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Sankar

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(54) **WIRELESS POWER SYSTEM WITH A SELF-REGULATING WIRELESS POWER RECEIVER**

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H02J 5/00	(2016.01)
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H02J 7/02	(2016.01)
H04B 5/00	(2006.01)
H02J 7/00	(2006.01)

(52) **U.S. Cl.**

CPC ***H02J 5/005*** (2013.01); ***H02J 7/025*** (2013.01); ***H03H 7/40*** (2013.01); ***H04B 5/0031*** (2013.01); ***H04B 5/0037*** (2013.01); ***H04B 5/0081*** (2013.01); *H02J 2007/0001* (2013.01)

(58) **Field of Classification Search**

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See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2005/0227648	A1*	10/2005	Tan	H03J 1/0091 455/154.1
2007/0064457	A1*	3/2007	Perreault	H02M 3/155 363/78

(Continued)

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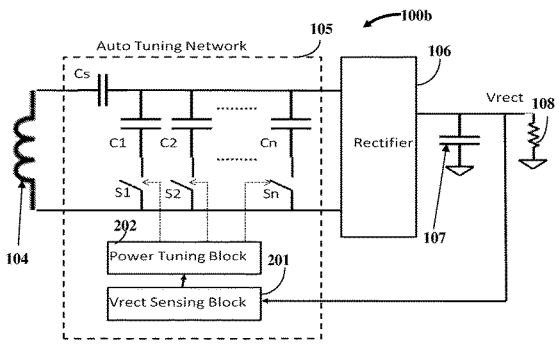
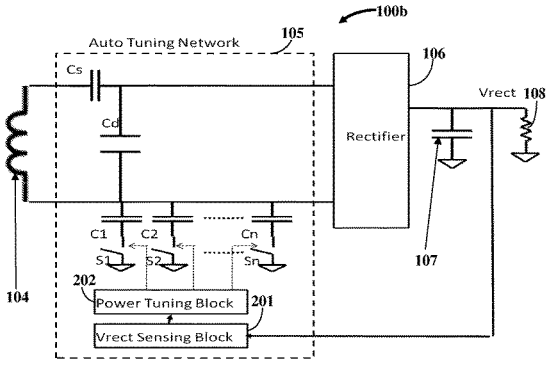
(57) **ABSTRACT**

A method and a system for self-regulating wireless power transmitted to a wireless power receiver (WPR) are provided. An auto-tuning network is operably coupled within the WPR. The auto-tuning network includes an impedance network that dynamically increases, decreases, or maintains an amount of the received wirelessly transmitted power by detecting changes in a rectifier load disposed in the WPR and/or in a rectifier output voltage in the WPR. The auto-tuning network self-regulates the wireless power received from a wireless power transmitter (WPT) obviating the need for conventional communication messages. The WPT is hence free from a modulator/demodulator block and an out-of-band communication block and operates over a limited operating range to enable a simpler design for passing electromagnetic compliance regulations. The WPR implements a receiver-maximum-power-signature algorithm for enabling the WPT to detect unsupported receivers, configure its operating point and range, and terminate power transmission when not needed by the WPR.

15 Claims, 5 Drawing Sheets





(56) **References Cited**

U.S. PATENT DOCUMENTS

2010/0110741	A1*	5/2010	Lin	H02J 5/005 363/127
2010/0283600	A1*	11/2010	Herbert	G08B 13/1427 340/539.1
2011/0021237	A1*	1/2011	He	H04W 52/52 455/522
2011/0080056	A1*	4/2011	Low	H02J 5/005 307/104
2011/0148215	A1*	6/2011	Marzetta	H02J 5/005 307/104
2012/0299769	A1*	11/2012	Li	H01Q 3/267 342/174

* cited by examiner

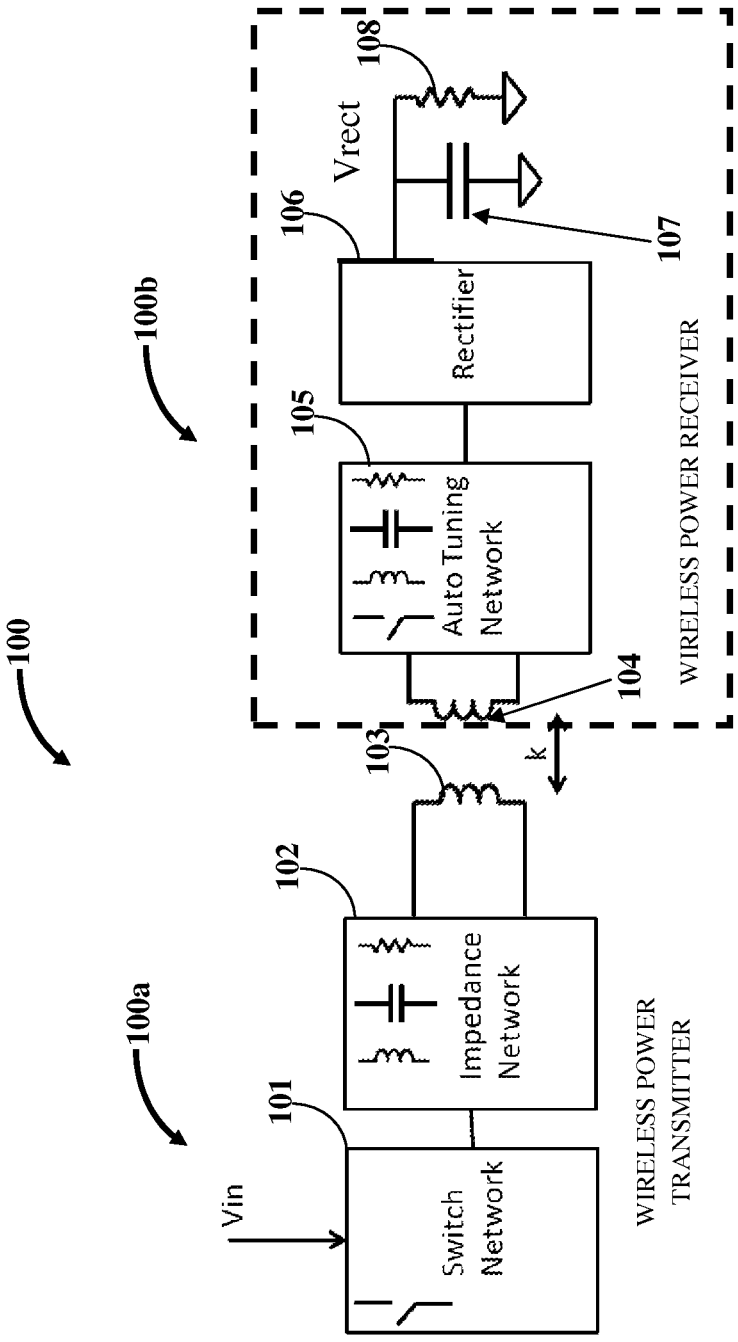

100
100a
100b
Vin
101
Switch Network
102
Impedance Network
103
k
104
105
Auto Tuning Network
106
Rectifier
107
108
Vrect
WIRELESS POWER TRANSMITTER
WIRELESS POWER RECEIVER

