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(54) **RESONANT MAGNETIC COUPLING WIRELESS POWER TRANSFER SYSTEM WITH CALIBRATION CAPABILITIES OF ITS INDUCTOR-CAPACITOR RESONANT FREQUENCIES**

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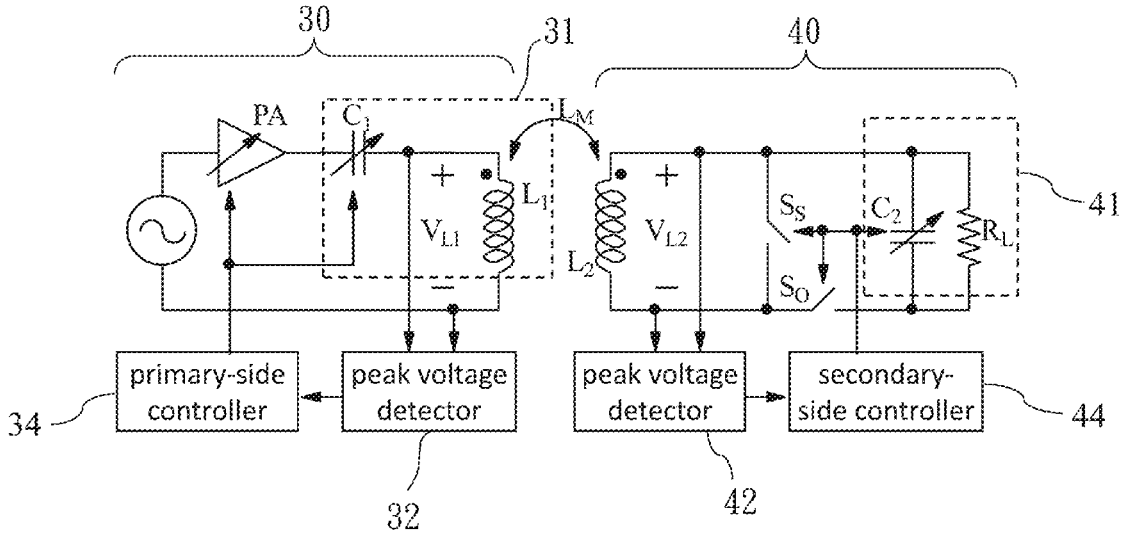
(57) **ABSTRACT**

A resonant magnetic coupling wireless power transfer system with calibration capabilities of the resonant frequencies of its power transmitter(s) and power receiver(s) is disclosed. The system detects the peak voltages of the coil inductors or the resonant capacitors and tunes the resonant capacitors until the detected peak voltages reach their maximal values given proper setup conditions, so as to calibrate the inductor-capacitor (LC) resonance frequencies of the power transmitter(s) and the power receiver(s) in the resonant magnetic coupling wireless power transfer system to achieve the highest power transferred to the load and a high PTE.



