US009077192B2

(12) **United States Patent**
Lisi et al.

(10) **Patent No.: US 9,077,192 B2**
(45) **Date of Patent: Jul. 7, 2015**

(54) **TRANSMITTER AND RECEIVER TUNING IN A WIRELESS CHARGING SYSTEM**

(75) Inventors: **Gianpaolo Lisi**, Campbell, CA (US); **Gerard G. Socci**, Palo Alto, CA (US); **Ali Kiaei**, San Jose, CA (US); **Kosha Mahmodieh**, Hayward, CA (US); **Ali Djabbari**, Saratoga, CA (US)

(73) Assignee: **NATIONAL SEMICONDUCTOR CORPORATION**, Santa Clara, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1071 days.

(21) Appl. No.: **13/150,868**

(22) Filed: **Jun. 1, 2011**

(65) **Prior Publication Data**

US 2012/0169133 A1 Jul. 5, 2012

Related U.S. Application Data

(60) Provisional application No. 61/428,126, filed on Dec. 29, 2010.

(51) **Int. Cl.**
H02J 5/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H02J 5/005*** (2013.01)

(58) **Field of Classification Search**
CPC H02J 5/005
USPC 702/107
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,435,344 A * 3/1969 Blair et al. 455/265
4,458,248 A * 7/1984 Lyasko 343/719
7,741,734 B2 6/2010 Joannopoulos et al.
2010/0034238 A1 2/2010 Bennett
2010/0036773 A1 2/2010 Bennett
2010/0244576 A1 9/2010 Hillan et al.
2010/0276995 A1 11/2010 Marzetta et al.

OTHER PUBLICATIONS

Hideaki Abe, et al., "A Noncontact Charger Using a Resonant Converter with Parallel Capacitor of the Secondary Coil" 2000 IEEE Xplore.

Chwei-Sen Wang, et al., "Power Transfer Capability and Bifurcation Phenomena of Loosely Coupled Inductive Power Transfer Systems", 2004 IEEE Xplore.

R. Laouamer, et al., "A Multi-Resonant Converter for Non-Contact Charging with Electromagnetic Coupling," Jul. 22, 2010, IEEE Xplore.

Andre Kurs, et al., "Wireless Power Transfer via Strongly Coupled Magnetic Resonances," Science Express, Jun. 2007.

(Continued)

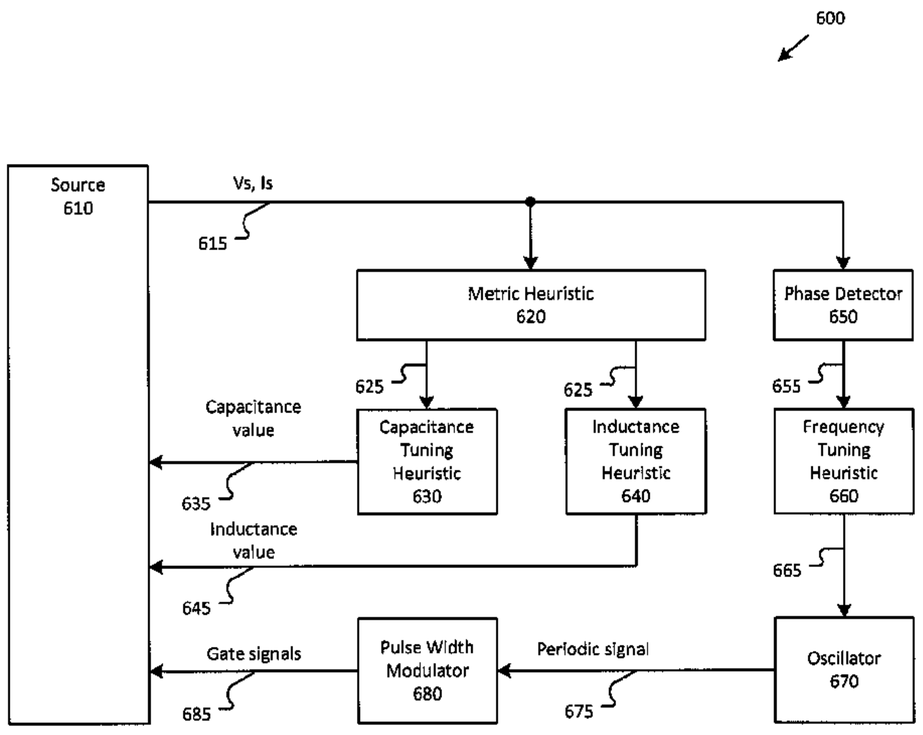
Primary Examiner — Bryan Bui

(74) *Attorney, Agent, or Firm* — Andrew Viger; Frank D. Cimino

(57) **ABSTRACT**

A wireless charging system includes a transmitter with tunable reactive components (such as capacitance or inductance). A metric related to power transfer from the transmitter through a coil is used to determine an amount to modify a Parameter. One metric is equal to $|Vs|\cdot|Is|\cdot\cos(\phi)\cdot(Vcoil_ref/Vcoil)$, where $|Vs|$ is magnitude of the power source voltage, $|Is|$ is magnitude of the power source current, ϕ is phase difference between the power source voltage and power source current, Vcoil_ref is a normalization value, and Vcoil is voltage across the coil. The transmitter can further include a phase tracking and adjustment loop (such as a phase-locked loop).

12 Claims, 4 Drawing Sheets



(56) **References Cited**

OTHER PUBLICATIONS

Yuequan Hu, et al.; "Universal-Input Single-Stage PFC Flyback with Variable Boost Inductance for High-Brightness LED Applications," IEEE (2010).
G. Vandevoorde, et al.; "Wireless energy transfer for stand-alone systems: a comparison between low and high power applicability," Published by Elsevier Science B.V. (2001).
Xiao Zhi Jian, et al.; "A Novel Wirless Charging System for Movable Telephone with Printed-circuit-board WIndings of Different Structure and Shape Respectively," International Conference on Electrical Machines and Systems Oct. 8-11, 2007, Seoul, Korea.
Jun Pan, et al.; "A Self-Powered Sensor Module Using Vibration-Based Energy Generation for Ubiquitous Systems," IEEE (2005).
Geffrey K. Ottman,e t al.; "Adaptive Piezoelectric Energy Harvesting Circuit for Wireless Remote Power Supply," IEEE (2002).
C.-C., Tsai, B., et al.; "Design Wireless Transcutaneous Energy Transmission System for Totally Artificial Hearts," IEEE (2000).
David L. Mascarenas, et al.; "Experimental studies of using wireless energy transmission for powering embedded sensor nodes," Journal of Sound and Vibration, Published by Elsevier Ltd. (2009).
Jonsensor Zhao,; "A new calculation for designing multilayer planar spiral inductors," EDN (Jul. 29, 2010).
Takehiro Imura, et al, "Basic Experimental Study on Helical Antennas of Wireless Power Transfer for Electric Vehicles by using Magnetic Resonant Couplings," IEEE (2009).
Aristeidis Karalis, et al., "Efficient wireless non-radiative mid-range energy transfer," Elsevier, Science Direct, Annals of Physics, (2007).

