different from the first magnetic field, generated by a load connected to the conductor at a second location different from the first location.

[0004] In some aspects, the sense element may comprise an electrically conductive coil disposed on a substrate and positioned adjacent the conductor. The current sensor may further include a filter circuit comprising the electrically conductive coil connected to a resistor and a capacitor. In some
aspects, the filter circuit may be a bandpass filter. In some aspects, the substrate that carries the electrically conductive coil may be disposed perpendicular to a printed circuit board (PCB) that carries the conductor.

[0005] In some aspects, the load is a power transmitting element configured to generate an external magnetic field for wireless power transfer. The external magnetic field constitutes the second magnetic field. In some aspects, the sense element may include an electrically conductive coil. In some aspects, the current sensor may include filter comprising the electrically conductive coil of the sense element. The filter may be tuned to a resonant frequency of the power transmitting element.

[0006] In some aspects, the current sensor may further include a capacitive shield disposed adjacent to the sense element. The capacitive shield can prevent an electric field generated by the voltage in the conductor from being capacitively coupled to the sense element. In some aspects, the capacitive shield may be a conductive lead disposed adjacent to both the sense element and the conductor. The conductive lead may have a free first end and a second end configured for a connection to ground potential.

[0007] In some aspects, the sense element may include a first electrically conductive coil disposed on a first plane and at least a second electrically conductive coil disposed on at least a second plane spaced apart from the first plane. The first electrically conductive coil may be connected in series with the second electrically conductive coil. In some aspects, the first electrically conductive coil may be a trace formed on a first layer of a multi-layer PCB and the second electrically conductive coil may be a trace formed on a second layer of the multi-layer PCB. In some aspects, the first electrically conductive coil may be disposed on one side of the conductor and the second electrically conductive coil may be disposed on another side of the conductor.

[0008] In some aspects, the current sensor may include a first capacitive shield configured to be disposed adjacent to both the first electrically conductive coil and the conductor, and at least a second capacitive shield configured to be disposed adjacent to both the second electrically conductive coil and the conductor.

[0009] In some aspects, the current sensor may include a filter circuit comprising either or both the first electrically conductive coil and the second electrically conductive coil.

[0010] In some aspects, the sense element may include a first electrically conductive coil and at least a second electrically conductive coil, the first and second coils both spaced apart from each other on the same plane.
In some aspects according to the present disclosure, a method of sensing a flow of current in a conductor may include generating a sensed signal by magnetically coupling to a first magnetic field arising from the conductor due a flow of current in the conductor and generating an output signal from the sensed signal. The magnetic coupling may occur in a plane parallel to field lines of a second magnetic field generated by the flow of current through a load electrically connected to the conductor.

In some aspects, magnetically coupling to the first magnetic field may include inducing a current, using the first magnetic field, in a coil of electrically conductive material disposed adjacent the conductor and aligned in the plane parallel to field lines of the second magnetic field.

In some aspects, the method may further include filtering the sensed signal to attenuate frequency components in the sensed signal determined by a filter circuit that includes the coil of electrically conductive material.

In some aspects, the load may be a power transmitting element configured to generate an external magnetic field for wireless power transfer, wherein the external magnetic field constitutes the second magnetic field.

In some aspects, the method may further include shielding the sensed signal from an electric field generated in the conductor so that the generated output signal is substantially free of influence from the electric field.

In some aspects, magnetically coupling to the first magnetic field may include coupling the first magnetic field to a first coil of electrically conductive material disposed adjacent the conductor and coupling the first magnetic field to a second coil of electrically conductive material disposed adjacent the conductor.

In some aspects of the present disclosure, an apparatus for sensing a flow of current in a conductor may include means for magnetically coupling to a first magnetic field arising from the conductor due a flow of current in the conductor to generate a sensed signal and means for generating an output signal from the sensed signal. The means for magnetically coupling to a first magnetic field may be aligned in a plane parallel to field lines of a second magnetic field generated by the flow of current through a load electrically connected to the conductor.

In some aspects, the apparatus may include means for filtering the sensed signal including the means for magnetically coupling to a first magnetic field. The means for magnetically coupling to a first magnetic field may be a coil of electrically conductive material. The means for filtering may be a bandpass filter.
In some aspects of the present disclosure, an apparatus for wirelessly transmitting charging power to a receiver device may include a transmit coil, a driver circuit electrically coupled to the transmit coil via a conductor, and a current sensor configured to sense a flow of current in the conductor. The driver circuit may be configured to drive the transmit coil with an alternating current via the conductor. The current sensor may include a sense coil configured to couple to a first magnetic field generated by the alternating current in the conductor to produce a signal that is indicative of the flow of current in the conductor. The transmit coil may be configured to generate a second magnetic field for wirelessly transmitting charging power to the receiver device in response to being driven by the alternating current. The sense coil may be oriented in a plane parallel to field lines of the second magnetic field.

In some aspects, the apparatus may include a filter circuit comprising the sense coil and a resistor and capacitor electrically connected to the sense coil. The filter may be a bandpass filter.

In some aspects, the current sensor may include a capacitive shield disposed adjacent to the sense coil. The capacitive shield can prevent an electric field generated in the conductor from being capacitively coupled to the sense coil, wherein the capacitive shield comprises a second conductor disposed between the conductor and the sense coil.

The following detailed description and accompanying drawings provide a better understanding of the nature and advantages of the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

With respect to the discussion to follow and in particular to the drawings, it is stressed that the particulars shown represent examples for purposes of illustrative discussion, and are presented in the cause of providing a description of principles and conceptual aspects of the present disclosure. In this regard, no attempt is made to show implementation details beyond what is needed for a fundamental understanding of the present disclosure. The discussion to follow, in conjunction with the drawings, makes apparent to those of skill in the art how embodiments in accordance with the present disclosure may be practiced. In the accompanying drawings:

Fig. 1 is a functional block diagram of a wireless power transfer system in accordance with an illustrative embodiment.

Fig. 2 is a functional block diagram of a wireless power transfer system in accordance with an illustrative embodiment.
[0026] Fig. 3 is a schematic diagram of a portion of transmit circuitry or receive circuitry of Fig. 2 including a power transmitting or receiving element in accordance with an illustrative embodiment.

[0027] Figs. 4A and 4B represent illustrative configurations that embody a current sensor in accordance with the present disclosure.