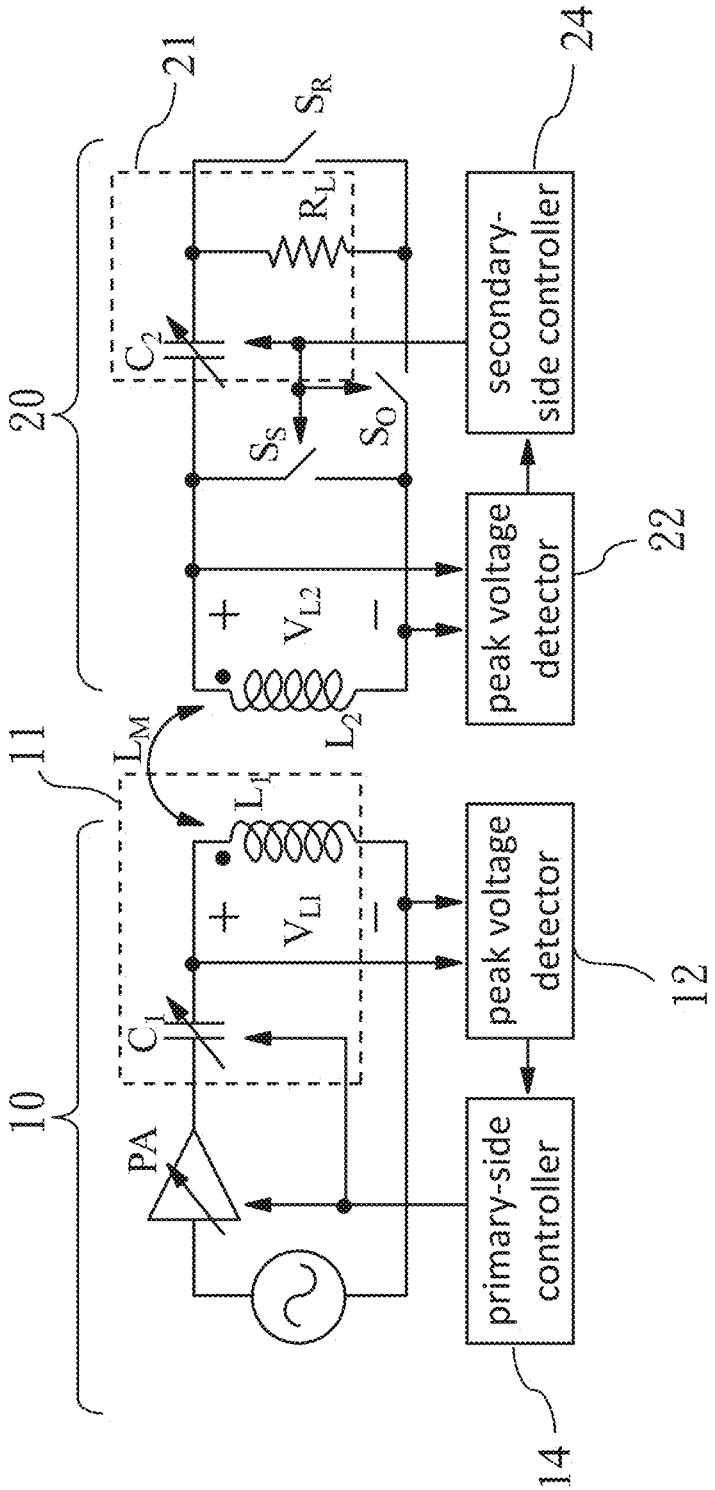

10
11
12
14
20
21
22
24
PA
C_1
L_1
L_M
L_2
C_2
R_L
S_R
S_S
S_O
V_{L1}
V_{L2}
+
−
primary-side controller
peak voltage detector
peak voltage detector
secondary-side controller