* cited by examiner

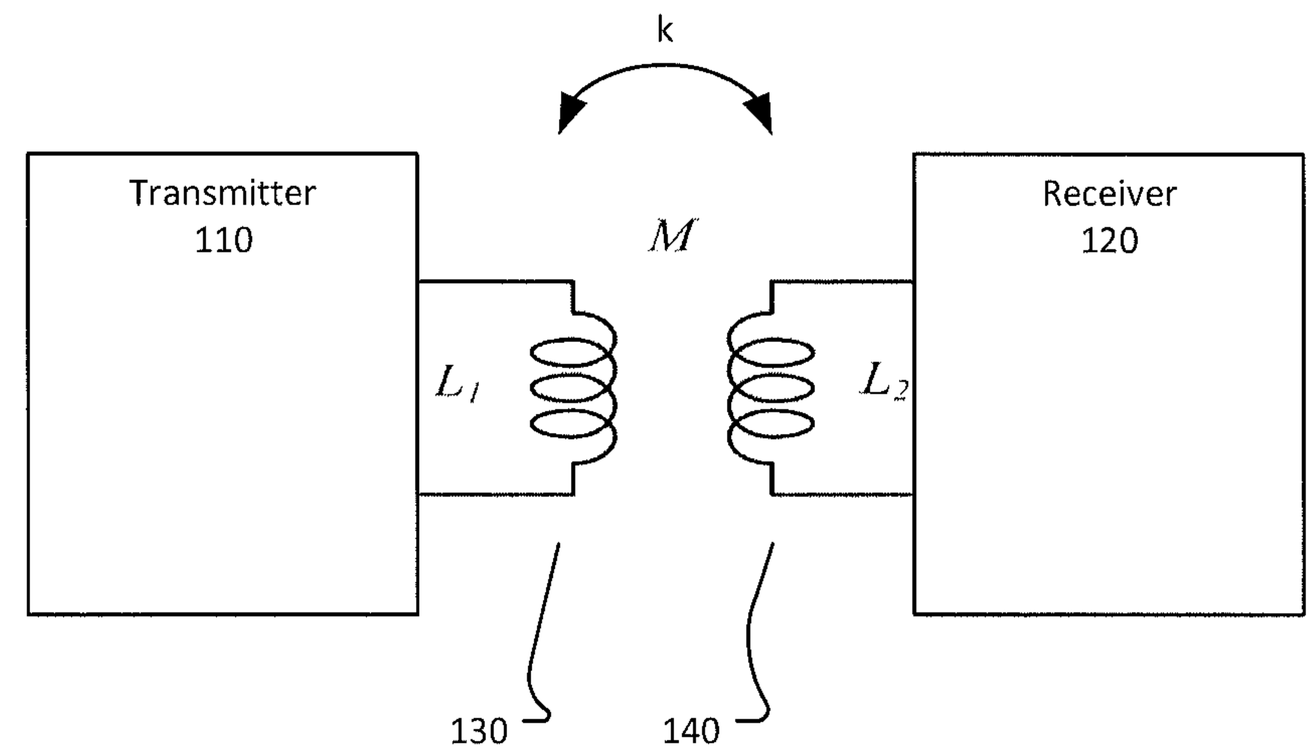

k
Transmitter
110
M
Receiver
120
L_1
L_2
130
140

FIG. 1

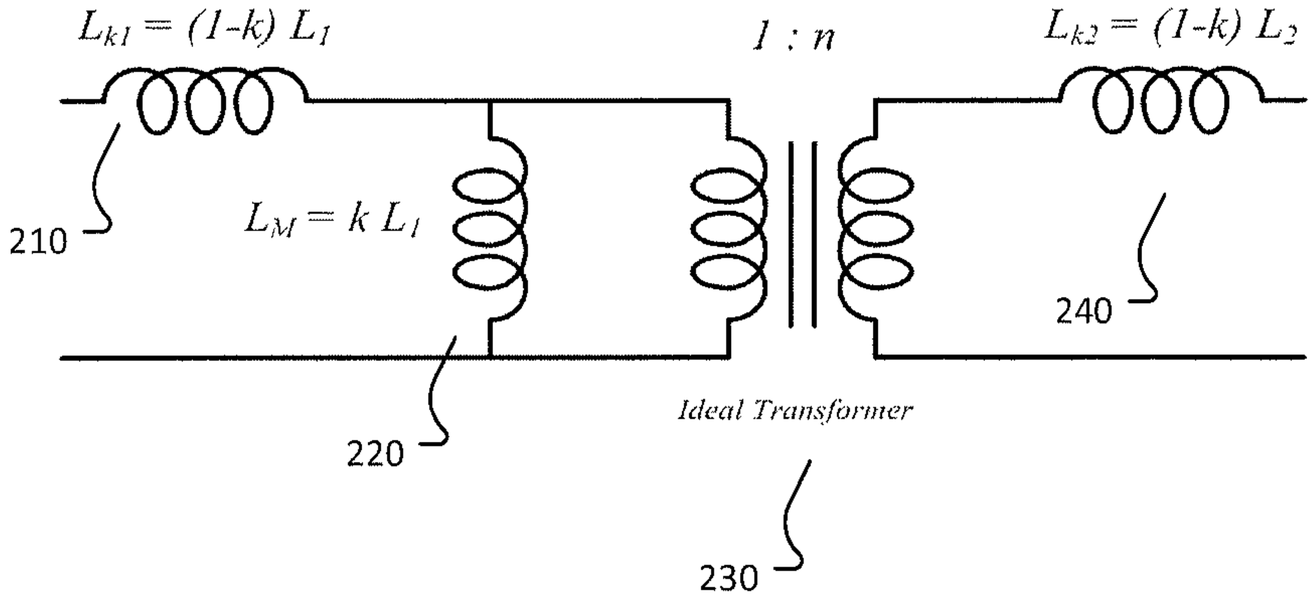

$L_{k1} = (1-k)\ L_1$
1 : n
$L_{k2} = (1-k)\ L_2$
210
$L_M = k\ L_1$
240
220
Ideal Transformer
230