[0028] Figs. 5A, 5B, and 5C illustrate aspects of a current sensor in accordance with the present disclosure.

[0029] Fig. 6 illustrates details of a current sensor in accordance with the present disclosure.

[0030] Figs 6A and 6B illustrate additional embodiments of a current sensor.

[0031] Fig. 7 illustrates a configuration of a current sensor in accordance with the present disclosure.

[0032] Fig. 8 illustrates a filter configured in accordance with the present disclosure.

[0033] Figs. 9 and 9A illustrate additional embodiments of a current sensor.

[0034] Figs. 10A, 10B, 10C, and 10D show illustrative configurations of current sensors in accordance with the present disclosure.

DETAILED DESCRIPTION

[0035] Wireless power transfer may refer to transferring any form of energy associated with electric fields, magnetic fields, electromagnetic fields, or otherwise from a transmitter to a receiver without the use of physical electrical conductors (e.g., power may be transferred through free space). The power output into a wireless field (e.g., a magnetic field or an electromagnetic field) may be received, captured by, or coupled by a "power receiving element" to achieve power transfer.

[0036] Fig. 1 is a functional block diagram of a wireless power transfer system 100, in accordance with an illustrative embodiment. Input power 102 may be provided to a transmitter 104 from a power source (not shown in this figure) to generate a wireless (e.g., magnetic or electromagnetic) field 105 for performing energy transfer. A receiver 108 may couple to the wireless field 105 and generate output power 110 for storing or consumption by a device (not shown in this figure) coupled to the output power 110. The transmitter 104 and the receiver 108 may be separated by a distance 112. The transmitter 104 may include a power transmitting element 114 for transmitting/coupling energy to the receiver 108. The receiver 108 may include a power receiving element 118 for receiving or capturing/coupling energy transmitted from the transmitter 104.
In one illustrative embodiment, the transmitter 104 and the receiver 108 may be configured according to a mutual resonant relationship. When the resonant frequency of the receiver 108 and the resonant frequency of the transmitter 104 are substantially the same or very close, transmission losses between the transmitter 104 and the receiver 108 are reduced. As such, wireless power transfer may be provided over larger distances. Resonant inductive coupling techniques may thus allow for improved efficiency and power transfer over various distances and with a variety of inductive power transmitting and receiving element configurations.

In certain embodiments, the wireless field 105 may correspond to the "near field" of the transmitter 104. The near-field may correspond to a region in which there are strong reactive fields resulting from the currents and charges in the power transmitting element 114 that minimally radiate power away from the power transmitting element 114. The near-field may correspond to a region that is within about one wavelength (or a fraction thereof) of the power transmitting element 114.

In certain embodiments, efficient energy transfer may occur by coupling a large portion of the energy in the wireless field 105 to the power receiving element 118 rather than propagating most of the energy in an electromagnetic wave to the far field.

In certain implementations, the transmitter 104 may output a time varying magnetic (or electromagnetic) field with a frequency corresponding to the resonant frequency of the power transmitting element 114. When the receiver 108 is within the wireless field 105, the time varying magnetic (or electromagnetic) field may induce a current in the power receiving element 118. As described above, if the power receiving element 118 is configured as a resonant circuit to resonate at the frequency of the power transmitting element 114, energy may be efficiently transferred. An alternating current (AC) signal induced in the power receiving element 118 may be rectified to produce a direct current (DC) signal that may be provided to charge or to power a load.

Fig. 2 is a functional block diagram of a wireless power transfer system 200, in accordance with another illustrative embodiment. The system 200 may include a transmitter 204 and a receiver 208. The transmitter 204 (also referred to herein as power transfer unit, PTU) may include transmit circuitry 206 that may include an oscillator 222, a driver circuit 224, and a front-end circuit 226. The oscillator 222 may be configured to generate a signal at a desired frequency that may adjust in response to a frequency control signal 223. The oscillator 222 may provide the oscillator signal to the driver circuit 224. The driver circuit 224 may be configured to drive the power transmitting element 214 at, for example, a resonant frequency of the power transmitting element 214 based on an input voltage signal (VD) 225. The driver circuit 224 may be a switching amplifier configured to receive a square wave from the oscillator 222 and output a sine wave.
The front-end circuit 226 may include a filter circuit configured to filter out harmonics or other unwanted frequencies. The front-end circuit 226 may include a matching circuit configured to match the impedance of the transmitter 204 to the impedance of the power transmitting element 214. As will explained in more detail below, the front-end circuit 226 may include a tuning circuit to create a resonant circuit with the power transmitting element 214. As a result of driving the power transmitting element 214, the power transmitting element 214 may generate a wireless field 205 to wirelessly output power at a level sufficient for charging a battery 236, or otherwise powering a load.

The transmitter 204 may further include a controller 240 operably coupled to the transmit circuitry 206 configured to control one or aspects of the transmit circuitry 206 or accomplish other operations relevant to managing the transfer of power. The controller 240 may be a micro-controller or a processor. The controller 240 may be implemented as an application-specific integrated circuit (ASIC). The controller 240 may be operably connected, directly or indirectly, to each component of the transmit circuitry 206. The controller 240 may further be configured to receive information from each of the components of the transmit circuitry 206 and perform calculations based on the received information. The controller 240 may be configured to generate control signals (e.g., signal 223) for each of the components that may adjust the operation of that component. As such, the controller 240 may be configured to adjust or manage the power transfer based on a result of the operations performed by it. The transmitter 204 may further include a memory (not shown) configured to store data, for example, such as instructions for causing the controller 240 to perform particular functions, such as those related to management of wireless power transfer.

The receiver 208 (also referred to herein as power receiving unit, PRU) may include receive circuitry 210 that may include a front-end circuit 232 and a rectifier circuit 234. The front-end circuit 232 may include matching circuitry configured to match the impedance of the receive circuitry 210 to the impedance of the power receiving element 218. As will be explained below, the front-end circuit 232 may further include a tuning circuit to create a resonant circuit with the power receiving element 218. The rectifier circuit 234 may generate a DC power output from an AC power input to charge the battery 236, as shown in Fig. 2. The receiver 208 and the transmitter 204 may additionally communicate on a separate communication channel 219 (e.g., Bluetooth, Zigbee, cellular, etc.). The receiver 208 and the transmitter 204 may alternatively communicate via in-band signaling using characteristics of the wireless field 205.