FIG.1

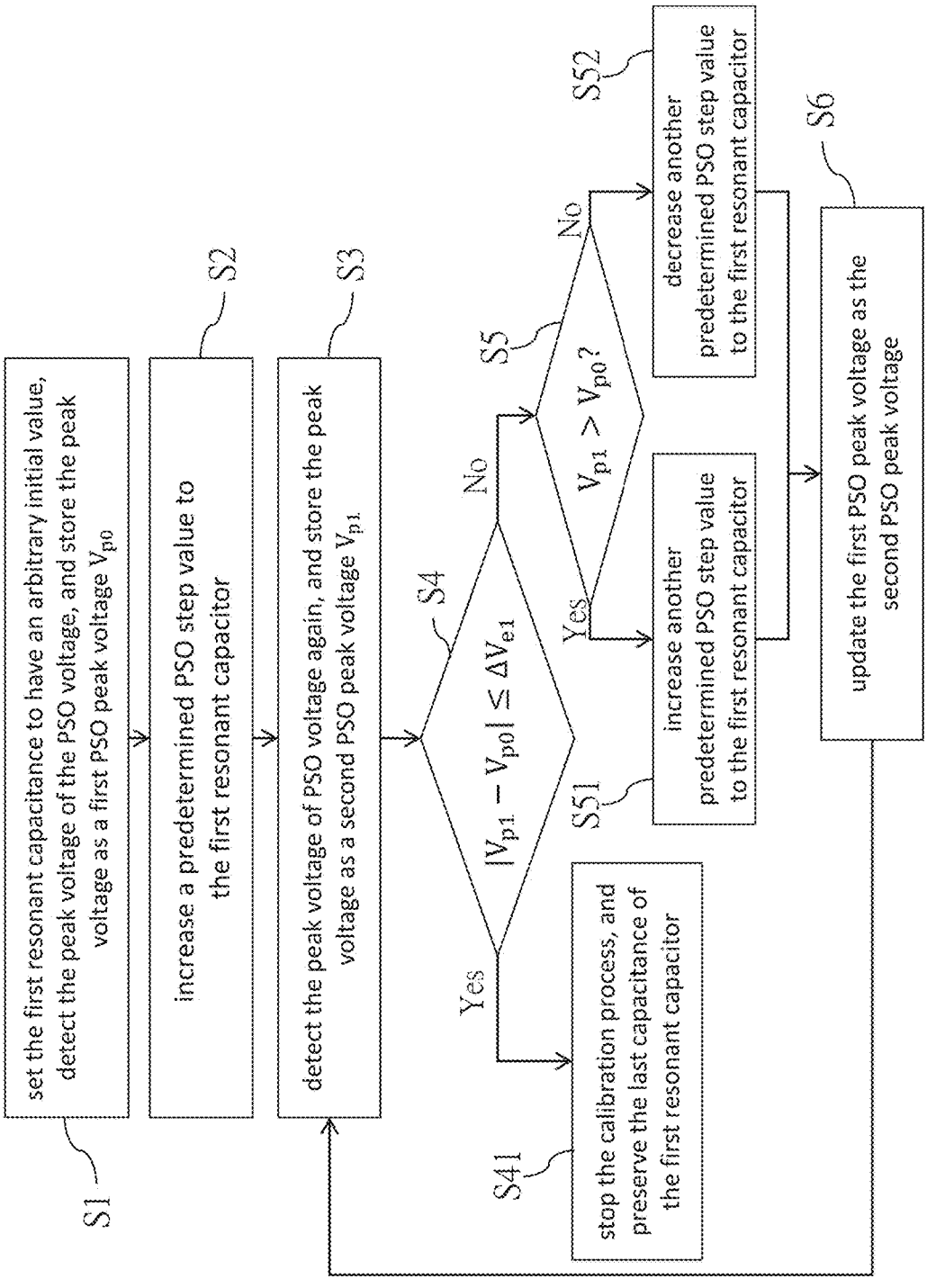

S1
set the first resonant capacitance to have an arbitrary initial value, detect the peak voltage of the PSO voltage, and store the peak voltage as a first PSO peak voltage V_{p0}
S2
increase a predetermined PSO step value to the first resonant capacitor
S3
detect the peak voltage of PSO voltage again, and store the peak voltage as a second PSO peak voltage V_{p1}
S4
$|V_{p1} - V_{p0}| \leq \Delta V_{e1}$
Yes
No
S41
stop the calibration process, and preserve the last capacitance of the first resonant capacitor
S5
$V_{p1} > V_{p0}$?
Yes
No
S51
increase another predetermined PSO step value to the first resonant capacitor
S52
decrease another predetermined PSO step value to the first resonant capacitor
S6
update the first PSO peak voltage as the second PSO peak voltage