FIG. 2

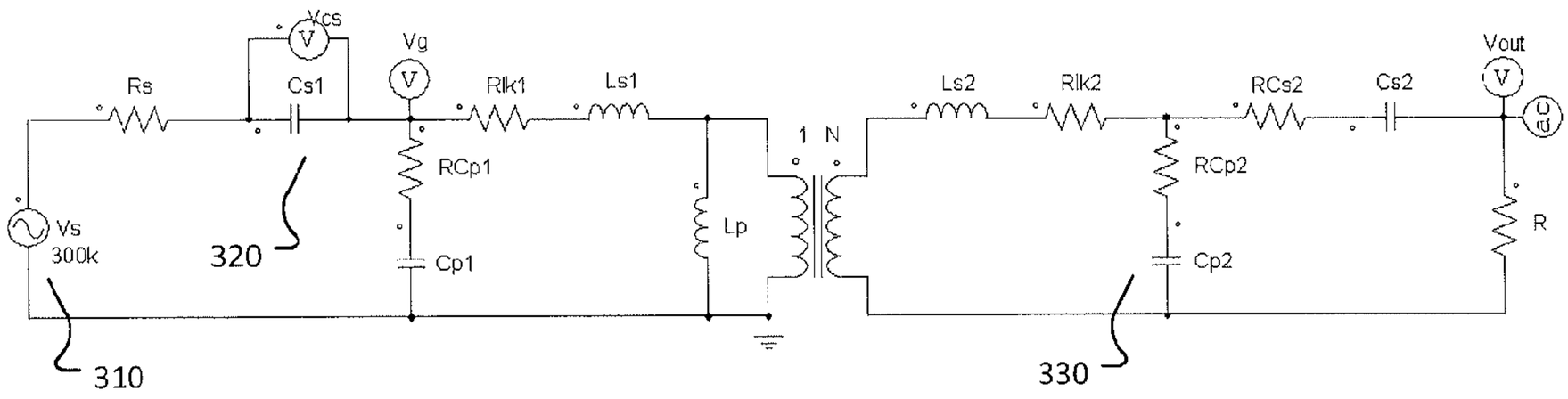

Vcs
Vg
Vout
Rs
Cs1
Rlk1
Ls1
Ls2
Rlk2
RCs2
Cs2
1 N
RCp1
RCp2
Vs
300k
320
Cp1
Lp
Cp2
R
310
330

FIG. 3

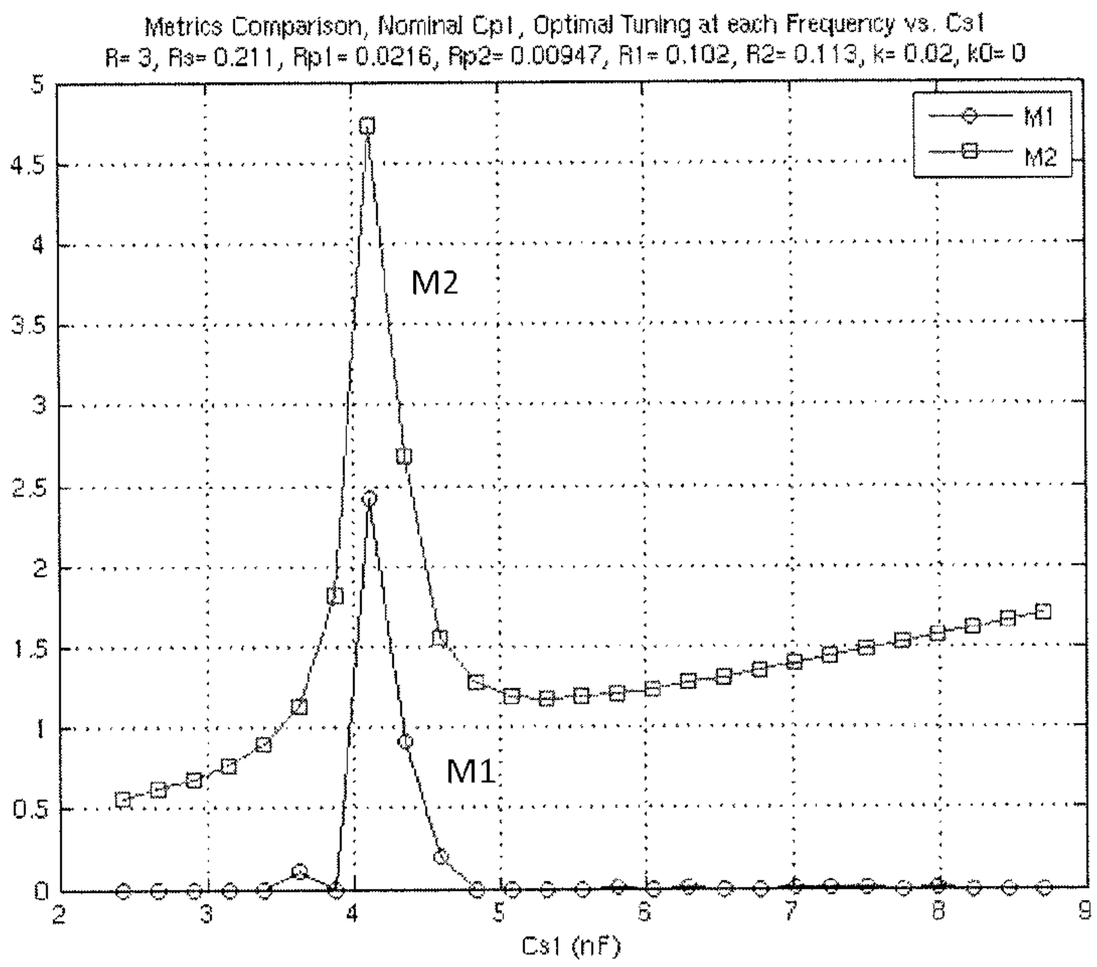

Metrics Comparison, Nominal Cp1, Optimal Tuning at each Frequency vs. Cs1
R= 3, Rs= 0.211, Rp1= 0.0216, Rp2= 0.00947, R1= 0.102, R2= 0.113, k= 0.02, k0= 0
M1
M2
M2
M1
Cs1 (nF)