The receiver 208 may be configured to determine whether an amount of power transmitted by the transmitter 204 and received by the receiver 208 is appropriate for charging the battery 236. In certain embodiments, the transmitter 204 may be configured to generate a predominantly non-radiative...
field with a direct field coupling coefficient (k) for providing energy transfer. Receiver 208 may
directly couple to the wireless field 205 and may generate an output power for storing or consumption
by a battery (or load) 236 coupled to the output or receive circuitry 210.

[0046] The receiver 208 may further include a controller 250 configured similarly to the transmit
controller 240 as described above for managing one or more aspects of the wireless power receiver
208. The receiver 208 may further include a memory (not shown) configured to store data, for
example, such as instructions for causing the controller 250 to perform particular functions, such as
those related to management of wireless power transfer.

[0047] As discussed above, transmitter 204 and receiver 208 may be separated by a distance and
may be configured according to a mutual resonant relationship to minimize transmission losses
between the transmitter 204 and the receiver 208.

[0048] Fig. 3 is a schematic diagram of a portion of the transmit circuitry 206 or the receive circuitry
210 of Fig. 2, in accordance with illustrative embodiments. As illustrated in Fig. 3, transmit or receive
circuitry 350 may include a power transmitting or receiving element 352 and a tuning circuit 360. The
power transmitting or receiving element 352 may also be referred to or be configured as an antenna or
a "loop" antenna. The term "antenna" generally refers to a component that may wirelessly output or
receive energy for coupling to another "antenna." The power transmitting or receiving element 352
may also be referred to herein or be configured as a "magnetic" antenna, or an induction coil, a
resonator, or a portion of a resonator. The power transmitting or receiving element 352 may also be
referred to as a coil or resonator of a type that is configured to wirelessly output or receive power. As
used herein, the power transmitting or receiving element 352 is an example of a "power transfer
component" of a type that is configured to wirelessly output and/or receive power. The power
transmitting or receiving element 352 may include an air core or a physical core such as a ferrite core
(not shown in this figure).

[0049] When the power transmitting or receiving element 352 is configured as a resonant circuit or
resonator with tuning circuit 360, the resonant frequency of the power transmitting or receiving
element 352 may be based on the inductance and capacitance. Inductance may be simply the
inductance created by a coil or other inductor forming the power transmitting or receiving element
352. Capacitance (e.g., a capacitor) may be provided by the tuning circuit 360 to create a resonant
structure at a desired resonant frequency. As a non limiting example, the tuning circuit 360 may
comprise a capacitor 354 and a capacitor 356 may be added to the transmit and/or receive circuitry 350
to create a resonant circuit.
[0050] The tuning circuit 360 may include other components to form a resonant circuit with the power transmitting or receiving element 352. As another non limiting example, the tuning circuit 360 may include a capacitor (not shown) placed in parallel between the two terminals of the circuitry 350. Still other designs are possible. In some embodiments, the tuning circuit in the front-end circuit 226 may have the same design (e.g., 360) as the tuning circuit in front-end circuit 232. In other embodiments, the front-end circuit 226 may use a tuning circuit design different than in the front-end circuit 232.

[0051] For power transmitting elements, the signal 358, with a frequency that substantially corresponds to the resonant frequency of the power transmitting or receiving element 352, may be an input to the power transmitting or receiving element 352. For power receiving elements, the signal 358, with a frequency that substantially corresponds to the resonant frequency of the power transmitting or receiving element 352, may be an output from the power transmitting or receiving element 352. Although aspects disclosed herein may be generally directed to resonant wireless power transfer, persons of ordinary skill will appreciate that aspects disclosed herein may be used in non-resonant implementations for wireless power transfer.

[0052] Accurate measurement of the current injected into the power transmitting element 214 shown in Fig. 2 (e.g., transmit coil) may be used to maintain proper levels of electromagnetic (EM) radiation that radiate into the environment, measure power transfer characteristics, and the like. Some solutions may be based on measuring the voltage drop across two series capacitors (e.g., using a differential amplifier), one capacitor attached to each of the coil leads of the transmit coil. Measuring the voltage directly in this way can create technical challenges relating to the design of the differential voltage buffer and amplifier circuits that comprise a differential amplifier because both coil leads are at a high voltage. In addition, this process for making measurements can be complex, requiring the measurement of the voltage across the power transmitting element 214 behind the series capacitors and then measuring the voltage after the series capacitors, along with fast switching of voltages that feed into low pass filters, and so on. The circuitry may require costly components to implement; and the process of taking measurements can create a good amount of electromagnetic interference (EMI) due to switching noise which can be injected into the power transmitting element 214.

[0053] Referring to Figs. 4A and 4B, the discussion will now turn to a description of current sensors in accordance with the present disclosure that may be used to make measurements of current injected into a load. Fig. 4A shows circuitry comprising a power amplifier 40 connected to a load 44 via a current-carrying conductor 42. A current sensor 402 in accordance with the present disclosure may be
configured to sense the flow of current in the current-carrying conductor 42 and produce a signal that is representative of the flow of current in the current-carrying conductor 42.

[0054] Merely as an example to illustrate a usage case, the current sensor 402 may be incorporated in the wireless power transfer system 200 shown in Fig. 2. In this example, the power amplifier 40 may correspond to the driver circuit 224 in transmitter 204, and the load 44 may correspond to the power transmitting element 214 (e.g., transmit coil). The current sensor 402 may detect load changes in the power transmitting element 214 during wireless power transfer as a consequence of variations in the amount of power that is being coupled to a receiver 208 (e.g., PRU) via the magnetic field generated by the power transmitting element 214. For example, variations in power coupling may arise from the amount of power a PRU draws, the number of PRUs engaged in wireless power transfer with the transmitter 204, and so on. The current-carrying conductor 42 may correspond to a connection (e.g., a wire not shown) that provides current from the driver circuit 224 to the power transmitting element 214. It will be appreciated, of course, that a current sensor 402 in accordance with the present disclosure may be readily adapted for use in other circuits.