FIG.2

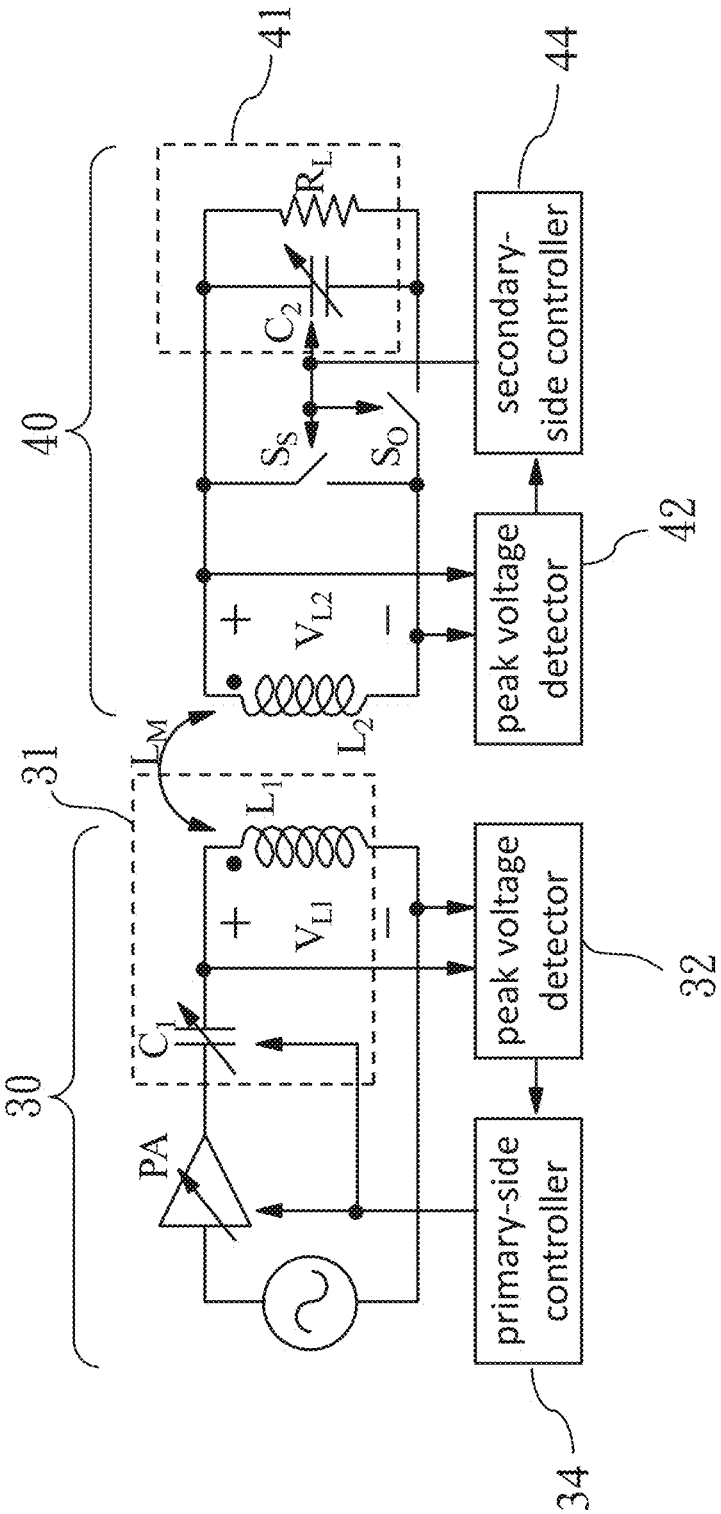

41
44
R_L
C_2
secondary-side controller
40
S_S
S_O
peak voltage detector
42
+
V_{L2}
−
L_2
L_M
31
L_1
+
V_{L1}
−
peak voltage detector
32
C_1
30
PA
primary-side controller
34