FIG. 4

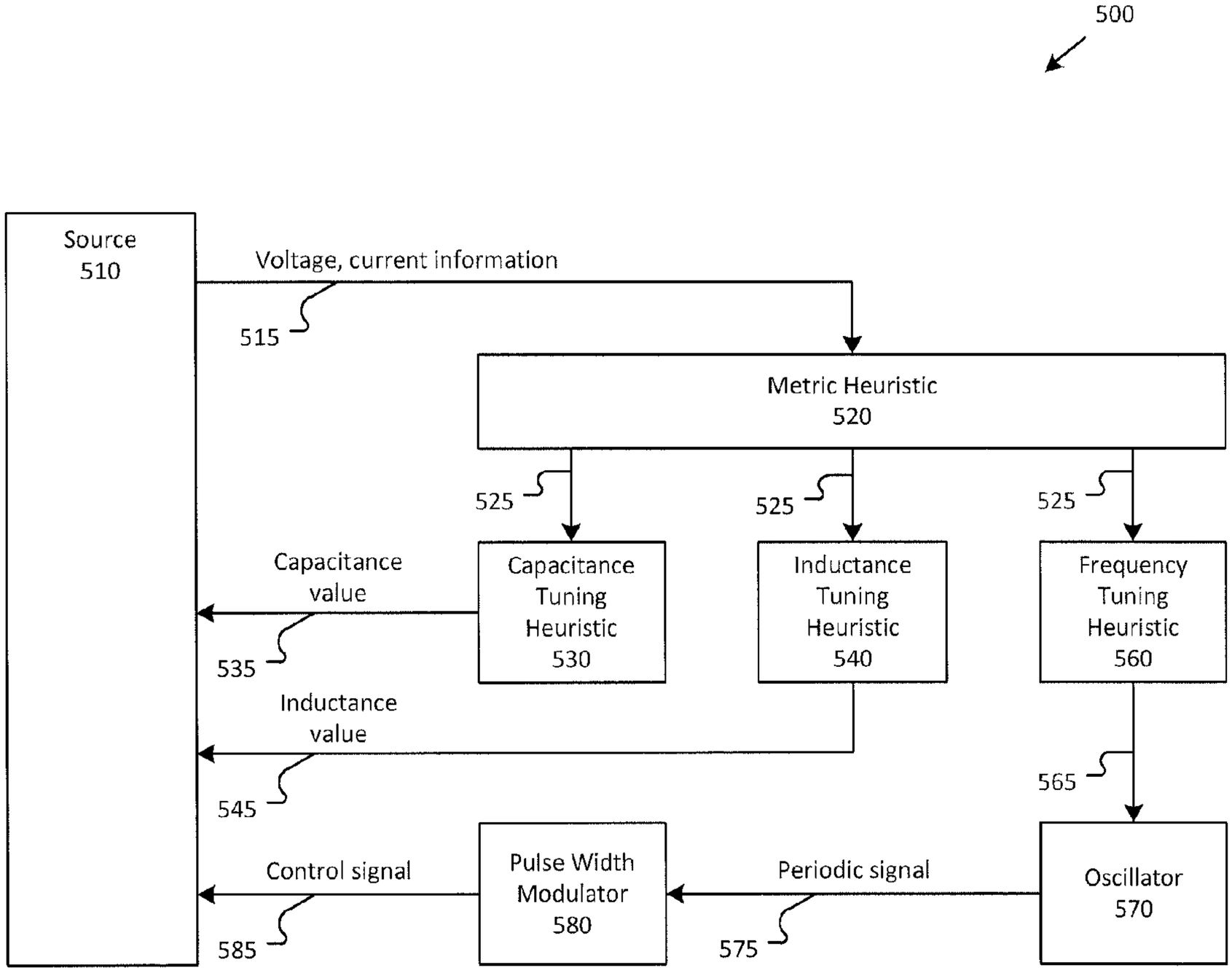

500
Source
510
Voltage, current information
515
Metric Heuristic
520
525
525
525
Capacitance
value
535
Capacitance
Tuning
Heuristic
530
Inductance
Tuning
Heuristic
540
Frequency
Tuning
Heuristic
560
Inductance
value
545
565
Control signal
585
Pulse Width
Modulator
580
Periodic signal
575
Oscillator
570

FIG. 5

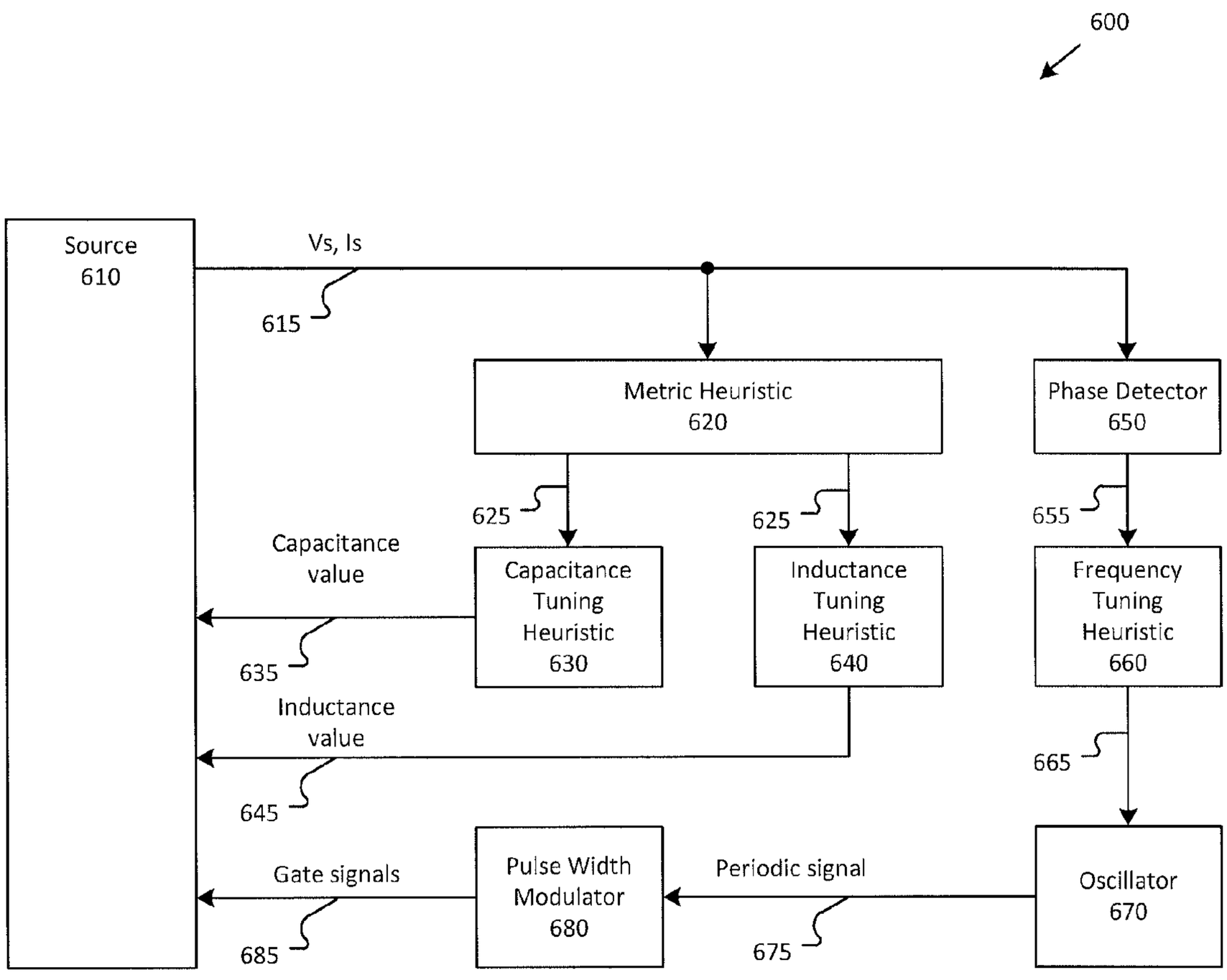

600
Source
610
Vs, Is
615
Metric Heuristic
620
Phase Detector
650
625
625
655
Capacitance
value
Capacitance
Tuning
Heuristic
630
Inductance
Tuning
Heuristic
640
Frequency
Tuning
Heuristic
660
635
Inductance
value
665
645
Gate signals
Pulse Width
Modulator
680
Periodic signal
Oscillator
670
685
675