FIG. 1

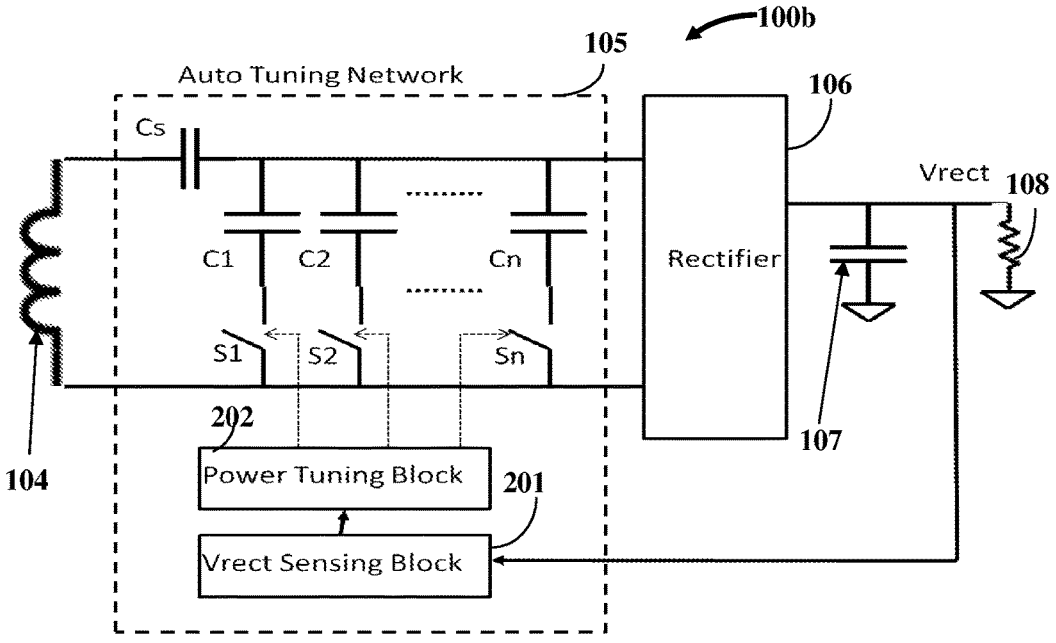

100b
105
Auto Tuning Network
106
Cs
Vrect
108
C1
C2
Cn
Rectifier
S1
S2
Sn
202
107
104
Power Tuning Block
201
Vrect Sensing Block

FIG. 2A

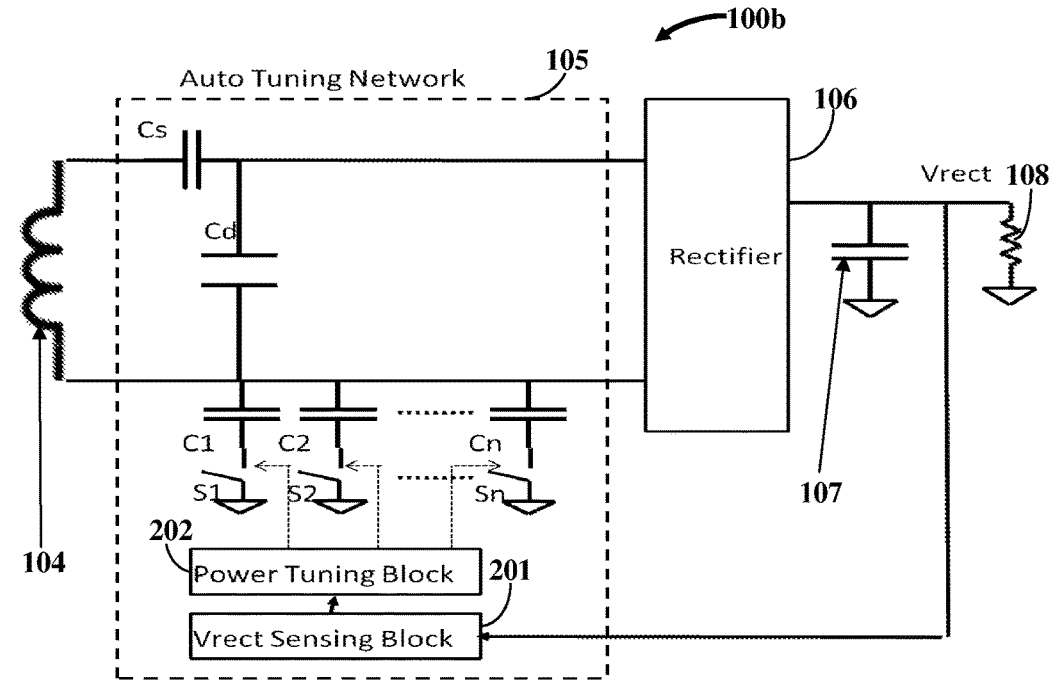

100b
105
Auto Tuning Network
106
Cs
Vrect
108
Cd
Rectifier
C1
C2
Cn
S1
S2
Sn
107
202
104
Power Tuning Block
201
Vrect Sensing Block

FIG. 2B

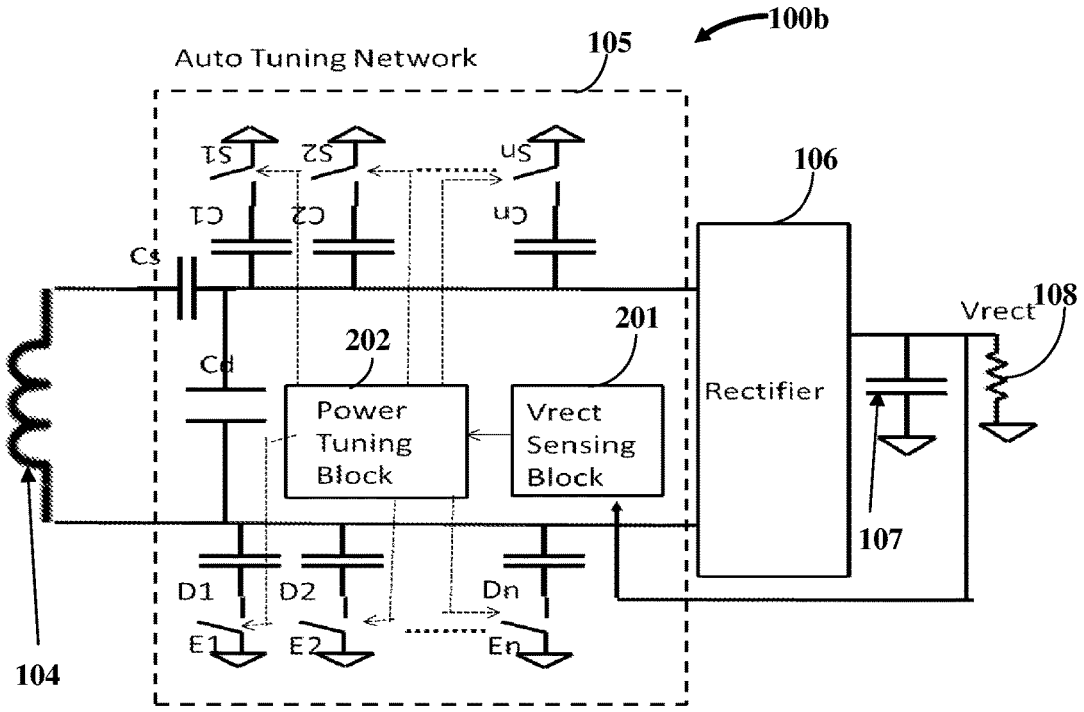

100b
Auto Tuning Network
105
S1
S2
Sn
C1
C2
Cn
Cs
106
Vrect
108
201
202
Cd
Power Tuning Block
Vrect Sensing Block
Rectifier
107
D1
D2
Dn
E1
E2
En
104