FIG.3

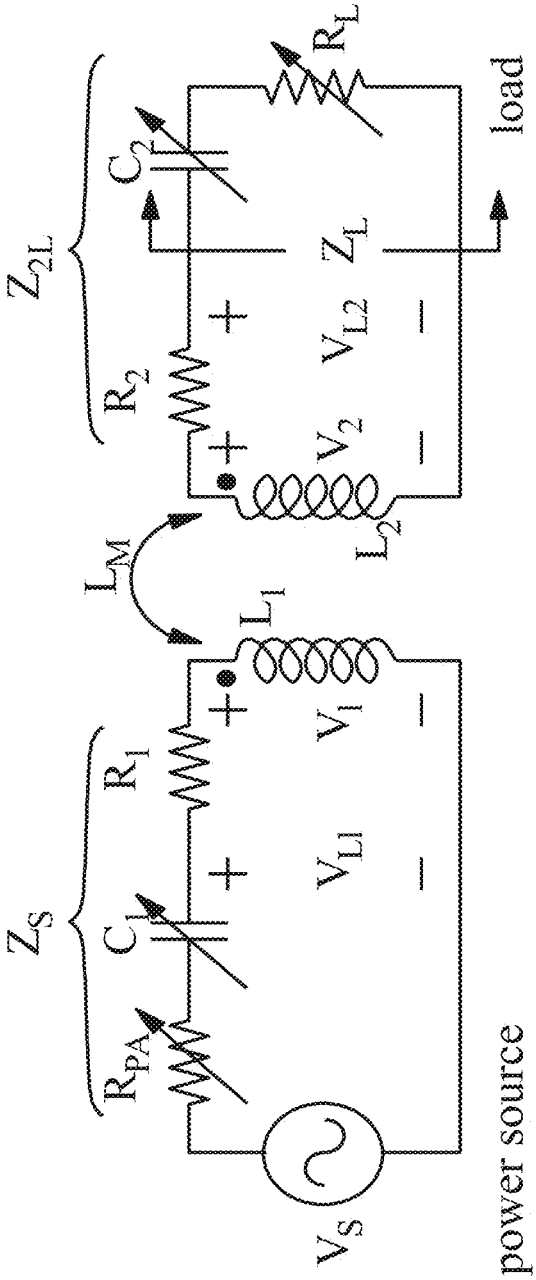

Z_{2L}
C_2
R_L
load
Z_L
R_2
V_{L2}
V_2
L_2
L_M
L_1
V_1
R_1
V_{L1}
Z_S
C_1
R_{PA}
V_S
power source

FIG.4

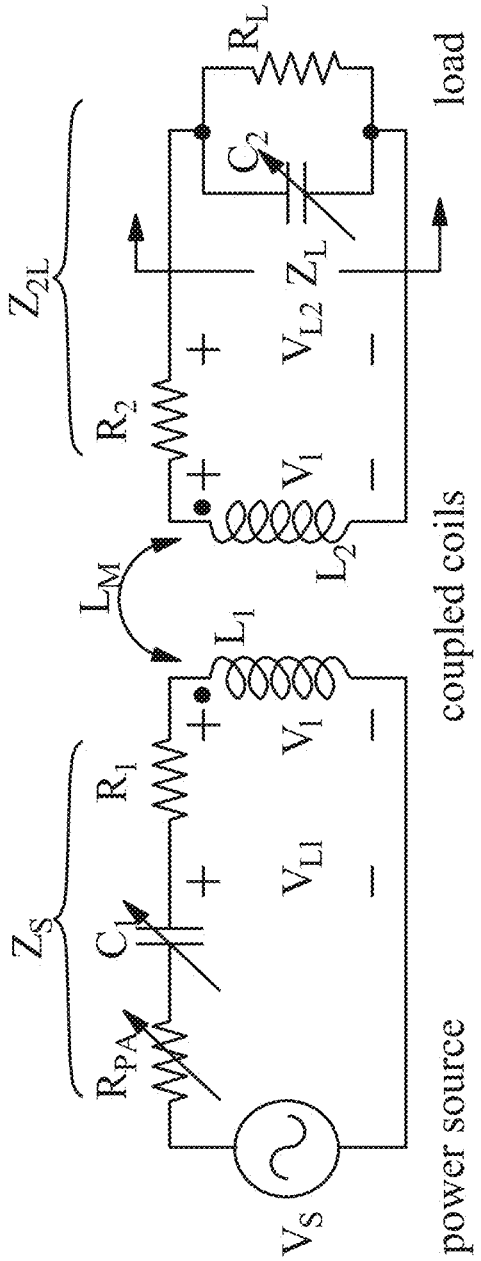

Z_{2L}
R_L
load
C_2
Z_L
V_{L2}
R_2
V_1
L_2
L_M
L_1
coupled coils
Z_S
C_1
R_1
V_{L1}
R_{PA}
V_S
power source