FIG. 6

TRANSMITTER AND RECEIVER TUNING IN A WIRELESS CHARGING SYSTEM

CROSS REFERENCE TO RELATED APPLICATIONS

The present application claims benefit to U.S. provisional application 61/428,126 filed Dec. 29, 2010 entitled TRANSMITTER AND RECEIVER TUNING IN A WIRELESS CHARGING SYSTEM, the contents of which is incorporated herein in its entirety.

BACKGROUND

Energy may be transferred wirelessly between two devices from an inductive component of a transmitting device to an inductive component of a receiving device. Alternatively, energy may be transferred wirelessly from a capacitive component of a transmitting device to a capacitive component of a receiving device. For ease of discussion and not by way of limitation, energy transfer via inductive components is discussed herein.

Energy transfer occurs when the receiving device is placed in the proximity of a magnetic field generated by the transmitting device. The magnetic field at the transmitting device is generated by exciting the coil at the transmitting device with an alternating current.

Power may be described mathematically as having a real component and an imaginary component, referred to as active power and reactive power, respectively. Generally speaking, active power is either transferred to a load or dissipated in parasitic components within or in close proximity of the system, whereas reactive power is stored in the system in the form of oscillating voltages and currents in reactive elements such as inductors and capacitors.

Ideally, all active power is transferred from the transmitting device to one or more receiving devices. However, power may be lost in the transmitting device, for example to heat, or lost when power is absorbed by metal objects near the transmitting device. Further, power may be lost in the receiving device.

Many other factors affect power transfer, including distance between transmitting and receiving devices, resonant frequency of transmitting and receiving devices, frequency at which the transmitter device is excited, number of receiving devices, objects other than receiving devices near the transmitting device, size and relative size of coils, and orientation of coils, to name just a few. It is desirable to optimize power transfer and efficiency.

It would be desirable, therefore, to have the capability to dynamically adjust one or more operating parameters of a transmitting device or receiving device to adapt to changing operating conditions, component tolerances, and component parameter drift over time. It would be useful to define a metric whose value adequately indicates the power transmission efficiency and an amount of power or a relative amount of power being transferred. Such a metric may then be used in determining appropriate operating parameters to adjust.

FIGURES

FIG. **1** illustrates an exemplary wireless power transfer system with a transmitter and a receiver.

FIG. **2** illustrates an exemplary equivalent electrical model for coils in a wireless power transfer system.

FIG. **3** illustrates an exemplary wireless power transfer system model using a coupled coil model.

FIG. **4** illustrates an exemplary comparison of two metrics over a sweep of source frequencies and a sweep of capacitor values.

FIG. **5** illustrates an exemplary wireless power transfer device using metrics in the determination of one or more circuit parameters to adjust.

FIG. **6** illustrates an exemplary wireless power transfer device including metric analysis and a frequency tracking loop.

DETAILED DESCRIPTION

Wireless power transfer may be achieved by coupling energy from an inductive component in a power delivery device (transmitter) to an inductive component in a power receiving device (receiver). Alternatively, capacitive components may be coupled. Power transfer or the efficiency of power transfer may increase or decrease depending on operating and environment conditions of a system including a transmitter and at least one receiver. To provide the capability to adjust the amount of power transferred in response to changing conditions, a transmitter or receiver may include components having tunable parameters such as tunable circuit parameters, tunable frequency, or tunable phase. A metric may be used to identify when to modify tunable parameters and how much to modify the parameters.

A first metric is derived from information received via communication between a wireless power transfer transmitter and receiver. A second metric is derived from input voltage and current measurements. A third metric is derived from input voltage and current measurements and from coil voltage.

In some implementations tunable parameters may be used for impedance matching or the like. Tunable parameters include without limitation frequency, phase, capacitance, and inductance.

In some implementations a resonant circuit may be used to maximize power transfer. Resonance is achieved when voltage and current of the source are in phase. One tunable parameter that may be used to achieve resonant or near resonant operation is the excitation frequency of the resonant circuit. This frequency may be controlled to achieve optimal operation in different operating conditions. The second and third metric described below include information related to the phase difference between source voltage and current. The second and third metric are used in control of the excitation frequency and other tunable parameters.

FIG. **1** illustrates an exemplary wireless power transfer system **100** with a transmitter **110** and a receiver **120**. Transmitter **110** includes coil **130** having inductance L**1**. Receiver **120** includes coil **140** having inductance L**2**. Coils **130** and **140** are coupled with coupling coefficient k, which is at least in part a function of distance between the coils and relative orientation of the coils. A mutual inductance M is established between coils **130** and **140** at least in part as a function of coupling coefficient k and inductances L**1** and L**2**. The mutual inductance M and coupling coefficient k affect the amount of power transferred, and it is therefore desirable to model system **100** in such a way that the effects of M and k may be analyzed.

FIG. **2** illustrates an equivalent electrical model for the coils in the system **100** shown in FIG. **1**. Coils **210**, **220**, and **240** together with ideal transformer **230** model the effect of the coupling of coils **130** and **140** in FIG. **1**. Coils **210**, **220**,

and **240** as modeled have the inductances shown in equations 1, 2, and 3, respectively.

$$L_{k1}=(1-k)\cdot L1 \tag{1}$$

$$L_M=k\cdot L1 \tag{2}$$

$$L_{k2}=(1-k)\cdot L2 \tag{3}$$

Coupling coefficient k is defined in equation 4.

$$k=\frac{M}{\sqrt{L1\cdot L2}} \tag{4}$$

Ideal transformer **230** in the equivalent circuit of FIG. **2** is illustrated as having a 1:n turns ratio, where n is defined in equation 5.

$$n=\sqrt{\frac{L2}{L1}} \tag{5}$$

As coupling coefficient k decreases, for example due to increased distance between the coils, power transferred between the coils decreases. Circuits on the transmitter or receiver may be tuned for improved power transfer. Tuning may be used to match the resonant frequencies of transmitter and receiver circuits.