FIG. 2C

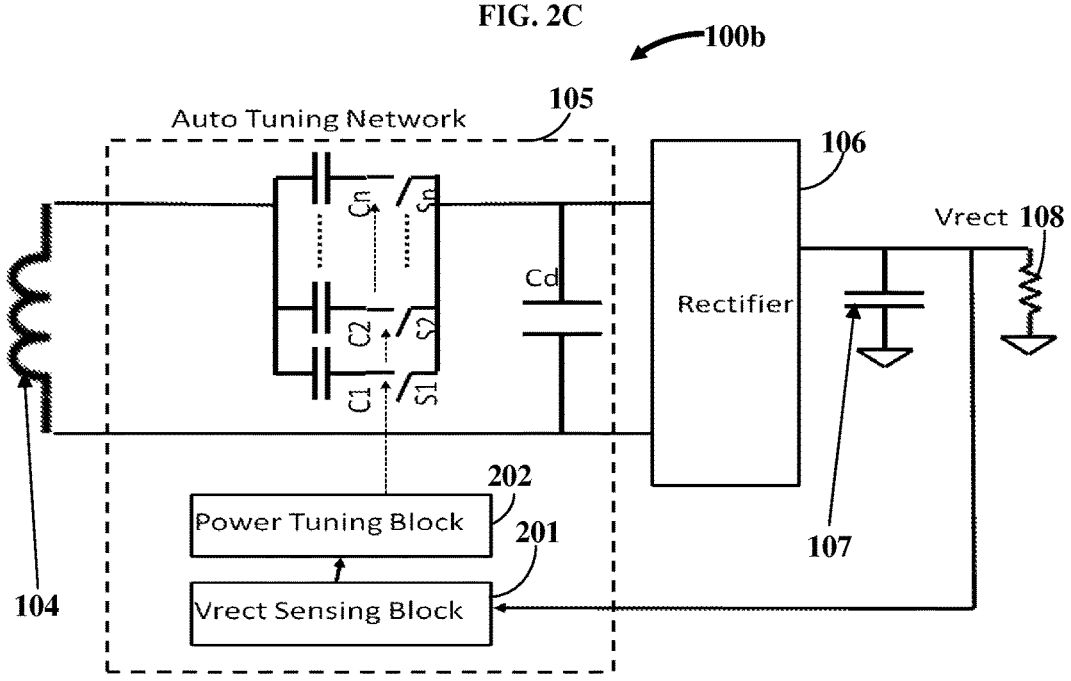

100b
Auto Tuning Network
105
106
Vrect
108
Cn
Sn
Cd
C2
S2
C1
S1
Rectifier
107
202
Power Tuning Block
201
Vrect Sensing Block
104

FIG. 2D

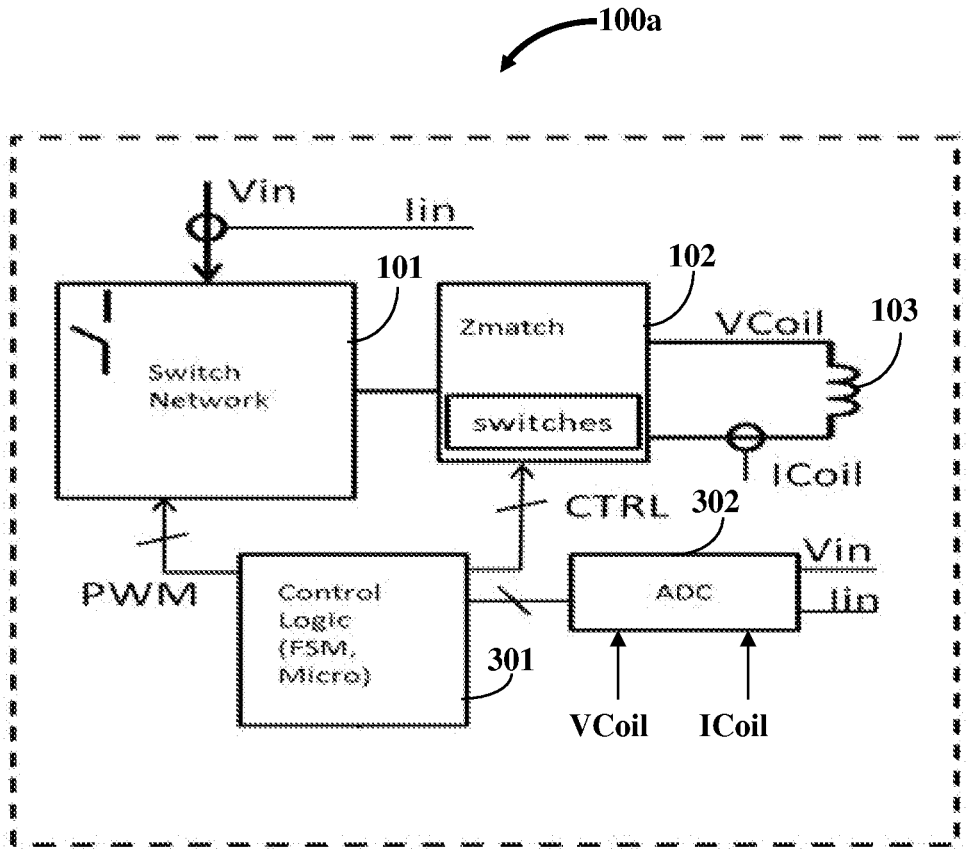

100a
Vin
Iin
101
102
Zmatch
VCoil
103
Switch Network
switches
ICoil
CTRL
302
Vin
Iin
PWM
Control Logic (FSM, Micro)
ADC
301
VCoil
ICoil