FIG.5

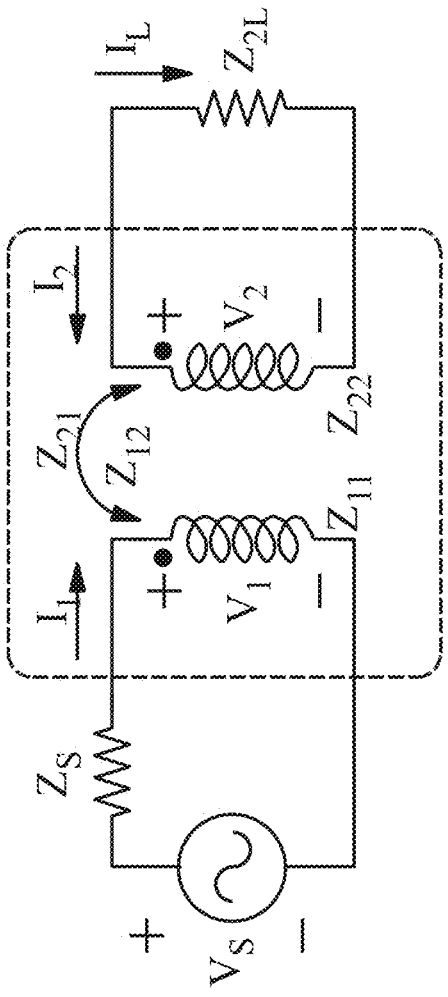


FIG.6

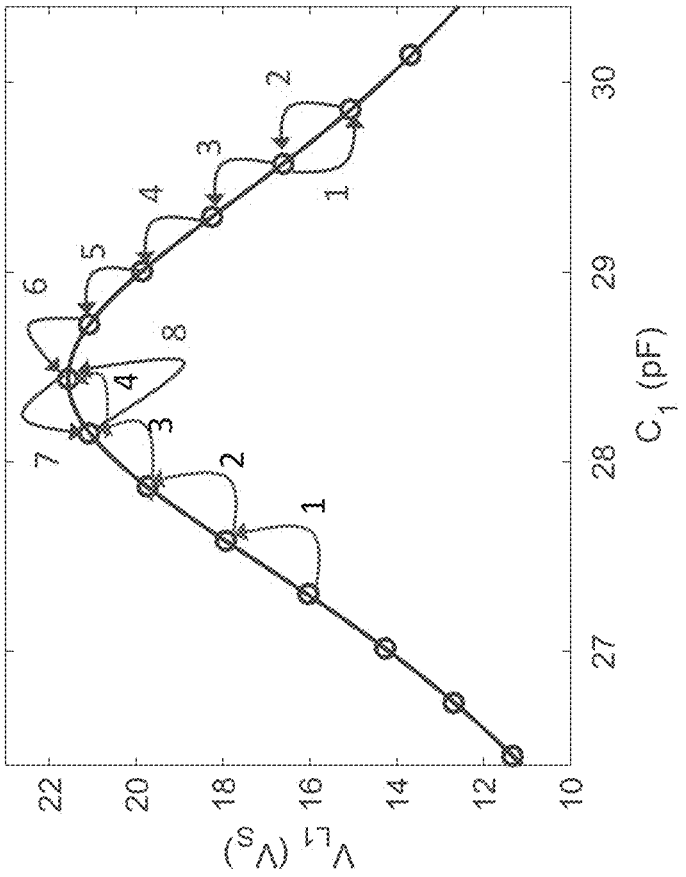


FIG.7

RESONANT MAGNETIC COUPLING WIRELESS POWER TRANSFER SYSTEM WITH CALIBRATION CAPABILITIES OF ITS INDUCTOR-CAPACITOR RESONANT FREQUENCIES

[0001] This application claims priority for Taiwan patent application no. 106128204 filed on Aug. 21, 2017, the content of which is incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates to a resonant magnetic coupling wireless power transfer system, particularly to a resonant magnetic coupling wireless power transfer system able to automatically calibrate the inductor-capacitor resonant frequencies.

Description of the Related Art

[0003] Wireless power transfer (WPT) is a very convenient technology applicable to various portable devices, such as mobile phones, implantable biomedical devices, sensors, and electric vehicles. There are two main specifications involved with a WPT system. One is the power transfer efficiency (PTE), which is the ratio of the power transferred to the load and the supplied power. PTE is smaller than or equal to 1. The other is the maximal transferred power (MTP), which is the maximal power the load receives from the WPT system.

[0004] Both the non-resonant magnetic coupling (NRMC) WPT system and the resonant magnetic coupling (RMC) WPT system are popular WPT technologies. The NRMC WPT system cannot achieve a good enough PTE or a satisfying MTP unless the coupling coefficient (k) of the transmitter coil and the receiver coil approaches 1, i.e. when the two coils have similar diameters, and the distance between the coils is far smaller than the diameters of the coils. Therefore, the NRMC WPT system is usually applicable to one-to-one mode only.

[0005] On the other hand, in an application environment having a small coupling coefficient, the RMC WPT system can achieve a PTE that the NRMC WPT system can achieve only in an environment with a larger coupling coefficient. In other words, the RMC WPT system can operate in a longer distance using the same coils. Besides, the RMC WPT system does not need coils having similar diameters. Furthermore, one power transmitter can transfer power to several power receivers in the RMC WPT system. The abovementioned features of the RMC WPT system expand the application field of WPT systems.