FIG. **3** illustrates an exemplary system **100** model using the coupled coil model of FIG. **2** with tuning circuits on both the transmitter and receiver side. Capacitors **320**, **330** and **340** are tunable such that capacitance values Cs**1**, Cp**1**, and Cp**2** are variable, respectively. Power source **310** produces a voltage Vs and current Is, and is tunable such that source frequency and phase are variable. Thus, either the transmitter or receiver is tunable. Other tunable circuits may be alternatively implemented, and may include different tunable parameters. For example, inductance and power source phase may also be tunable. Further, a receiver may also include a tunable power source.

A metric may be defined to provide a relative measurement of the power transfer between a transmitter and a receiver. The metric may then be used to dynamically determine whether tuning of a circuit is desirable and, if so, how much tuning should be done.

A metric M**1** is defined in equation 6 as a basic measure of power transfer effectiveness. In equation 6, Pout is the average power delivered to a load and the symbol eta (η) represents total system efficiency as measured by the ratio of average system **100** output power to average system **100** input power.

$$M1=P\text{out}\cdot\eta \tag{6}$$

Metric M**1** increases with increases in power delivered to the load or increases in efficiency. Metric M**1** is equal to zero when either power delivered to the load is equal to zero or efficiency is equal to zero. Thus, metric M**1** provides a relative measure of power transfer effectiveness that is useful in tuning a system **100**.

Metric M**1** requires knowledge of electrical measurements on both the transmitter and receiver. In a system with communication between transmitter and receiver such information may be readily available. However, not all wireless power transfer systems include communication capability between transmitter and receiver. Even in systems with communication capability, the communication may not include the information needed to calculate metric M**1**. Thus, it is desirable to define a different metric that does not rely on communication between the transmitter and receiver.

A second metric, M**2**, is defined in equation 7 for use in systems where electrical system parameters are not part of the communication between transmitter and receiver, or in systems without communication between transmitter or receiver. In equation 7, Vs is the source voltage and Is is the source current, where the source is a power source at the transmitter. Vs and Is are defined in equation 8 and equation 9, respectively.

$$M2=Re(Vs\cdot Is^*) \tag{7}$$

$$Vs=|Vs|e^{j\omega t} \tag{8}$$

$$Is=|Is|e^{j\omega t+\phi} \tag{9}$$

Using equations 7-9, metric M**2** may be rewritten as shown in equation 10.

$$M2=|Vs|\cdot|Is|\cdot\cos(\phi) \tag{10}$$

For systems such as those illustrated in FIG. **3**, metric M**2** exhibits a peak under the same operating conditions as M**1**. Therefore, although M**2** is based on measurements made only on the transmitter, M**2** is also an effective relative measure of power transferred to the receiver, useful in tuning a system **100**.

In some implementations of a wireless power transfer system it may be useful to limit source current of the transmitter. For example, as a parameter of the transmitter is changed during the tuning process, the voltage across the transmitter coil will change, therefore changing the magnetic field intensity generated by the transmitter. Metric M**2** may increase as coil voltage increases; however, higher coil voltage does not necessarily indicate better power transfer efficiency. To maximize power transfer efficiency, it is preferable to maximize the ratio of active power to reactive power. In order to have a consistent comparison between metric values in different operating conditions it is convenient to keep the transmitter coil voltage (and therefore the transmitter magnetic field intensity) constant by limiting the input current.

Metric M**2** matches metric M**1** more closely under conditions of limited source current than when source current is not limited. Thus, if metric M**1** describes a preferred measurement, metric M**2** may provide an approximation of metric M**1** under limited source current conditions.

FIG. **4** provides a comparison of metrics M**1** and M**2** for the circuits of FIG. **3** over a sweep of source frequencies and a sweep of values for capacitor **320** using a current-limited voltage source. The following values for FIG. **3** circuit elements were used in the simulation: R=3Ω; Rs=0.211Ω; Rp**1**=0.0216Ω; Rp**2**=0.00947Ω; R**1**=0.102Ω; R**2**=0.113Ω; k=0.02; k**0**=0. At each capacitor **320** value Cs**1** a sweep of the source frequency was performed and the optimal tuning frequency, as determined by a heuristic using one of the metrics, was plotted. As seen in FIG. **4**, both metric M**1** and M**2** resulted in substantially similar optimal tuning under the given operating conditions.

As noted, metric M**2** approximates metric M**1** closely in systems with limited source current. It may be desirable to define a new metric for indicating power transfer that provides a good approximation of metric M**1** without a limitation on source current.

Metric M**3** is defined in equation 11. In equation 11, the term Vcoil is the voltage across the transmitter coil, and the

term Vcoil_ref is an arbitrary normalization coefficient for the transmitter coil voltage, and may be equal to maximum coil voltage.

$$M3 = \mathrm{Re}(Vs \cdot Is^*) \cdot \left(\frac{\mathrm{Vcoil_ref}}{Vcoil}\right) \quad (11)$$
$$= |Vs| \cdot |Is| \cdot \cos(\phi) \cdot \left(\frac{\mathrm{Vcoil_ref}}{Vcoil}\right)$$

Three metrics have been described for providing an indication of relative power transfer between the coils of a wireless power transfer system. Other metrics may also be used. For example, a metric may include only the magnitude information |Vs|*|Is|, or may only include phase information. Further, multiple metrics may be used; for example, one metric may be used for coarse tuning and one metric used for fine tuning.

FIG. **5** illustrates a portion of a wireless device **500** using metrics in the determination of one or more circuit parameters to adjust for tuning wireless device **500**. Blocks **520**, **530**, **540**, **560**, **570**, and **580** represent functions of wireless device **500**. Arrows shown in FIG. **5** indicate information provided between functional blocks. Information may be provided as, for example and without limitation, electrical signals, data, pointers, memory locations or offsets, function calls, and arguments. Information is transferred via an appropriate medium, such as wires, communication interfaces, and the like.

In FIG. **5**, a source **510** provides energy to circuitry in the wireless device. Source **510** includes tunable parameters such as tunable circuit parameters. Information **515** regarding voltage and current produced by source **510** is provided to a metric heuristic **520** that determines the value of a metric (or metrics) and provides information **525** regarding the value to various tuning heuristics. The various tuning heuristics determine some further value based on information **525**. Capacitance tuning heuristic **530** determines a capacitance value **535** for a tunable capacitor in source **510**. Inductance tuning heuristic **540** determines an inductance value **545** for a tunable inductor in source **510** or for a tunable transmitter coil. Frequency tuning heuristic **560** determines a value **565** to use for adjusting an oscillator **570** that outputs a periodic signal **575** to a pulse width modulator **580** that in turn outputs one or more control signals **585** to circuits in source **510**.