FIG. 3

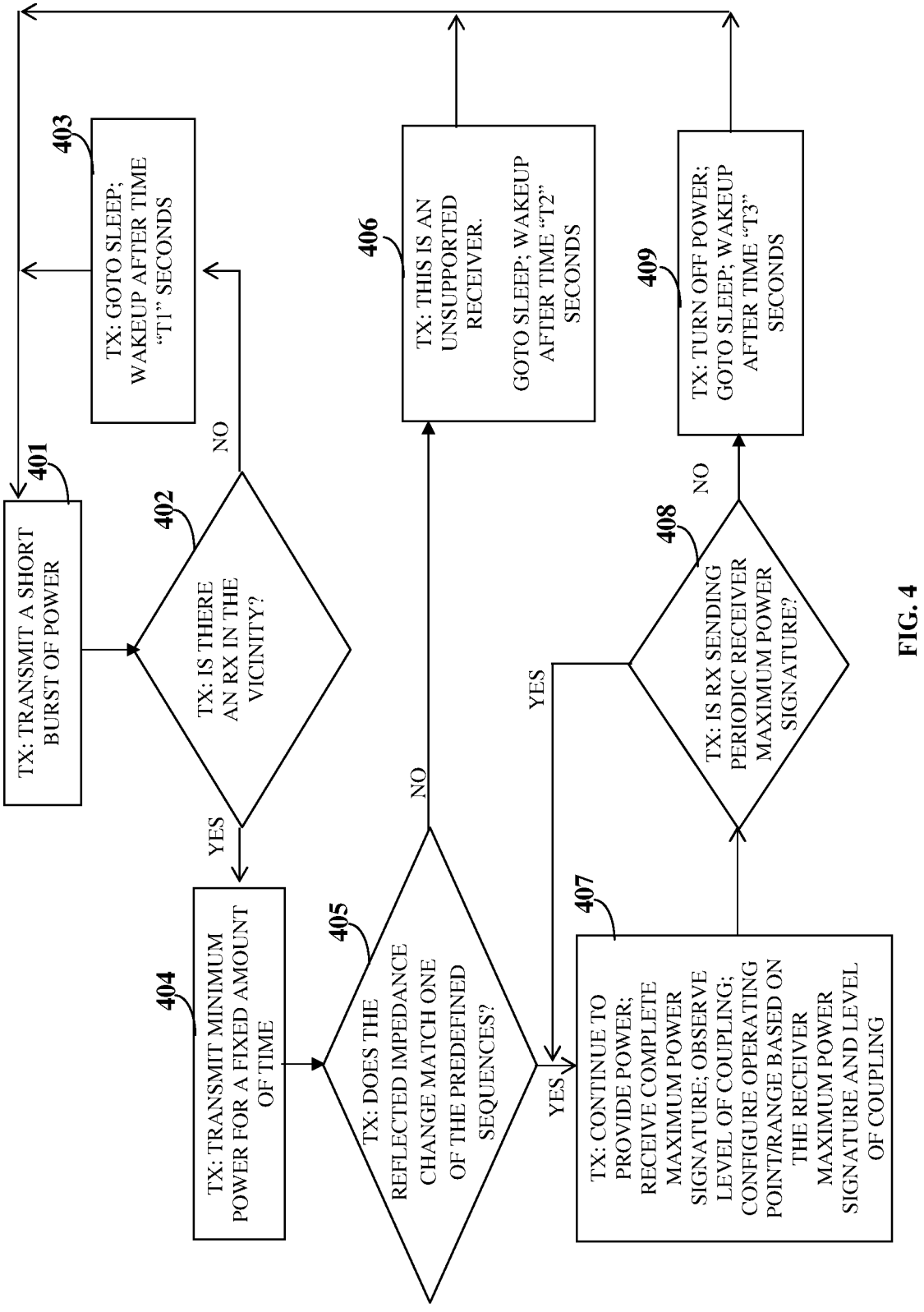

401
TX: TRANSMIT A SHORT BURST OF POWER
402
TX: IS THERE AN RX IN THE VICINITY?
NO
403
TX: GOTO SLEEP; WAKEUP AFTER TIME "T1" SECONDS
YES
404
TX: TRANSMIT MINIMUM POWER FOR A FIXED AMOUNT OF TIME
405
TX: DOES THE REFLECTED IMPEDANCE CHANGE MATCH ONE OF THE PREDEFINED SEQUENCES?
NO
406
TX: THIS IS AN UNSUPPORTED RECEIVER.
GOTO SLEEP; WAKEUP AFTER TIME "T2" SECONDS
YES
407
TX: CONTINUE TO PROVIDE POWER; RECEIVE COMPLETE MAXIMUM POWER SIGNATURE; OBSERVE LEVEL OF COUPLING; CONFIGURE OPERATING POINT/RANGE BASED ON THE RECEIVER MAXIMUM POWER SIGNATURE AND LEVEL OF COUPLING
408
TX: IS RX SENDING PERIODIC RECEIVER MAXIMUM POWER SIGNATURE?
NO
409
TX: TURN OFF POWER; GOTO SLEEP; WAKEUP AFTER TIME "T3" SECONDS

FIG. 4

WIRELESS POWER SYSTEM WITH A SELF-REGULATING WIRELESS POWER RECEIVER

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to and the benefit of provisional patent application No. 61/732,412 titled "Wireless Charging System With A Self-regulating Wireless Power Receiver", filed in the United States Patent and Trademark Office on Dec. 3, 2012. The specification of the above referenced patent application is incorporated herein by reference in its entirety.

BACKGROUND

In wireless power systems, a receiver and a transmitter communicate with one another using a communication protocol. In a conventional communication protocol, the receiver requests the transmitter to increase, decrease, maintain, stop, etc., the power provided to the receiver. The communication protocol can be "in band", for example, via a load modulation technique, or be "out of band", for example, via Bluetooth® of Bluetooth SIG, Inc., Wi-Fi® of the Wireless Ethernet Compatibility Alliance, etc.

Conventional communication protocol based power transfer control involves the transmitter changing its frequency across a few hundred kilo hertz (kHz). However, for some applications, it is not desirable to have a wide range of frequency of operation for wireless power transfer. Also, Federal Communications Commission (FCC) Part 15 Subpart C compliance testing becomes difficult because of varying frequency and the corresponding harmonics.

The conventional communication protocol between the receiver and the transmitter is also used to send, for example, distress signals, over voltage conditions, etc. The receiver takes a considerable amount of time to send a message and the transmitter takes a considerable amount of time to decipher the message and react to the sent message; therefore latency is inherent and there is a time delay. Also, the transmitter may decipher the message incorrectly, the message may be corrupted, etc., which could considerably delay the receiver in exiting from an over voltage condition. The receiver includes additional over voltage protection (OVP) circuitry that protects the receiver from excessive power during the time delay. The additional protection circuitry is rated to handle a certain amount of power, but if the power exceeds the rated power in the protection circuitry, the receiver may be susceptible to damages. Also, while operating, the protection circuitry causes a rise in temperature of the receiver which is detrimental to neighboring components, for example, a battery, etc.

Metal object detection is a key safety issue in wireless power delivery. Metal objects, for example, coins, pin-clips, etc., may couple and absorb some of the magnetic flux emanating from a transmitter when placed atop or in close proximity to the transmitter. Because of the eddy currents induced, the metal objects are heated. The heated metal objects cause damage to the plastic surface of the transmitter or burn skin on contact.

Therefore, there is a long felt but unresolved need for a method and a system that regulate the amount of wireless power delivered to a wireless power receiver without causing any damages to the wireless power receiver and the neighboring components of the wireless power receiver. Furthermore, there is a need for a method and a system that

enable a transmitter to detect a metal object placed atop or in close proximity to the transmitter and terminate transmission of power.

SUMMARY OF THE INVENTION

A method and a system for self-regulating a wireless power receiver are provided. The method and the system disclosed herein regulates an amount of wireless power delivered to the wireless power receiver. The wireless power receiver is configured to receive wirelessly transmitted power. An auto-tuning network is operably coupled within the wireless power receiver. The auto-tuning network is configured to control and regulate the received wirelessly transmitted power. The auto-tuning network comprises an impedance network dynamically configured to increase, decrease, or maintain the amount of the received wirelessly transmitted power. The impedance network comprises one or more of passive electronic components, active electronic components, and electronic switches. The auto-tuning network is configured to detect changes in one or more of a load of a rectifier operably disposed in the self-regulating wireless power receiver, and in an output voltage of the rectifier, and to counteract the detected changes if the detected changes exceed a safe operating range.

The wireless power receiver, via the auto-tuning network, self-regulates to draw the required amount of power from a wireless power transmitter. In a sudden over voltage condition, for example, on account of a load transient, the auto-tuning network detects the over voltage and performs a quick remedial action. The auto-tuning network provides effective and faster over voltage protection (OVP) than possible with a scheme that relies on communicating with the wireless power transmitter. The need for a conventional communication protocol from the wireless power receiver to the wireless power transmitter is obviated since the functions that require the communication protocol to exist are handled by the auto-tuning network with significantly faster response times.

The method and the system disclosed herein also simplify the wireless power transmitter design. The wireless power transmitter does not need a conventional modulator/demodulator block and an out-of-band communication block typically contained in the wireless power transmitter for processing messages from and communicating messages to the wireless power receiver. The wireless power receiver, via the auto-tuning network, receives the required amount of wirelessly transmitted power from the wireless power transmitter without communicating messages to the wireless power transmitter. As a result, a few of the wireless protocol communication function blocks such as the modulator/demodulator block and the out-of-band communication block that are typically contained in the wireless power transmitter can be eliminated. The modulator/demodulator block and the out-of-band communication block are built with many passive components, active components, switches, and firmware resources. Therefore, elimination of the modulator/demodulator block and the out-of-band communication block simplifies and substantially reduces the cost of the wireless power transmitter design. Also, the wireless power transmitter can operate at a fixed operating point, for example, a frequency, a duty cycle etc., or within a narrow range and/or a set of operating points. Such an implementation will allow the wireless power transmitter to pass electromagnetic compliance (EMC) regulation easily.

In an embodiment, to avoid a heated metal object safety issue caused by eddy currents induced when metal objects

are placed atop or in close proximity to the transmitter, the method and the system disclosed herein implement a receiver-maximum-power-signature algorithm that enables the wireless power transmitter to detect metal objects and unsupported receivers, and terminate transmission of power. The wireless power transmitter is aware of the maximum power needs of the wireless power receiver via the receiver-maximum-power-signature algorithm. The wireless power transmitter configures its circuitry, input voltage, operating point, etc., to deliver no more than the required level of maximum power to the wireless power receiver. Via the receiver-maximum-power-signature algorithm, the wireless power transmitter also terminates transmission of wireless power when the wireless power receiver does not need any further power or if the wireless power receiver is removed, thereby increasing the overall efficiency of wireless power delivery.

By incorporating the self-regulating wireless power receiver, the receiver-maximum-power-signature algorithm and the simplified, limited operating point wireless power transmitter, the method and the system disclosed herein allow building of a wireless power system that provides wireless power to an electronic device without the need for a conventional communication protocol between the wireless power transmitter and the wireless power receiver.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** exemplarily illustrates a schematic diagram of a wireless power system comprising a wireless power transmitter and a self-regulating wireless power receiver.

FIG. **2**A exemplarily illustrates a first embodiment of an auto-tuning network of the self-regulating wireless power receiver.