[0055] The current sensor 402 may include connections 404 and 406 to provide points of connection for the current-carrying conductor 42. The current sensor 402 may include outputs 408 to output a sensed signal in response to the flow of current in conductor 42. The outputs 408 may be connected to a means for generating an output signal from the sensed signal, such as amplifier 48, for example, to produce an output signal \( V_{out} \) that represents or is otherwise indicative of the flow of current in the current-carrying conductor 42. In some embodiments, the output of amplifier 48 may be a current signal that represents the flow of current in the current-carrying conductor 42. In other embodiments, such as shown in Fig. 4A, the output of amplifier 48 may be an output voltage \( V_{out} \) that represents the flow of current in the current-carrying conductor 42. In some embodiments, the output of amplifier 48 may be used as a feedback signal to control the flow of current out of the power amplifier 40. In other embodiments, the output of amplifier 48 may be used to monitor the operating conditions of the system. For example, in the context of the wireless power transfer system 200 shown in Fig. 2, in some embodiments, the current sensor 402 may be used to detect an overload condition. In other embodiments, the current sensor 402 may be used to detect placement of a PRU on the charging surface of the transmitter 204, and so on.

[0056] The power amplifier 40 in Fig. 4A represents an example of a single-ended output. Referring to Fig. 4B, in some embodiments, a power amplifier 40a may have a differential output configured to provide power using two current-carrying conductors 42a and 42b. Accordingly, a current sensor 412 in accordance with some embodiments of the present disclosure may be configured to provide current
sensing on multiple current-carrying conductors (e.g., 42a, 42b). In some embodiments, for example, the current sensor 412 may include connections 404a, 404b and 406a, 406b to provide points of connection for the current-carrying conductors 42a, 42b.

[0057] Fig. 5A shows a current sensor 402 configured in accordance with the present disclosure. The current sensor 402 may be disposed on a circuit board 502. In some embodiments, for example, the circuit board 502 may be an electronic component in a power transmitting unit (e.g., transmitter 204, Fig. 2) of a wireless power transfer system (e.g., Fig. 2). The current sensor 402 may be disposed or otherwise positioned adjacent or near a conductor 542 supported on the circuit board 502. In some embodiments, the conductor 542 may be a wire affixed to the circuit board 502. In other embodiments, the conductor 542 may be a trace formed on the circuit board 502, and so on.

[0058] The conductor 542 may be connected to a transmit coil 544 of the wireless power transfer system. In some embodiments, the current sensor 402 may be placed adjacent the conductor 542 at the high side of a power source (e.g., power amplifier 40, Fig. 4A). For example, the conductor 542 may be connected between the output of the power source and the transmit coil 544. In other embodiments, the current sensor 402 may be positioned at the low side of conductor 542. For example, the conductor 542 may be connected between the transmit coil 544 and ground. Since, in some embodiments, the voltage in the conductor 542 can be tens of volts, placing the current sensor 402 on the low-side of conductor 542 can reduce the voltage by a factor of two to three orders of magnitude, thus reducing the induced voltage in the current sensor 402.

[0059] In accordance with the present disclosure, the current sensor 402 may be oriented relative to a magnetic field 546, which can be generated by the transmit coil 544 during a wireless power transfer operation, such that the field lines intersect a minimal cross-sectional area of the current sensor 402. In some embodiments, for example, the current sensor 402 may be oriented in a plane parallel to some field lines (flux) of the magnetic field 546. In the particular embodiment shown in Fig. 5A, for example, the transmit coil 544 is oriented in the same plane as the circuit board 502. Accordingly, the current sensor 402 is disposed perpendicular relative to the circuit board 502, since the magnetic field 542 would be perpendicular to the transmit coil 544. In other embodiments, the transmit coil 544 may lie at a non-perpendicular angle relative to the circuit board 502. The current sensor 402, accordingly, would be attached to the circuit board 502 at a suitable angle so as to be oriented in a plane parallel to field lines of the magnetic field 546 from transmit coil 544.

[0060] The plan view in Fig. 5B and the top view in Fig. 5C further illustrate the relative orientation between the current sensor 402 and magnetic field 546 in accordance with the present disclosure. An XYZ coordinate is used to establish a reference. In some embodiments for example, without loss of
generality, circuit board 502 and transmit coil 544 lie in the XY plane. Accordingly, the current sensor 402 is oriented in the XZ plane. The plan view in Fig. 5B shows certain field lines 546a of magnetic field 546 that lie the XZ plane, and the orientation of current sensor 402 is also in a plane parallel to those field lines 546a. The orientation of current sensor 402 relative to field lines 546a is further illustrated in the top view shown in Fig. 5C.

[0061] Fig. 6 shows details of current sensor 402 in accordance with the present disclosure, along with some circuit elements shown in Fig. 4A for context. The inset represents a view taken along view line A-A. The conductor 542 may connect a power supply (e.g., power amplifier 40, Fig. 4A) to the transmit coil 544. As can be seen in the inset, the conductor 542 and the current sensor 402 may be disposed on the circuit board 502, as described above. The XYZ coordinate reference established in Fig. 5A illustrates the relative orientation of the current sensor 402 and the conductor 542 on the circuit board 502.

[0062] In some embodiments, the current sensor 402 may comprise a sense element 604 disposed on a plane, for example, as defined by a substrate 632. The sense element 604 may comprise a coil 612 (or loop) of electrically conductive material. The substrate 632 may be a printed circuit board (PCB). The coil 612 may be a trace or a plurality of trace segments formed on the substrate 632. The conductive material used for coil 612 may be copper or any suitable electrically conductive material. The conductive material may be formed or otherwise deposited on the substrate 632 using any of a number of known techniques.

[0063] Fig. 6 depicts the coil 612 formed on a first face of the substrate 632. In some embodiments, the coil 612 may have one or more turns. The outer end 612b of the coil 612 may terminate at a conductive pad B on the substrate 632. The inner end 612a of the coil 612 may terminate at a conductive pad A on the substrate 632 by way of a return path that comprises vias 614 and 618 formed through the substrate 632 and a trace 616 formed on a second face of the substrate 632 that connects via 614 to via 618. A trace may connect the via 618 to pad A. An amplifier (e.g., 48, Fig. 4A) may be connected to the pads A, B.