A heuristic, including heuristics **520**, **530**, **540**, and **560** or other heuristics mentioned below, may be implemented in hardware, firmware, or software or some combination of hardware, firmware, and software.

Presented above was an overview of FIG. **5**. Details of the components of FIG. **5** follow.

Information **515** may be electrical signals representing the voltage and current of source **510**. For example, information **515** may include an analog or digital signal representing the voltage at one side of a wireless power transfer coil or current through the coil. Information **515** may be, for another example, a memory block storing voltage or current history. In yet another example, information **515** may be a set of values including magnitude and phase values for voltage and current. The examples given of information **515** are not limiting. Further, information **515** may include a combination of information types provided via multiple transmission media.

Metric heuristic **520** uses information **515** to determine the value of a metric such as metric M**1**, M**2**, or M**3** described above. Metric heuristic **520** may determine the values for multiple metrics and may further select between the metrics according to the current environmental conditions. For example, a first metric may be used when only one receiver is being charged via wireless power transfer whereas a second metric may be used when multiple receivers are being charged. For another example, as coil voltage changes different metrics may be applied. Further, multiple metrics may be used in metric heuristic **520**.

Information **525** from metric heuristic **520** may include values calculated for the metrics or changes in the values of the metrics. Each block receiving information **525** may receive different information **525**; such as information related to different metrics, or information in different forms.

Representative tuning heuristics **530**, **540**, and **560** shown in FIG. **5** are not limiting, and fewer, more, or different heuristics may be used. One or more heuristics may be combined. A heuristic may be divided into multiple heuristics.

Capacitance tuning heuristic **530** receives information **525** and determines a value **535** for one or more tunable capacitors in source **510**, or an indication **535** of whether to increase or decrease the capacitance of one or more tunable capacitors. Inductance tuning heuristic **540** receives information **525** and determines a value **545** for one or more tunable inductors in source **510**, or an indication **545** of whether to increase or decrease the inductance of one or more tunable inductors.

Frequency tuning heuristic **560** receives information **525** and determines information **565** to provide to oscillator **570**. Information **565** may be, for example, a value for a desired frequency or a difference value between a desired frequency and the actual frequency of source **510**. An example of a metric used by metric heuristic **520** to provide information **525** to frequency tuning heuristic **560** is given in equation 12, where metric Mdiff is representative of a phase difference between the voltage and current of source **510**.

$$M\mathrm{diff} = \mathrm{sign}(Vs) \cdot \mathrm{sign}(Is) \cdot \sin(\phi) \quad (12)$$

A value of Mdiff=0 indicates that voltage and current are in phase and therefore the circuit is operating at or near a resonance frequency. A simpler version of Mdiff uses only sign (Vs)*sign(Is) without the sin(□) term. The value for Mdiff may be used by frequency tuning heuristic **540** to provide information **565** to oscillator **570** regarding an amount to adjust oscillator **570** frequency, for example to approach resonance and thereby improve power transfer.

Oscillator **570** outputs a periodic signal **575** based on information **565**. For example, oscillator **570** may output a sine wave or square wave at a desired frequency specified by information **565**. In another example, oscillator **570** may adjust the frequency of a periodic signal **575** by an amount indicated in information **565**.

Pulse width modulator **580** receives periodic signal **575** and outputs a pulse width modulated (PWM) control signal **585**. Control signal **585** is a train of pulses of fixed amplitude with frequency and phase equal to the periodic signal **575**. The duty cycle of control signal **585** may be variable. For the example of FIG. **5**, control signal **585** may be a set of control signals applied to switching mechanisms in source **510** for generating a voltage or current at a certain frequency and phase.

Wireless device **500** illustrated in FIG. **5** thus uses information from source **510** to evaluate power transfer according to one or more metrics and adjust one or more parameters of source **510** to adjust the amount of power transferred.

Often source **510** is adjusted to increase power transfer, for example by tuning the power delivery circuit at or near a resonance frequency. However, source **510** may also be adjusted to decrease power transfer, for example during overload conditions or when a metal object is present.

The exemplary wireless device **510** of FIG. **5** illustrates power transfer analysis and adjustment based solely on metrics. Other implementations use metrics in addition to various feedback mechanisms for maintaining stability and control.

FIG. **6** illustrates an exemplary wireless device **600** including metric analysis and a frequency tracking loop. Blocks **620**, **630**, **640**, **650**, **660**, **670**, and **680** represent functions of wireless device **600**. Arrows shown in FIG. **6** indicate information provided between functional blocks as described above with respect to FIG. **5**.

In FIG. **6**, a source **610** provides energy to circuitry in the wireless device. Source **610** includes tunable parameters such as tunable circuit parameters. Information **615** regarding voltage and current produced by source **610** is provided to a metric heuristic **620** that determines the value of a metric (or metrics) and provides information **625** regarding the value to various tuning heuristics. The various tuning heuristics determine some further value based on the information **625**. Capacitance tuning heuristic **630** and inductance tuning heuristic **640** are similar to capacitance tuning heuristic **530** and inductance tuning heuristic **540** of FIG. **5**, respectively.

In a frequency tracking loop, a phase detector **650** monitors source **610** and provides source **610** phase information **655**. Frequency tuning heuristic **660** determines a value **665** to use for adjusting an oscillator **670** that outputs a periodic signal **675** to a pulse width modulator **680** that in turn outputs one or more control signals **685** to circuits in source **610**.

Presented above was an overview of FIG. **6**. Details of the components of FIG. **6** follow.

Information **615** is substantially similar to information **515** of FIG. **5** as described above.

Metric heuristic **620**, capacitance tuning heuristic **630**, and inductance tuning heuristic **640** operate substantially similar to heuristics **520**, **530**, and **540** of FIG. **5**, respectively, as described above.

Phase detector **650** receives voltage and current information **615** from source **610** and determines from information **615** the phase difference between the voltage and current of source **610**. For example, a phase detection circuit of phase detector **650** may provide an analog electrical signal **655** representing the phase difference. In another example, phase detector **650** may analyze the voltage and current information **615** and provide a value **655** representing the phase difference.

Frequency tuning heuristic **660** receives phase information **655** from phase detector **650** and determines information **665** to provide to oscillator **670**. Information **665** may be, for example, a value for a desired frequency or a difference value between a desired frequency and the actual frequency of source **610**.

Oscillator **670** outputs a periodic signal **675** based on information **665**. For example, oscillator **670** may output a sine wave or square wave at a desired frequency specified by information **665**. In another example, oscillator **670** may adjust the frequency of a periodic signal **675** by an amount indicated in information **665**.