FIG. **2**B exemplarily illustrates a second embodiment of the auto-tuning network of the self-regulating wireless power receiver.

FIG. **2**C exemplarily illustrates a third embodiment of the auto-tuning network of the self-regulating wireless power receiver.

FIG. **2**D exemplarily illustrates a fourth embodiment of the auto-tuning network of the self-regulating wireless power receiver.

FIG. **3** exemplarily illustrates a schematic diagram of a wireless power transmitter without a modulator/demodulator block and an out-of-band communication block.

FIG. **4** exemplarily illustrates a flow chart comprising the steps for establishing a stable and optimal power transfer from the wireless power transmitter to the wireless power receiver.

DETAILED DESCRIPTION OF THE INVENTION

FIG. **1** exemplarily illustrates a schematic diagram of a wireless power system **100** comprising a wireless power transmitter **100***a* and a self-regulating wireless power receiver **100***b*. The wireless power receiver **100***b* of the wireless power system **100** employs an auto-tuning scheme to control the amount of power that the wireless power receiver **100***b* receives. A switch network **101** is configured to receive an input power and an input voltage. An impedance network **102** is connected between the switch network **101** and a transmitter coil **103**. The input power wirelessly transmitted to the wireless power receiver **100***b* is magnetic field based using inductive coupling. The transmitter coil **103** is used for inducing a magnetic field to a coupling region for providing energy transfer to the wireless power receiver **100***b*. The wireless power transmitter **100***a* transmits input power to the wireless power receiver **100***b* by emanating the magnetic field using the transmitter coil **103**. The wireless power receiver **100***b* comprises a receiver coil **104** that picks up the magnetic field with a certain coupling coefficient that exists between the transmitter coil **103** and the receiver coil **104**, an auto-tuning network **105** that regulates power received by the wireless power receiver **100***b*, and a rectifier **106** that rectifies alternating current (AC) to obtain direct current (DC). A capacitor **107** in the wireless power receiver **100***b* filters stray AC components. A pure DC output is received across a rectifier load **108**.

The auto-tuning network **105** controls and regulates the wireless input power received by the wireless power receiver **100***b*. The auto-tuning network **105** in the wireless power receiver **100***b* controls power transfer, protects against over voltage, and provides improved load transient response. The auto-tuning network **105** comprises an impedance network that is dynamically tuned to increase, decrease, or maintain the amount of wireless input power received by the wireless power receiver **100***b*. The impedance network comprises a combination of passive components such as inductors, capacitors, resistors, etc., active components such as metal oxide semiconductor field effect transistors (MOSFETs), bipolars, operational amplifiers, an analog to digital converter (ADC), microcontrollers (MCUs), etc., and switches.

The auto-tuning network **105** regulates the output voltage Vrect of the rectifier **106** across the rectifier load **108** that can swing instantaneously and exceed recommended limits when the load across the rectifier **106** changes. By performing this action, the auto-tuning network **105** protects the wireless power receiver **100***b* from an unsafe condition. The auto-tuning network **105** senses the changes in the rectifier load **108** and/or the output voltage Vrect of the rectifier **106** and quickly counteracts the changes if the changes exceed a safe operating range. For example, the auto-tuning network **105** rapidly tunes to increase the wireless input power at the wireless power receiver **100***b* when the rectifier output voltage Vrect drops below the safe operating range. In another example, the auto-tuning network **105** rapidly tunes to decrease the wireless input power at the wireless power receiver **100***b* when the rectifier output voltage Vrect increases above the safe operating range. The output voltage Vrect of the rectifier **106** is therefore maintained within a safe range without the need for a more elaborate over voltage protection (OVP) scheme. Changes in the auto-tuning network **105** affect the reflected impedance seen by the wireless power transmitter **100***a*. This alters the wireless power transmitted by the wireless power transmitter **100***a* to the wireless power receiver **100***b*.

FIG. **2**A exemplarily illustrates a first embodiment of the auto-tuning network **105** of the self-regulating wireless power receiver **100***b*. In this embodiment, the auto-tuning network **105** includes a Vrect sensing block **201**, a power tuning block **202**, a series resonant capacitor Cs, and a parallel switch-capacitor network consisting of "n" parallel capacitors C1, C2, . . . , Cn and "n" switches S1, S2, . . . , Sn. In this embodiment, the parallel switch-capacitor network is connected across two alternating current (AC) IOs of the rectifier **106**. The Vrect sensing block **201** measures the rectifier output voltage Vrect constantly or periodically. The power tuning block **202** compares the measured voltage Vrect with its configured threshold levels. Based on the comparison, the power tuning block **202** activates switches S1, S2, . . . , Sn. The switches may be turned on or turned

off or may be pulsed on and off at a certain frequency and duty cycle. When a switch S1, S2, . . . , Sn is turned on, the associated capacitor C1, C2, . . . , Cn on the same leg is activated and impacts the reflected impedance of the wireless power receiver **100***b* and hence the amount of wireless power received. The Vrect sensing block **201** senses the changes in the rectifier output voltage Vrect and the power tuning block **202** quickly counteracts the changes if the changes exceed a safe operating range. For example, if the rectifier output voltage Vrect drops below the safe operating range, the power tuning block **202** turns on switches S1 and S2 to increase the amount of wireless power received. The power tuning block **202** progressively turns on more switches until wireless power received restores the output voltage Vrect of the rectifier **106** to the safe operating range. In another example, if the rectifier output voltage Vrect increases above the safe operating range, the power tuning block **202** progressively decreases the on-time duty cycle of switches S1, S2, . . . , Sn to decrease the level of wireless power received until Vrect is restored to the safe operating range. As an additional embodiment, the resonant series capacitor Cs may not be present and the receiver coil **104** is connected directly to the parallel switch-capacitor network.

FIG. **2**B exemplarily illustrates a second embodiment of the auto-tuning network **105** of the self-regulating wireless power receiver **100***b*. In this embodiment, the auto-tuning network **105** includes a Vrect sensing block **201**, a power tuning block **202**, a series resonant capacitor Cs, a parallel resonant capacitor Cd, and a parallel switch-capacitor network consisting of "n" parallel capacitors C1, C2, . . . , Cn and "n" switches S1, S2, . . . , Sn. In this embodiment, the parallel switch-capacitor network is connected asymmetrically between one of the alternating current (AC) IOs of the rectifier **106** and ground. The Vrect sensing block **201** measures the rectifier output voltage Vrect constantly or periodically. The power tuning block **202** compares the measured voltage Vrect with its configured threshold levels. Based on the comparison, the power tuning block **202** activates switches S1, S2, . . . , Sn. The switches may be turned on or turned off, or may be pulsed on and off at a certain frequency and duty cycle. When a switch S1, S2, . . . , Sn is turned on, the associated capacitor C1, C2, . . . , Cn on the same leg is activated and impacts the reflected impedance of the wireless power receiver **100***b* and hence the amount of wireless power received. The Vrect sensing block **201** senses the changes in the rectifier output voltage Vrect and the power tuning block **202** quickly counteracts the changes if the changes exceed a safe operating range. For example, if the rectifier output voltage Vrect drops below the safe operating range, the power tuning block **202** turns on switches S1 and S2 to increase the amount of wireless power received. The power tuning block **202** progressively turns on more switches until wireless power received restores the output voltage Vrect of the rectifier **106** to the safe operating range. In another example, if the rectifier output voltage Vrect increases above the safe operating range, the power tuning block **202** progressively decreases the on-time duty cycle of switches S1, S2, . . . , Sn, to decrease the level of wireless power received until Vrect is restored to the safe operating range. As an additional embodiment, the resonant series capacitor Cs may not be present and the receiver coil **104** is connected directly across Cd.