[0064] In accordance with the present disclosure, the current sensor 402 may further comprise a capacitive shield 622 disposed adjacent to the sense element 604, and to the conductor 542, for example, by virtue of the current sensor 402 being positioned near the conductor 542. In some embodiments, the capacitive shield 622 may comprise a conductive trace (lead) formed on the substrate 632. One end 622a of the capacitive shield 622 may be "free," or not otherwise connected. Another end 622b of the capacitive shield 622 may be electrically connected to a conductive pad C via a trace 624. In some embodiments, the pad C may be connected to ground potential. In other
embodiments, the pad B and the pad C may be connected to a common voltage reference. This aspect of the present disclosure will be discussed below.

[0065] In operation, with reference to Figs. 5A and 6, when an AC drive current is provided to drive the transmit coil 544, the flow of the current through conductor 542 can generate a magnetic field 548 (inset, Fig. 6) at a first location in the conductor 542 near the current sensor 402. The magnetic field 548, being in the Y-Z plane is generally orthogonal to the magnetic field 546 (e.g., Fig. 5B) which lies in the X-Z plane. The sense element 604 component of the current sensor 402 can serve as a means for coupling to the magnetic field 548, which in turn can result in an induced flow of current (sensed signal) in the sense element 604. The sensed signal generated in the sense element 604 can be provided at ends 612a, 612b and amplified by amplifier 48 to produce an output signal \( V_{out} \) that is indicative of the amount of current flowing through the conductor 542.

[0066] As explained above, the current sensor 402 is based on magnetic coupling between the conductor 542 carrying the current and the coils 612 (measurement loops) that comprise the sense element 604. Accordingly, an increase in the coupling between conductor 542 and sense element 604 can improve the signal to noise ratio (SNR) of the sensed signal. At the same time, however, a reduction of the magnetic coupling between sense element 604 and any other sources of magnetic fields may be preferable in order to avoid inaccuracies in the sense signal.

[0067] In some embodiments, the transmit coil 544 may be physically close to the circuit board 502 that carries the current sensor 542. As a result, current sensor 402 can be exposed to the magnetic fields 546 generated by the transmit coil 544; e.g., during a wireless power transfer operation. On the one hand, since such externally generated magnetic fields 546 are proportional to the current, the resulting induced current flow (sensed signal) in the sense element 604 of the current sensor 402 may improve the SNR. On the other hand, the magnetic field 546 generated by the transmit coil 544 can be affected by the power receiving devices and other devices in the vicinity of the magnetic field. Accordingly, such variations in the magnetic field 546 can be a source of error for the current sensor 402. The error can be pronounced if the magnetic field 546 varies (e.g., due to varying load conditions at the receiver side) but the current flowing in conductor 542 is constant. In other words, variations in the magnetic field 546 can produce variations in the output signal \( V_{out} \) even though current flow in conductor 542 is constant. Since the current sensor 402 may be used to provide feedback to adjust the magnetic field 546 or to detect foreign objects in the magnetic field 546, it may be beneficial to ensure that the magnetic field 546 does not interfere with the sensed signal.

[0068] In accordance with the present disclosure, as illustrated in Figs. 5A - 5C for example, magnetic shielding of the magnetic field 546 can be achieved by orienting the sense element 604 in
parallel to the flux that is generated by the transmit coil 544. In some implementations, for example, the circuit board 502 is in the same plane as transmit coil 544. Accordingly, the sense element 604 in such an implementation is oriented perpendicular to the circuit board 502.

[0069] It can be appreciated that orienting the sense element 604 relative to the transmit coil 544 in accordance with the present disclosure can minimize the cross-sectional area of the sense element 604 that is intersected by the field lines of the magnetic field 546. Minimizing the intersected cross-section area results in minimizing the induced current effect of the magnetic field 546 generated by the transmit coil 544, and hence the effect of variations in the magnetic field 546 on the sensed signal in the sense element 604.

[0070] Still referring to Figs. 5A and 6, as explained above when current flows through the conductor 542, a magnetic field 548 (see inset of FIG. 6) may arise from the conductor 542. The sense element 604, being in the vicinity of the conductor 542, may magnetically couple to the magnetic field 548. The area in the vicinity of the sense element 604 and the conductor 542 may be referred to as the sensing area. A voltage may be induced in the sense element 604 that results from magnetically coupling to the magnetic field 548. The induced voltage may be amplified by amplifier 48 to generate an output voltage $V_{out}$ representative of the current flowing in the conductor 542.

[0071] The proximity of conductor 542 to the sense element 604 can create a capacitor. If the transmit coil 544 is driven by a high voltage at high frequency, the capacitive coupling between conductor 542 and sense element 604 may be significant even though the capacitance may be small. For example, in some embodiments, the transmit coil 544 may be driven by a 6.78 MHz signal on the order of tens of volts. As a result, capacitive coupling of an electric field generated due to the voltage potential of the conductor 542 to the sense element 604 can be significant. The energy that can be coupled to the sense element 604 can create an error in the generated output voltage $V_{out}$.

[0072] In accordance with the present disclosure, the capacitive shield 622 between conductor 542 and sense element 604 can provide electric field isolation. The capacitive shield 622 can isolate the electric field from the sense element 604 by capacitively coupling the electric field to ground potential, thus shielding the output voltage $V_{out}$ from the influence of the electric field generated by the conductor 542.

[0073] Fig. 6A shows a current sensor 402' in accordance with some embodiments of the present disclosure. In some embodiments, the current sensor 402' may comprise a sense element 604 comprising a first coil (or loop) of conductive material 612-1 disposed on a first plane (e.g., as defined
by a substrate 632-1) and a second coil of conductive material 612-2 disposed on a second plane (e.g., as defined by a substrate 632-2).

[0074] In some embodiments, the substrates 632-1, 632-2 may be layers in a multilayer PCB 632'. The coils 612-1, 612-2 may be traces formed on respective layers of the PCB 632'. The conductive material used to form coils 612-1, 612-2 may be copper or any suitable material. The traces may be formed on the substrates 632-1, 632-2 using any of a number of known techniques.

[0075] In some embodiments, the coils 612-1, 612-2 may be connected in series, as shown in Fig. 6A for example. The outer end 612-1b of the coil 612-1 may terminate at a conductive pad B on the substrate 632-1. A via 614b may serve to connect the inner end 612-la of coil 612-1 on substrate 632-1 to the inner end 612-2a of coil 612-2 on substrate 632-2. A via 614c may connect the outer end 612-2b of coil 612-2 on substrate 632-2 to a conductive pad A on substrate 632-1.