Pulse width modulator **680** receives periodic signal **675** and outputs a pulse width modulated (PWM) control signal **685** in a manner substantially similar to that described for pulse width modulator **580** of FIG. **5** as described above.

Phase detector **650**, frequency tuning heuristic **660**, oscillator **670**, and pulse width modulator **680** combined may be implemented in the form of a phase-locked loop (PLL). In such implementations, because the resonant frequency of a power transfer system is close to the resonant frequency of the transmitter, and because it is desirable to operate at the system resonant frequency, the PLL may be used to more quickly tune a transmitter. During tuning, following each stepping of a source **610** parameter such as inductance or capacitance, the PLL automatically and rapidly tunes the transmitter to the new system resonant frequency. Thus, tuning time is reduced to the time required for the parameter sweep.

Wireless device **600** illustrated in FIG. **6** thus uses information from source **610** to evaluate power transfer according to one or more metrics and adjust one or more parameters of source **610** to adjust the amount of power transferred. Substantially concurrently, a frequency tuning loop uses information from source **610** to tune the frequency of wireless device **600**.

Often source **610** is adjusted to increase power transfer. However, source **610** may also be adjusted to decrease power transfer.

In addition to providing capability for adjusting power transfer, the tunable parameters of sources **510** and **610** provide the capability to detect metal objects located close to wireless device **500** or **600**, respectively. For a wireless power transfer transmitter, selected values (or all values) of a tunable parameter may be applied in turn (i.e., a parameter sweep). A power transfer metric may be evaluated for each value of the tunable parameter. If the metric is substantially the same for each value of the tunable parameter then there is a metal object nearby that is absorbing power from the transmitter wirelessly. The transmitter may react by disabling power transfer to protect against an overload condition. Power transfer may be interrupted occasionally to perform a parameter sweep as described for metal detection.

Transmitters and receivers may be implemented in a variety of ways, and may be or may include at least one computing device. Examples of computing devices include, without limitation, a computer workstation, server, desktop computer, notebook computer, laptop computer, handheld computer, personal data assistant (PDA), smart phone, or any other device including an embedded processing device.

Computing devices generally include computer-executable instructions, where the instructions may be executable by one or more computing devices such as those listed above. In general, a processor receives instructions, for example from a memory or a computer-readable medium or the like, and executes these instructions, thereby performing one or more processes including one or more of the processes described herein. Such instructions and other data may be stored and transmitted using a variety of known computer-readable media.

A computer-readable medium (also referred to as a processor-readable medium) includes any tangible medium that participates in providing data (instructions, for example) that may be read by a computing device.

CONCLUSION

With regard to the processes, systems, methods, heuristics, etc. described herein, it should be understood that, although the steps of such processes, etc. have been described as occurring according to a certain ordered sequence, such processes could be practiced with the described steps performed in an order other than the order described herein. It further should be understood that certain steps could be performed simultaneously, that other steps could be added, or that certain steps described herein could be omitted. In other words, the descriptions of processes herein are provided for the purpose of illustrating certain embodiments, and should in no way be construed so as to limit the claimed invention.

Accordingly, it is to be understood that the above description is intended to be illustrative and not restrictive. Many

embodiments and applications other than the examples provided would be apparent upon reading the above description. The scope of the invention should be determined, not with reference to the above description, but should instead be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. It is anticipated and intended that future developments will occur in the technologies discussed herein, and that the disclosed systems and methods will be incorporated into such future embodiments. In sum, it should be understood that the invention is capable of modification and variation.

All terms used in the claims are intended to be given their broadest reasonable constructions and their ordinary meanings as understood by those knowledgeable in the technologies described herein unless an explicit indication to the contrary in made herein. In particular, use of the singular articles such as "a," "the," "said," etc. should be read to recite one or more of the indicated elements unless a claim recites an explicit limitation to the contrary.

What is claimed is:

1. A transmitter circuit suitable for use in wireless power transfer to a power receiving device, the transmitter circuit operable with an alternating current power source; the transmitter circuit comprising:

a transmitter coil;

Power transfer circuitry coupled between the power source and the transmitter coil, and including at least one tunable reactive component;

tuning heuristic circuitry configured to control power transfer from the power source to the power receiving device by tuning the at least one tunable reactive component based on a metric equal to:

$$|Vs|\cdot|Is|\cdot\cos(\phi)\cdot(V\text{coil_ref}/V\text{coil}),$$

where, |Vs| is the magnitude of the power source voltage, |Is| is the magnitude of the power source current, ϕ is the phase difference between the power source voltage and power source current, Vcoil_ref is a normalization value, and Vcoil is the voltage across the transmitter coil.

2. The circuit of claim **1**, wherein the at least one tunable reactive component comprises a tunable capacitance.

3. The circuit of claim **1**, wherein the at least one tunable reactive component comprises a tunable inductance.

4. The circuit of claim **1**, further comprising:

an oscillator providing a periodic signal;

a pulse width modulator controlling the frequency of the power source based on the periodic signal provided by the oscillator;

a phase detector detecting the difference between the phase of the power source voltage and the phase of the power source current; and

frequency tuning heuristic circuitry configured to adjust the oscillator based on the phase of the power source.

5. The circuit of claim **4**, the oscillator, the pulse width modulator, the phase detector, and the frequency tuning heuristic circuitry being implemented as a phase-locked loop (PLL).

6. The circuit of claim **1**, wherein the power source is configured with a tunable duty cycle, the duty cycle being adjusted to control transmitter magnetic field intensity and thereby adjust the amount of power being transferred.

7. A method suitable for use in wireless power transfer from a transmitter including a transmitter coil, to a power receiving device, the transmitter operable with an alternating current power source, comprising:

controlling power transfer from the power source to the transmitter coil with power transfer circuitry that includes at least one tunable reactive component;

tuning the at least one tunable reactive component based on a metric equal to:

$$|Vs|\cdot|Is|\cdot\cos(\phi)\cdot(V\text{coil_ref}/V\text{coil}),$$

where, |Vs| is the magnitude of the power source voltage, |Is| is the magnitude of the power source current, ϕ is the phase difference between the Power source voltage and power source current, Vcoil_ref is a normalization value, and Vcoil is the voltage across the transmitter coil.

8. The method of claim **7**, wherein the at least one tunable reactive component comprises a tunable capacitance.

9. The method of claim **7**, wherein the at least one tunable reactive component comprises a tunable inductance.

10. The method of claim **7**, further comprising adjusting the frequency of the power source based on the difference between the phase of the power source voltage and the phase of the power source current.

11. The method of claim **10**, adjusting the frequency of the power source using a phase-locked loop (PLL).

12. The method of claim **7**, further comprising adjusting a duty cycle of the power source to control transmitter magnetic field intensity and thereby adjusting the amount of power being transferred.

* * * * *