FIG. **2**C exemplarily illustrates a third embodiment of the auto-tuning network **105** of the self-regulating wireless power receiver **100***b*. In this embodiment, the auto-tuning network **105** includes a Vrect sensing block **201**, a power tuning block **202**, a series resonant capacitor Cs, a parallel resonant capacitor Cd, a first parallel switch-capacitor network consisting of "n" parallel capacitors C1, C2, . . . , Cn and "n" switches S1, S2, . . . , Sn, and a second parallel switch-capacitor network consisting of "n" parallel capacitors D1, D2, . . . , Dn and "n" switches E1, E2, . . . , En. In this embodiment, the two parallel switch-capacitor networks in combination together are connected symmetrically between both the alternating current (AC) IOs of the rectifier **106** and ground. The Vrect sensing block **201** measures the rectifier output voltage Vrect constantly or periodically. The power tuning block **202** compares the measured voltage Vrect with its configured threshold levels. Based on the comparison, the power tuning block **202** activates switches S1, S2, . . . , Sn and switches E1, E2, . . . , En. The switches may be turned on or turned off, or may be pulsed on and off at a certain frequency and duty cycle. When a switch, for example, S1, is turned on, the associated capacitor, for example, C1 on the same leg is activated and impacts the reflected impedance of the wireless power receiver **100***b* and hence the amount of wireless power received. The Vrect sensing block **201** senses the changes in the rectifier output voltage Vrect and the power tuning block **202** quickly counteracts the changes if the changes exceed a safe operating range. For example, if the rectifier output voltage Vrect drops below the safe operating range, the power tuning block **202** turns on switches S1 and E1 to increase the amount of wireless power received. The power tuning block **202** progressively turns on more switches symmetrically until wireless power received restores the output voltage Vrect of the rectifier **106** to the safe operating range. In another example, if the rectifier output voltage Vrect increases above the safe operating range, the power tuning block **202** progressively decreases the on-time duty cycle of switches S1, E1 to decrease the level of wireless power received until Vrect is restored to the safe operating range. As an additional embodiment, the resonant series capacitor Cs may not be present and the receiver coil **104** is connected directly across Cd.

FIG. **2**D exemplarily illustrates a fourth embodiment of the auto-tuning network **105** of the self-regulating wireless power receiver **100***b*. In this embodiment, the auto-tuning network **105** includes a Vrect sensing block **201**, a power tuning block **202**, a paralleled resonant capacitor Cd, and a parallel switch-capacitor network consisting of "n" parallel capacitors C1, C2, . . . , Cn and "n" switches S1, S2, . . . , Sn. In this embodiment, the parallel switch-capacitor network is connected between the receiver coil **104** and one of the alternating current (AC) IOs of the rectifier **106**. The Vrect sensing block **201** measures the rectifier output voltage Vrect constantly or periodically. The power tuning block **202** compares the measured voltage Vrect with its configured threshold levels. Based on the comparison, the power tuning block **202** activates switches S1, S2, . . . , Sn. The switches may be turned on or turned off, or may be pulsed on and off at a certain frequency and duty cycle. When a switch S1, S2, . . . , Sn is turned on, the associated capacitor C1, C2, . . . , Cn on the same leg is activated and impacts the reflected impedance of the wireless power receiver **100***b* and hence the amount of wireless power received. The Vrect sensing block **201** senses the changes in the rectifier output voltage Vrect and the power tuning block **202** quickly counteracts the changes if the changes exceed a safe operating range. For example, if the rectifier output voltage Vrect drops below the safe operating range, the power tuning block **202** turns on switches S1 and S2 to increase the amount of wireless power received. The power tuning block **202** progressively turns on more switches until wireless

power received restores the output voltage Vrect of the rectifier **106** to the safe operating range. In another example, if the rectifier output voltage Vrect increases above the safe operating range, the power tuning block **202** progressively decreases the on-time duty cycle of switches S1, S2, . . . , Sn, to decrease the level of wireless power received until Vrect is restored to the safe operating range. As an additional embodiment, the resonant parallel capacitor Cd may not be present in certain applications.

FIG. **3** exemplarily illustrates a schematic diagram of a wireless power transmitter **100***a* without a modulator/demodulator block and an out-of-band communication block. The wireless power transmitter **100***a* disclosed herein comprises a switch network **101** configured to receive an input voltage and an input current from a voltage source. The wireless power transmitter **100***a* further comprises an impedance network **102** represented as a Zmatch block connected between the switch network **101** and a transmitter coil **103**. The impedance network **102** comprises one or more of passive electronic components, for example, a resistor, a capacitor, a magnetic device, a transducer, etc., active electronic components, for example, a diode, a transistor such as a metal oxide semiconductor field effect transistor (MOSFET), a bipolar transistor, operational amplifiers, an optoelectronic device, etc.; and electronic switches. The wireless power transmitter **100***a* further comprises an analog to digital converter (ADC) **302**, where the ADC **302** is operably coupled to a control logic circuit **301** of the wireless power transmitter **100***a*. The ADC **302** measures various parameters such as the input voltage Vin, the input current Iin, the voltage VCoil of the transmitter coil **103**, the temperature of the transmitter coil **103**, the current ICoil of the transmitter coil **103**, etc., and feeds such information in real time to the control logic circuit **301**. The control logic circuit **301** processes all the collected real time information via its control circuits, state machines, algorithms, firmware, etc., and in turn outputs a pulse width modulation (PWM) signal to the switch network **101**.

The wireless power transmitter **100***a* scans and detects the presence of a wireless power receiver **100***b*, exemplarily illustrated in FIG. **1**, in its vicinity. On detecting the presence of the wireless power receiver **100***b*, the wireless power transmitter **100***a* configures the switch network **101** and tunes the impedance network **102** to create sufficient field linkage, for example, a magnetic flux field linkage to transmit power wirelessly to the wireless power receiver **100***b*. In the wireless power system **100** exemplarily illustrated in FIG. **1**, the wireless power transmitter **100***a* does not contain a conventional modulator/demodulator block which is typically needed for processing in-band messages from and communicating in-band messages to the wireless power receiver **100***b* in a wireless power protocol of the wireless power receiver **100***b*. The wireless power transmitter **100***a* disclosed herein also does not contain a conventional out-of-band communication block which is also typically used for processing out-of-band messages from and communicating out-of-band messages to the wireless power receiver **100***b* in a wireless power protocol of the wireless power receiver **100***b*.

The wireless power receiver **100***b*, using the auto-tuning network **105** exemplarily illustrated in FIG. **1** and FIGS. **2**A-**2**D is configured to safely receive the wirelessly transmitted power from the wireless power transmitter **100***a* via the self regulatory auto-tuning network **105**. The wireless power receiver **100***b*, via the auto-tuning network **105**, receives the required amount of wirelessly transmitted power from the wireless power transmitter **100***a* without communicating conventional messages such as increase power, decrease power, maintain power, stop power, etc., to the wireless power transmitter **100***a*. The need for such conventional communication messages from the wireless power receiver **100***b* to the wireless power transmitter **100***a* is obviated since the end result targeted by those communication messages is achieved by the auto-tuning network **105** with substantially faster response times. The elimination of such conventional communication messages enables simplification of the design of the wireless power transmitter **100***a* and the wireless power receiver **100***b* by elimination of circuitry, for example, the modulator/demodulator block and the out-of-band communication block, and firmware to process, error-correct, decipher, and respond to those communication messages. Because of such a simplification, the wireless power system **100** can be built at a lower cost and a smaller size and can operate at higher efficiency. Also, because of the auto-tuning network **105** operably coupled within the self-regulating wireless power receiver **100***b*, the wireless power transmitter **100***a* can operate at a fixed operating point, for example, at a fixed frequency and duty cycle, or within a narrow range and/or set of operating points, which enables the wireless power transmitter **100***a* to implement and pass electromagnetic compliance (EMC) regulations more easily.