[0076] In accordance with the present disclosure, the current sensor 402' may further comprise a first capacitive shield 622-1 disposed adjacent to both the coil 612-1 of sense element 604 and the conductor 542, and a second capacitive shield 622-2 disposed adjacent to the coil 612-2 of sense element 604 and to the conductor 542 by virtue of the current sensor 402' being placed near the conductor 542. In some embodiments, the first capacitive shield 622-1 may comprise a conductive trace (lead) formed on substrate 632-1 and likewise the second capacitive shield 622-2 may comprise a conductive trace (lead) formed on substrate 632-2.

[0077] In accordance with the present disclosure, the capacitive shields 622-1, 622-2 may be connected together so that each capacitive shield has a free end and a grounded end, so that the capacitive shields do not form a closed loop. Fig. 6A, for example, shows a connection configuration in accordance with some embodiments. One end 622-1a of the capacitive shield 622-1 may be "free," or not otherwise connected. Another end 622-1b of the capacitive shield 622-1 may connect to a conductive pad C, for example, via a trace 624. Likewise, one end 622-2a of the capacitive shield 622-2 may be "free," or not otherwise connected. Another end 622-2b of the capacitive shield 622-2 may connect to a conductive pad C; for example, a via 614a may connect end 622-2b to end 622-1a. In some embodiments, the pad C may be connected to ground potential. In other embodiments, the pad B and the pad C may be connected to a common voltage reference.

[0078] Fig. 6B shows a current sensor 402" in accordance with some embodiments of the present disclosure. In the configuration shown in Fig. 6B, the capacitive shields 622-1, 622-2 may be connected in end-to-end fashion to form a continuous trace. For example, one end 622-2b of capacitive shield 622-2 may be the free end. The other end 622-2a of capacitive shield 622-2 may
connect to one end 622-1a of capacitive shield 622-1, for example, using via 614a. The other end 622-1b of capacitive shield 622-1 may connect to pad C, for example, using trace 624. One of ordinary skill will appreciate that still other connection configurations in accordance with the present disclosure may be possible.

5 [0079] One of ordinary skill will appreciate that in accordance with the present disclosure, the sense element 604 in Fig. 6A or Fig. 6B may comprise coils provided on respective additional layers of the multi-layer PCB 632' in addition to coils 612-1, 612-2. In some embodiments, for example, the PCB 632' may be an N-layer PCB supporting a sense element 604 comprising N coils, one coil in each layer. Accompanying each additional coil may be a capacitive shield (trace lead) disposed adjacent to the coil on the same layer (e.g., co-planar with the coil).

10 [0080] Fig. 7 shows a current sensor 702 in accordance with some embodiments of the present disclosure. In some embodiments, a current sensor 702 disposed on circuit board 502 may have a dual structure to sense the current flow in conductor 542. The current sensor 702 may comprise a first sensor component 702a and a second sensor component 702b spaced apart from the first sensor component 702a. The current sensor 702 may straddle the conductor 542 so that the first sensor component 702a lies on one side of the conductor 542 and the second sensor component 702b lies in opposition to the first sensor component 702a on the other side of the conductor 542. The sense element (e.g., 604, Fig. 6) in the first sensor component 702a may comprise a coil (e.g., 612, Fig. 6) that is wound in the same direction, either clockwise or counterclockwise, as the winding of a coil that comprises a sense element in the second sensor component 702b. The respective coils in the first and second sensor components 702a, 702b may be connected together to sum the current flow in the respective coils. This dual structure can provide increased current sensing sensitivity as compared to the single structure current sensor 402 shown in Fig. 6.

15 [0081] Fig. 8 illustrates a means for filtering 800 the sensed signal in accordance with the present disclosure. Referring first for a moment to Fig. 6A, measuring current flow in the conductor 542 may involve determining the root mean square (RMS) of the waveform of the sensed signal induced in the sense element 612. The RMS may be determined by measuring the peaks in the sensed signal and determining the phase angle by detecting the zero crossings. This approach, however, has a constraint in that the waveform of the sensed signal should not have any harmonics.

20 [0082] The source of the harmonics can arise in the power amplifier (e.g., 40, Fig. 4A) that provides the current in the conductor 542. In some implementations, the power amplifier may be a non-linear amplifier. For example, the high power output requirements of a wireless power system and cost
constraints may dictate a non-linear design. The current and voltage produced by a non-linear power amplifier typically have substantial harmonic content.

[0083] In accordance with the present disclosure, a bandpass filter may be used on the sensed signal to filter out the higher and lower harmonics at the output 408 of the current sensor 402, for current measurements. Fig. 8 shows a means for filtering 800 the sensed signal in accordance with some embodiments of the present disclosure. As described above, the sense element 604 (Fig. 6) comprises a coil 612 (or loop) of electrically conductive material. The coil 612, therefore, has an inductance L. The coil 612 can be used to create a bandpass filter 800 using a resistor R and capacitor C. For example, resistor R may be connected between pad A (Fig. 6) on the current sensor 402 and an input to the amplifier 48. Capacitor C may be connected between pad B and another input to the amplifier 48. The value of C may be determined based on the inductance L of the coil 612 and an operating frequency of the power supply. For example, in some implementations, the operating frequency may be the resonant frequency of the transmit coil 544 in the wireless power transfer system. The resistor R may be a small resistor that can be added to detune the bandpass filter 800 and widen the bandpass frequencies in order to reduce sensitivity to actual component values.

[0084] For voltage measurements, a capacitive voltage divider (not shown) may be used. To achieve the desired harmonic rejection, for example, a 7th order, 4-stage Butterworth filter (not shown) may be used. It will be appreciated that any suitable bandpass filter design may be used.

[0085] Fig. 9 shows a current sensor 902 in accordance with some embodiments of the present disclosure. In some embodiments, the current sensor 902 may comprise a sense element 904 disposed on a plane, for example, as defined by substrate 932. The sense element 904 may comprise a first coil of conductive material 912-1 and a second coil of conductive material 912-2. The first and second coils 912-1, 912-2 may be connected in series. For example, vias may be used to route traces on an opposite face of the substrate 932 in order to connect the first and second coils 912-1, 912-2 in series.