[0006] Although the RMC WPT system has many advantages, however, some practical implementation issues remain. The main issue is that the RMC WPT system needs the resonance frequencies of the inductor-capacitor (LC) tanks on both the power transmitter and the power receiver sides to be accurately controlled to some particular values. A small deviation of the LC resonant frequency would significantly affect the system's PTE and MTP. Nevertheless, intrinsic errors always exist in the electronic components of a circuit, resulting in that the practical performance of the RMC WPT system is much lower than the optimal performance in theory.

[0007] A conventional method for calibrating the LC resonant frequency uses an LCR-meter instrument to measure the inductance and capacitance first and then uses a variable capacitor (varactor) to manually compensate for the inaccurate values of the inductors and capacitors. Another frequently-used method is adding matching networks to regulate the equivalent load impedance seen by the transmitter and the equivalent source impedance seen by the receiver. However, intrinsic errors still exist in the components of the matching networks. Canada patent CA2448316 A1 disclosed a calibration method, which measures the maximal and minimal resonant frequencies first and then uses linear interpolation to guess a target control code of a digitally-controlled capacitor, whereby the calibration time is decreased. While being applied to a WPT system, this method needs to measure the circuit parameters of the WPT system beforehand so as to calculate the target value of calibration. Therefore, the technology is laborious and time-consuming in such an application. Besides, the setup environment for calibration is different from that for normal WPT operation. Thus, the calibration environment and the normal WPT operation environment respectively have different parasitic capacitances and different parasitic inductances. As a result, the calibrated resonant frequency of the WPT system is still deviated from the target during normal WPT operation.

[0008] Other calibration methods adjust the PLL's oscillation frequency to calibrate the LC resonant frequency in the PLL, including U.S. Pat. No. 7,940,140 B2, U.S. Pat. No. 8,508,308 B2, U.S. Pat. No. 8,902,009 B1, and U.S. Pat. No. 8,766,712 B2. The U.S. Pat. No. 8,918,070 B2 adjusts the LNA oscillation frequency to calibrate the LC resonant frequency in it. To the best of our knowledge, there has not yet been a dedicated calibration technology developed to calibrate the resonant frequencies of the WPT system and to enhance the performance thereof.

[0009] Accordingly, the present invention proposes a RMC WPT system able to automatically calibrate its LC resonant frequencies to address the abovementioned issues.

SUMMARY OF THE INVENTION

[0010] The primary objective of the present invention is to provide a RMC WPT system able to automatically calibrate the resonant capacitors of the transmitter and the receiver and precisely control the LC resonant frequencies of the transmitter and the receiver, whereby to wirelessly transfer the maximal power to the load.

[0011] Another objective of the present invention is to provide a RMC WPT system, which can achieve a high (sub-optimal) PTE and the MTP simultaneously, and which can further cooperate with the optimal equivalent load resistor to achieve the optimal PTE.

[0012] To achieve the abovementioned objectives, the present invention proposes a RMC WPT system with calibration capabilities of its LC resonant frequencies, which comprises a power transmitter and at least one power receiver. The power transmitter transfers an alternating-current (AC) power to at least one power receiver. The power transmitter includes at least a power amplifier and an LC resonator. The LC resonator can be equivalent to a circuit including a first resonant capacitor and a primary coil connected in series. While the first resonant capacitor is calibrating, the first resonant capacitor thereof is tuned until the peak voltage of a primary-side-observation (PSO) volt-

age achieves its maximal value, whereby the first resonant capacitor achieves its optimal capacitance value enabling the maximal power to be transferred to the load. The PSO voltage is either the voltage across the primary coil or the voltage across the first resonant capacitor.

[0013] In one embodiment, the abovementioned power receiver includes a secondary coil and a series resonant load circuit connected in parallel. The series resonant load circuit can be equivalent to be a second resonant capacitor and a load resistor connected in series. A mutual inductance exists between the primary coil and the secondary coil. The mutual inductance can be expressed by a coupling coefficient and the inductances of the two coils.

[0014] In another embodiment, the abovementioned power receiver includes a secondary coil and a shunt resonant load circuit connected in parallel. The shunt resonant load circuit can be equivalent to be a second resonant capacitor and a load resistor connected in parallel. A mutual inductance exists between the primary coil and the secondary coil. The mutual inductance can be expressed by a coupling coefficient and the inductances of the two coils.