When metal objects are placed atop or in close proximity of the wireless power transmitter **100***a*, eddy currents are induced in the metal object as a result of the magnetic field emanating from the wireless power transmitter **100***a*. When the metal object has low resistivity, these eddy currents cause the metal object to heat up leading to a safety issue. The wireless power transmitter **100***a* has various algorithms for detecting metal objects and turning off power to eliminate this heated metal object safety issue. In addition, the wireless power transmitter **100***a* turns on substantial power delivery only when the wireless power transmitter **100***a* senses a good wireless power receiver **100***b*. This enables low standby power consumption at the wireless power transmitter **100***a* when there is not any good wireless power receiver **100***b* in the wireless power transmitter's **100***a* vicinity. Additionally, the wireless power transmitter **100***a* ensures that a careful level of power is delivered to the wireless power receiver **100***b* without compromising required performance and without overwhelming and damaging the wireless power receiver **100***b* with too much power. In an embodiment, so as to avoid hot metal objects, to have low standby power, and to have safe power delivery to the wireless power receiver **100***b*, the method and the wireless power system **100** disclosed herein implement a receiver-maximum-power-signature algorithm. This algorithm enables the wireless power transmitter **100***a* to detect metal objects and terminate transmission of power. This algorithm enables the wireless power transmitter **100***a* to detect the presence of a good wireless power receiver **100***b* and then start providing substantial power. Via this algorithm, the wireless power transmitter **100***a* is also aware of the maximum power needs of the wireless power receiver **100***b*. The wireless power transmitter **100***a* then configures its operating point to deliver the required level of maximum power. Via the receiver-maximum-power-signature algorithm, the wireless power transmitter **100***a* can also terminate transmission of wireless power when the wireless power receiver **100***b* does not need any further power, thereby increasing the overall efficiency of wireless power delivery.

FIG. **4** exemplarily illustrates a flow chart comprising the steps for establishing a stable and optimal power transfer

from the wireless power transmitter **100***a* to the wireless power receiver **100***b* exemplarily illustrated in FIG. **1**, via the receiver-maximum-power-signature algorithm. On reset, the process begins with the wireless power transmitter **100***a* transmitting **401** a short burst of wireless power to detect **402** the presence of a wireless power receiver **100***b* in its vicinity. If a wireless power receiver **100***b* is not detected, the wireless power transmitter **100***a* shuts down **403** into a deep sleep after programming a timer to restore the wireless power transmitter **100***a* back to its normal operating mode after "T1" seconds. If a wireless power receiver **100***b* is detected, the wireless power transmitter **100***a* transmits **404** a minimum amount of power to the wireless power receiver **100***b* for a fixed time interval.

On receiving initial power from the wireless power transmitter **100***a*, the self-regulating wireless power receiver **100***b* initiates implementation of the receiver-maximum-power-signature algorithm. The receiver-maximum-power-signature algorithm defines instructions for varying, that is, increasing and decreasing the input impedance of the wireless power receiver **100***b* by a specified amount for predetermined intervals of time. For example, as per the receiver-maximum-power-signature algorithm, the self-regulating wireless power receiver **100***b* may increase its input impedance by about 10% for 5 milliseconds and then reduce its input impedance by about 10% for 5 milliseconds and may repeat this pattern about 10 times for a total time period of 100 milliseconds. The input impedance of the wireless power receiver **100***b* is the impedance of the wireless power receiver **100***b* when looking into the wireless power receiver **100***b* from the receiving coil **104**. The input impedance of the wireless power receiver **100***b* is varied by varying its real and/or reactive parts. The reactive part of the input impedance of the wireless power receiver **100***b* is varied via changes in the auto-tuning network **105** of the wireless power receiver **100***b* as exemplarily illustrated in FIGS. **2**A-**2**D and described previously. The real part of the input impedance of the wireless power receiver **100***b* is varied by adding and removing resistive loads in parallel with the actual rectifier load **108**. As a result of the changes in the input impedance of the wireless power receiver **100***b*, the reflected impedance as seen by the wireless power transmitter **100***a* is consequently increased or decreased. The receiver-maximum-power-signature algorithm controls the pattern of input impedance change and via these impedance changes, the wireless power receiver **100***b* conveys its maximum-power-signature to the wireless power transmitter **100***a*.

On detecting a wireless power receiver **100***b*, the wireless power transmitter **100***a* provides initial power to the wireless power receiver **100***b* for a fixed amount of time, for example, 100 milliseconds. While providing initial power, the wireless power transmitter **100***a* tracks parameters such as transmitter coil voltage VCoil, transmitter coil current ICoil, etc., to observe changes in the reflected impedance caused as a result of changes in the input impedance of the wireless power receiver **100***b*. The reflected impedance changes may also be observed by tracking the voltage and/or current flowing in the switch network **101** or other parts of the wireless power transmitter **100***a*. Via tracking parameters that are dependent on the reflected impedance, the wireless power transmitter **100***a* can determine **405** whether the wireless power receiver **100***b* is a metal object. When the reflected impedance changes follows one of the predefined receiver-maximum-power-signatures for a predetermined fraction of the initial power time period, for example, 50% of the initial power time period which would be 50 milliseconds, the wireless power transmitter **100***a* recognizes that the wireless power transmitter **100***a* is transmitting power to a safe non-metal object wireless power receiver **100***b* and hence, continues to provide **407** power.

While providing power, the wireless power transmitter **100***a* receives the complete receiver-maximum-power-signature from the wireless power receiver **100***b*. The wireless power transmitter **100***a* decodes and determines the maximum power level of the wireless power receiver **100***b* from that signature. Based on the determined maximum power level, the wireless power transmitter **100***a* selects and set its operating point and operating range by configuring its switch network **101**, the impedance network **102**, and the transmitter coil **103** to be able to deliver that maximum amount of power. For example, if the received maximum-power-signature is "1010101010101010101010", the wireless power transmitter **100***a* determines the maximum power level to be 10 Watts and configures its operating frequency to (say) 130 kHz and its duty cycle to not exceed 40% so as to deliver a maximum of 10 W to the wireless power receiver **100***b*. Additionally, based on the strength of the reflected impedance changes, the wireless power transmitter **100***a* senses the level of magnetic field flux linkage coupling between the wireless power transmitter **100***a* and the wireless power receiver **100***b*. The wireless power transmitter **100***a* considers the sensed level of coupling when selecting and setting its operating point and range. For example, when the level of coupling is strong, to deliver a maximum power of 10 Watts, the wireless power transmitter **100***a* may configure itself to operate at a fixed frequency of 130 khz and a duty cycle not to exceed 40%. When the level of coupling is weak, to deliver a maximum power of 10 Watts, the wireless power transmitter **100***a* may configure itself to operate at a fixed frequency of 128 khz and allow a duty cycle of up to 50%.

When the reflected impedance changes do not follow any of the predefined receiver-maximum-power-signatures for the predetermined fraction of the initial power time period, the wireless power transmitter **100***a* recognizes the presence of an unsupported object, potentially, an unsafe, metal object and hence, terminates further power transmission. That is, if the wireless power receiver **100***b* is a metal object or some unknown object, the wireless power transmitter **100***a* shuts down **406** into a deep sleep after programming a timer to restore the wireless power transmitter **100***a* back to its normal operating mode after "T2" seconds.

The input impedance of a metal object does not vary in sync with the predefined receiver-maximum-power-signature patterns, thereby virtually guaranteeing that the wireless power transmitter **100***a* will not falsely recognize a metal object as a good wireless power receiver **100***b*. As per the receiver-maximum-power-signature algorithm, the wireless power receiver **100***b* modulates its input impedance as per its maximum power signature periodically, for example, every 0.5 seconds. For the purpose of the receiver-maximum-power-signature algorithm, the wireless power receiver **100***b* carefully adopts only those input impedance changes which preserve the rectifier output voltage Vrect in the safe operating range.

The wireless power transmitter **100***a* checks **408** whether the wireless power receiver **100***b* is sending the maximum power signature periodically. The wireless power transmitter **100***a* continues to provide power as long as the wireless power transmitter **100***a* receives the maximum power signature periodically, for example, at least one signature every 2 seconds. If the maximum power signature is received, the wireless power transmitter **100***a* continues to provide **407**

power and reconfigures its operating point and range if required. If the maximum power signature is not received as per its periodic rate, the wireless power transmitter **100***a* assumes that the wireless power receiver **100***b* has been removed or does not require further power. Hence, the wireless power transmitter **100***a* terminates transmitting power and shuts down **409** into a deep sleep after programming a timer to restore the wireless power transmitter **100***a* back to its normal operating mode after "T3" seconds.