[0086] In some embodiments, the first and second coils 912-1, 912-2 that comprise sense element 904 may be substantially co-planar on the substrate 932 and in opposed relation to each other. In accordance with the present disclosure, the sense element 904 may be oriented relative to the field lines of a magnetic field generated by the transmit coil 544 so as to minimize the area of intersection between the coils 912-1, 912-2 and the field lines. In some embodiments, for example, the sense element 904 may be oriented in a plane parallel to field lines of the magnetic field generated by the transmit coil 544.
[0087] The conductor 542 that provides drive current to the transmit coil 544 from a power source (e.g., power amplifier 40, Fig. 4A) may have a segment 542-1 that runs along the surface of substrate 932. The conductor segment 542-1 may run between the coils 912-1, 912-2. When a current flows through conductor 542 and hence conductor segment 542-1 (e.g., during wireless power transfer), a magnetic field can be generated. The magnetic field, in turn, can induce a flow of current in both coils 912-1, 912-2, which can then be amplified (e.g., using amplifier 48) to produce an output signal indicative of the flow of current in conductor 542.

[0088] In accordance with the present disclosure, the current sensor 902 may further comprise a first capacitive shield 922-1 disposed adjacent to both the first coil 912-1 and the conductor segment 542-1, and a second capacitive shield 922-2 disposed adjacent to both the second coil 912-2 and the conductor segment 542-1. In some embodiments, the first and second capacitive shields 922-1, 922-2 may comprise conductive traces (leads) formed on the substrate 932. One end of respective first and second capacitive shields 922-1, 922-2 may be "free," or not otherwise connected. Another end of respective first and second capacitive shields 922-1, 922-2 may be connected to a common point (e.g., GND).

[0089] Fig. 9A shows a current sensor 902' in accordance with some embodiments of the present disclosure. The current sensor 902' can be used to sense current flowing in two conductors 542a, 542b. For example, the current sensor 902' may be used to sense current flow in the conductors of a differential amplifier; see, for example, the configuration illustrated in Fig. 4B. The sense element 904' may comprise first, second, and third coils 912-1, 912-2, 912-3. The conductors 542a, 542b may have respective segments 542a-l, 542b-l that run on the substrate 932. For example, conductor segment 542a-l may run between coils 912-1 and 912-2, and conductor segment 542b-l may run between 912-2 and 912-3. The current sensor 902' may include capacitive shields 922-1, 922-2 configured to shield the coils 912-1, 912-2 from an electric field that can emanate from conductor segment 542a-l. The current sensor 902' may further include capacitive shields 922-3, 922-4 configured to shield the coils 912-2, 912-3 from an electric field that can emanate from conductor segment 542b-l.

[0090] In accordance with the present disclosure, the single-conductor current sensors (e.g., 402 in Fig. 5) may be used with a differential power amplifier. Differential power amplifiers, for example, may be integrated in wireless power transmit circuitry to drive a transmit coil. Figs. 10A and 10B schematically depict illustrative embodiments of differential power amplifier configurations. Fig. 10A for example, shows a differential power amplifier 1002 connected to loads 1004, 1006. Current sensors 1000a, 1000b may be disposed along conductors 1042a, 1042b to sense a flow of current in the
respective conductors. The current sensors 1000a, 1000b may be connected together in series to produce a single output (e.g., 408, Fig. 4B) that can be connected to an amplifier (e.g., 48, Fig. 4B). Referring to Fig. 6, for example, pad B of current sensor 1000a may be connected to pad A of current sensor 1000b. Pad A of current sensor 1000a and pad B of current sensor 1000b may be the inputs to an amplifier (e.g., 48).

[0091] Fig. 10B illustrates a configuration in which the conductors 1042a, 1042b that are sensed by current sensors 1000a, 1000b may be disposed along the ground paths from respective loads 1004, 1006. The current sensors 1000a, 1000b may be connected in series. The configuration shown in Fig. 10B may be advantageous in some applications, since the line voltage in conductors 1042a, 1042b is close to ground potential.

[0092] Fig. IOC illustrates a configuration of a dual-conductor single current sensor 1000c, such as illustrated in Fig. 9A for example, for sensing the current flow in conductors 1042a, 1042b of the differential amplifier 1002. The configuration shown in Fig. IOC shows the conductors 1042a, 1042b to be along the ground path. In other embodiments, however, the conductors 1042a, 1042b that are sensed by the current sensor 1000c may be at the outputs of the differential power amplifier 1002.

[0093] In still other embodiments, three or more current sensors may be used. For example, the configuration two single-conductor current sensors 1000a, 1000b shown in Fig. 10B may be combined in series fashion with the dual-conductor current sensor 1000c shown in Fig. IOC. Fig. 10D illustrates an example of such a configuration.

[0094] Current sensors may be used in wireless power circuitry; e.g., to provide feedback for power control. Current sensors may be particularly useful for lost power determination. For example, current sensors may used detect an amount of power transmitted in order to determine the amount of power lost based on what the receiver is receiving, or to detect the presence of objects consuming power on the pad.

[0095] Current sensors in accordance with the present disclosure do not interact directly with the current flow that is being sensed. Therefore, the current sensor creates no imbalance in the power amplifier that supplies the current. In addition, current sensors in accordance with the present disclosure can provide an output voltage that is isolated from the output of the power amplifier.

[0096] Current sensors in accordance with the present disclosure do not use switching circuitry, and so do not emit EMI that is typically associated with the use of switching circuitry.
[0097] Current sensors in accordance with the present disclosure can create a voltage waveform that is 90 degrees out of phase with current and thus can provide a usable phase angle measurement of the current flow. In addition, the zero crossing of this waveform can be compared to that of the power amplifier output voltage to provide an accurate measure of phase angle. This phase angle can be used for both load power and impedance measurements.

[0098] The above description illustrates various embodiments of the present disclosure along with examples of how aspects of the particular embodiments may be implemented. The above examples should not be deemed to be the only embodiments, and are presented to illustrate the flexibility and advantages of the particular embodiments as defined by the following claims. Based on the above disclosure and the following claims, other arrangements, embodiments, implementations and equivalents may be employed without departing from the scope of the present disclosure as defined by the claims.
What is claimed is:

1. A current sensor comprising:
   a conductor;
   a sense element configured to couple to a first magnetic field generated at a first location due to a flow of current in the conductor; and
   an output electrically connected to the sense element and configured to produce a signal that is representative of the flow of current in the conductor,
   the sense element oriented in a plane parallel to magnetic field lines of a second magnetic field, different from the first magnetic field, generated by a load electrically connected to the conductor at a second location different from the first location.