While providing initial power, the wireless power transmitter **100***a* tracks parameters such as transmitter coil voltage VCoil, transmitter coil current ICoil, etc., to observe changes in the reflected impedance caused as a result of changes in the input impedance of the wireless power receiver **100***b*. In an embodiment, the wireless power transmitter **100***a* employs a peak detector mechanism to extract the envelope of the voltage and/or current that is in the transmitter coil **103**, or the switch network **101**, or other parts of the wireless power transmitter **100***a*. Embedded in the envelope of the voltage and/or current is the receiver-maximum-power-signature. Via its analog to digital converter (ADC) **302** exemplarily illustrated in FIG. **3**, the wireless power transmitter **100***a* is aware of the extracted envelope of the voltage and/or current and hence, the wireless power receiver's **100***b* maximum power signature. Via its ADC **302**, the wireless power transmitter **100***a* is also aware of the strength of the reflected impedance changes. The wireless power transmitter **100***a* uses this information to estimate the level of coupling between the wireless power transmitter **100***a* and the wireless power receiver **100***b*. In a second embodiment, the wireless power transmitter **100***a* employs a zero crossing detector mechanism to extract the phase difference between the voltage and current that is in the transmitter coil **103**, or the switch network **101**, or other parts of the wireless power transmitter **100***a*. Embedded in the phase difference between the voltage and the current is the receiver-maximum-power-signature. The wireless power transmitter **100***a* observes the variations in the phase difference to extract the receiver-maximum-power-signature. The wireless power transmitter **100***a* also observes the magnitude of these phase difference variations. The wireless power transmitter **100***a* uses this magnitude information to estimate the level of coupling between the wireless power transmitter **100***a* and the wireless power receiver **100***b*.

By incorporating the self-regulating wireless power receiver **100***b*, the receiver-maximum-power-signature algorithm and the simplified, limited operating point wireless power transmitter **100***a*, the method and the system disclosed herein allow building of a wireless power system **100** that provides stable, safe, and efficient wireless power to an electronic device without the need for a conventional communication protocol messages between the wireless power transmitter **100***a* and the wireless power receiver **100***b*.

The foregoing examples have been provided merely for the purpose of explanation and are in no way to be construed as limiting of the present invention disclosed herein. While the invention has been described with reference to various embodiments, it is understood that the words, which have been used herein, are words of description and illustration, rather than words of limitation. Further, although the invention has been described herein with reference to particular means, materials, and embodiments, the invention is not intended to be limited to the particulars disclosed herein; rather, the invention extends to all functionally equivalent structures, methods and uses, such as are within the scope of the appended claims. Those skilled in the art, having the benefit of the teachings of this specification, may affect numerous modifications thereto and changes may be made without departing from the scope and spirit of the invention in its aspects.

I claim:

1. A wireless power system comprising:

a wireless power transmitter configured to transmit wireless power; and

one or more self-regulating wireless power receivers configured to receive wirelessly transmitted power, said one or more wireless power receivers each comprising:

an auto-tuning network operably coupled within said wireless power receiver, said auto-tuning network configured to control and regulate said received wirelessly transmitted power, and

a rectifier operably coupled within said wireless power receiver, said rectifier configured to convert the said received wirelessly transmitted power from alternating current (AC) power into direct current (DC) power;

wherein said auto-tuning network in said wireless power receiver is configured to detect changed in one or both of a load of said rectifier and an output voltage of said rectifier, and to dynamically counteract said detected changed if the changed exceed a safe operating range, said auto-tuning network counteracts said unsafe changes by dynamically tuning its network.

2. The wireless power system of claim **1**, wherein said auto-tuning network in said wireless power receiver comprises an impedance network, said impedance network dynamically configured to one of increase, decrease, and maintain amount of said received wirelessly transmitted power.

3. The wireless power system of claim **2**, wherein said impedance network of said auto-tuning network in said wireless power receiver comprises one or more of passive electronic components, active electronic components, and electronic switches.

4. The wireless power system of claim **1**, wherein said self-regulating wireless power receiver is configured to implement a receiver-maximum power-signature algorithm for enabling a wireless power transmitter to detect unsupported receivers and terminate transmission of power, wherein said receiver-maximum power-signature algorithm defines instructions for varying input impedance of said self-regulating wireless power receiver by a predefined amount for predetermined intervals of time, and wherein said input impedance of said self-regulating wireless power receiver is varied via impedance changes in said auto-tuning network of said self-regulating wireless power receiver.

5. The wireless power system of claim **4**, wherein said wireless power transmitter is aware of the maximum power needs of said wireless power receiver via said receiver-maximum power-signature messages from said wireless power receiver, wherein said wireless power transmitter configures its operating point and range to transmit a required level of maximum wireless power to said wireless power receiver based on the received said maximum-power-signature message and an estimated level of magnetic field flux coupling between said wireless power transmitter and said wireless power receiver.

6. The wireless power system of claim **5**, wherein said wireless power transmitter terminates said transmission of said wireless power to said wireless power receiver when said receiver-maximum power-signature messages are not periodically received.

7. The wireless power system of claim 1, wherein said wireless power transmitter does not contain one or both of a modulator/demodulator block and an out-of-band communication block configured to communicate conventional wireless power protocol messages to and from said self-regulating wireless power receiver, wherein said self-regulating wireless power receiver, via said auto-tuning network, is configured to regulate said wirelessly transmitted power from said wireless power transmitter without said communication of said conventional wireless power protocol messages to and from said modulator/demodulator block and said out-of-band communication block.

8. The wireless power system of claim 1, wherein said self-regulating wireless power receiver, via said auto-tuning network, is configured to receive said wirelessly transmitted power from a wireless power transmitter without establishing a conventional communication protocol with said wireless power transmitter.

9. A method for self regulating wireless power system, said method comprising:

providing a wireless power transmitter; and

providing one or more self-regulating wireless power receivers each comprising an auto-tuning network and a rectifier;

configuring said one or more self-regulating wireless power receivers to receive wirelessly transmitted power from said wireless power transmitter;

configuring said auto-tuning network in said wireless power receiver to control and regulate said received wirelessly transmitted power by detecting changes in one or both of a load of said rectifier and an output voltage of said rectifier, and dynamically counteracting said detected changes if the changes exceed a safe operating range by dynamically tuning its network.

10. The method of claim 9, wherein said auto-tuning network is comprising of an impedance network, wherein said impedance network is being dynamically configured to one of increase, decrease, and maintain amount of said received wirelessly transmitted power.

11. The method of claim 10, wherein said impedance network is comprising one or more of passive electronic components, active electronic components, and electronic switches.

12. The method of claim 9, further comprising implementing a receiver-maximum power-signature algorithm by said self-regulating wireless power receiver for enabling said wireless power transmitter to detect unsupported receivers and to configure its operating point to transmit a required level of maximum wireless power to said self-regulating wireless power receiver, wherein said receiver-maximum power-signature algorithm defines instructions for varying input impedance of said self-regulating wireless power receiver by a predefined amount for predetermined intervals of time, and wherein said input impedance of said self-regulating wireless power receiver is varied via impedance changes in said auto-tuning network of said self-regulating wireless power receiver.

13. The method of claim 9, wherein said self-regulating wireless power receiver, via said auto-tuning network, is configured to receive said wirelessly transmitted power from said wireless power transmitter that does not contain one or both of a modulator/demodulator block and an out-of-band communication block, that is used for communication of conventional wireless power protocol messages.

14. The method of claim 9, wherein said self-regulating wireless power receiver, via said auto-tuning network, is configured to receive said wirelessly transmitted power from said wireless power transmitter without establishing a conventional communication protocol with said wireless power transmitter, said conventional communication protocol comprising messages for increasing, decreasing, maintaining and stopping the wireless power transfer.

15. The method of claim 12, wherein said wireless power transmitter terminates said transmission of said wireless power to said wireless power receiver when said receiver-maximum power-signature messages are not periodically received.

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