2. The current sensor of claim 1, further comprising a substrate, wherein the sense element comprises an electrically conductive coil disposed on the substrate and adjacent the conductor.

3. The current sensor of claim 2, further comprising a filter circuit, the filter circuit comprising the electrically conductive coil.

4. The current sensor of claim 3, wherein the filter circuit is a bandpass filter.

5. The current sensor of claim 2, wherein the substrate is disposed perpendicular to a printed circuit board (PCB) that carries the conductor.

6. The current sensor of claim 1, wherein the load comprises a power transmitting element configured to generate an external magnetic field for wireless power transfer, wherein the external magnetic field constitutes the second magnetic field.

7. The current sensor of claim 6, wherein the sense element comprises an electrically conductive coil, the current sensor further comprising a filter comprising the electrically conductive coil of the sense element, wherein the filter is tuned to a resonant frequency of the power transmitting element.

8. The current sensor of claim 1, further comprising a capacitive shield disposed between the sense element and the conductor, the capacitive shield effective to prevent an electric field generated in the conductor from being capacitively coupled to the sense element.
9. The current sensor of claim 8, wherein the capacitive shield comprises a conductive lead disposed adjacent to both the sense element and the conductor, wherein the conductive lead comprises a free first end and a second end configured to electrically connect to ground potential.

10. The current sensor of claim 1, wherein the sense element comprises a first electrically conductive coil disposed on a first plane and at least a second electrically conductive coil disposed on at least a second plane spaced apart from the first plane.

11. The current sensor of claim 10, further comprising a first capacitive shield configured to be disposed adjacent to both the first electrically conductive coil and the conductor, and at least a second capacitive shield configured to be disposed adjacent to both the second electrically conductive coil and the conductor.

12. The current sensor of claim 10, wherein the first electrically conductive coil is connected in series with the second electrically conductive coil.

13. The current sensor of claim 10, wherein the first electrically conductive coil comprises a first trace formed on a first layer of a multi-layer PCB and the second electrically conductive coil comprises a second trace formed on a second layer of the multi-layer PCB.

14. The current sensor of claim 10, wherein the first electrically conductive coil is disposed on one side of the conductor and the second electrically conductive coil is disposed on another side of the conductor.

15. The current sensor of claim 10, further comprising a filter circuit, the filter circuit comprising either or both the first electrically conductive coil and the second electrically conductive coil.

16. The current sensor of claim 1, wherein the sense element comprises a first electrically conductive coil and at least a second electrically conductive coil, the first and second coils both spaced apart from each other on a same plane.
17. A method of sensing a flow of current in a conductor comprising:
   generating a sensed signal by magnetically coupling to a first magnetic field arising
   from the conductor due to the flow of current in the conductor, the magnetic coupling occurring in a
   plane parallel to field lines of a second magnetic field generated by the flow of current through a load
   electrically connected to the conductor; and
   generating an output signal from the sensed signal, the output signal representative of
   an amount of the flow of current through the conductor.

18. The method of claim 17, wherein magnetically coupling to the first magnetic
   field includes inducing a current, using the first magnetic field, in a coil of electrically conductive
   material disposed adjacent the conductor and aligned in the plane parallel to field lines of the second
   magnetic field.

19. The method of claim 18, further comprising filtering the sensed signal to
   attenuate frequency components in the sensed signal determined by a filter circuit that includes the coil
   of electrically conductive material.

20. The method of claim 18, wherein the load comprises a power transmitting
   element configured to generate an external magnetic field for wireless power transfer, wherein the
   external magnetic field constitutes the second magnetic field.

21. The method of claim 17, further comprising shielding the sensed signal from an
   electric field generated in the conductor so that the generated output signal is substantially free of
   influence from the electric field.

22. The method of claim 17, wherein magnetically coupling to the first magnetic
   field includes coupling the first magnetic field to a first coil of electrically conductive material
   disposed adjacent the conductor and coupling the first magnetic field to a second coil of electrically
   conductive material disposed adjacent the conductor.

23. An apparatus for sensing a flow of current in a conductor comprising:
   means for magnetically coupling to a first magnetic field arising from the conductor
   due to the flow of current in the conductor to generate a sensed signal, the means for magnetically
   coupling to a first magnetic field being aligned in a plane parallel to field lines of a second magnetic
   field generated by the flow of current through a load electrically connected to the conductor; and
   means for generating an output signal from the sensed signal.
24. The apparatus of claim 23, further comprising means for filtering the sensed signal, the means for filtering comprising the means for magnetically coupling to a first magnetic field.

25. The apparatus of claim 24, wherein the means for magnetically coupling to a first magnetic field comprises a coil of electrically conductive material.

26. The apparatus of claim 24, wherein the means for filtering is a bandpass filter.

27. An apparatus for wirelessly transmitting charging power to a receiver device, comprising:

- a transmit coil;
- a driver circuit electrically coupled to the transmit coil via a conductor, the driver circuit configured to drive the transmit coil with an alternating current via the conductor; and
- a current sensor configured to sense a flow of current in the conductor, the current sensor comprising a sense coil configured to couple to a first magnetic field generated by the alternating current in the conductor to produce a signal that is indicative of the flow of current in the conductor,

and

- the transmit coil configured to generate a second magnetic field for wirelessly transmitting charging power to the receiver device in response to being driven by the alternating current,
- the sense coil oriented in a plane parallel to field lines of the second magnetic field.

28. The apparatus of claim 27, further comprising a filter circuit, the filter circuit comprising the sense coil and a resistor and capacitor electrically connected to the sense coil.

29. The apparatus of claim 28, wherein the filter circuit is a bandpass filter.

30. The apparatus of claim 27, wherein the current sensor further comprises a capacitive shield disposed adjacent to the sense coil, the capacitive shield effective to prevent an electric field generated in the conductor from being capacitively coupled to the sense coil, wherein the capacitive shield comprises a second conductor disposed between the conductor and the sense coil.
Fig. 7

Fig. 8
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R 15/18
ADD. H04B 5/00

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01R H04B

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Date of mailing of the international search report: 02/01/2017

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

Authorized officer:

Melani, Chafik
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