[0015] A process to calibrate the abovementioned first resonant capacitor comprises steps: setting the first resonant capacitor to have an arbitrary initial value, detecting the peak voltage of the PSO voltage, and storing the peak voltage as a first PSO peak voltage (Step S**1**); adding a predetermined first-resonant-capacitor-incremental (FRCI) step value to the capacitance of the first resonant capacitor (Step S**2**); detecting the peak voltage of the PSO voltage again, and storing the peak voltage of the detected PSO voltage as a second PSO peak voltage (Step S**3**); determining whether the absolute value of the difference of the first PSO peak voltage and the second PSO peak voltage is within a predetermined PSO tolerable range; if the difference is within the predetermined PSO tolerable range, stopping the calibration process, and preserving the last value of the first resonant capacitor as the calibration result, else undertaking the next step (Step S**4**); if the second PSO peak voltage is greater than the first PSO peak voltage, adding a predetermined FRCI step value to the capacitance of the first resonant capacitor, else subtracting a predetermined FRCI step value from the capacitance of the first resonant capacitor (Step S**5**); replacing the value of the first PSO peak voltage with the value of the second PSO peak voltage, returning to Step S**3**, and undertaking the steps in sequence (Step S**6**).

[0016] In one embodiment, while the first resonant capacitor is being calibrated, the secondary coil may be in an open-circuit or a short-circuit state. Alternatively, the whole power receiver is removed before the first resonant capacitor is being calibrated to emulate the open-circuit state of the secondary coil. Thereby, the first resonant capacitor is calibrated to have a specified value ready for being used in calibrating the second resonant capacitor.

[0017] The present invention further undertakes a process to calibrate the abovementioned second resonant capacitor to achieve the sub-optimal PTE. While the second resonant capacitor is being calibrated, the second resonant capacitor thereof is tuned until the peak voltage of a secondary-side-observation (SSO) voltage achieves its maximal value, whereby the second resonant capacitor achieves its optimal value enabling the power to be transferred to the load with the sub-optimal PTE. The SSO voltage is the voltage across the secondary coil or the voltage across the second resonant capacitor.

[0018] The process to calibrate the second resonant capacitor comprises steps: setting the second resonant capacitor to have an initial value, detecting the peak voltage of the SSO voltage, and storing the peak voltage as a first SSO peak voltage (Step S**1**); adding a predetermined second-resonant-capacitor-incremental (SRCI) step value to the capacitance of the second resonant capacitor (Step S**2**); detecting the SSO voltage again, and storing its peak voltage as a second SSO peak voltage (Step S**3**); determining whether the absolute value of the difference of the first SSO peak voltage and the second SSO peak voltage is within a predetermined SSO tolerable range; if the absolute value of the difference is within the predetermined SSO tolerable range, stopping the calibration process, and preserving the last value of the second resonant capacitor as the calibration result, else undertaking the next step (Step S**4**); if the second SSO peak voltage is greater than the first SSO peak voltage, adding a predetermined SRCI step value to the capacitance of the second resonant capacitor, else subtracting a predetermined SRCI step value from the capacitance of the second resonant capacitor (Step S**5**); replacing the first SSO peak voltage with the second SSO peak voltage, returning to Step S**3**, and undertaking the steps in sequence (Step S**6**).

[0019] Below, embodiments are described in detail in cooperation with the attached drawings to make easily understood the objectives, technical contents, and accomplishments of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] FIG. **1** is a diagram schematically showing the circuit of a series-loaded RMC WPT system with calibration capabilities of its LC resonant frequencies according to one embodiment of the present invention;

[0021] FIG. **2** is a flowchart of calibrating a first resonant capacitor of a power transmitter according to one embodiment of the present invention;

[0022] FIG. **3** is a diagram schematically showing the circuit of a shunt-loaded RMC WPT system with calibration capabilities of its LC resonant frequencies according to one embodiment of the present invention;

[0023] FIG. **4** is a diagram schematically depicting an equivalent circuit of the circuit shown in FIG. **1** according to one embodiment of the present invention;

[0024] FIG. **5** is a diagram schematically depicting an equivalent circuit of the circuit shown in FIG. **3** according to one embodiment of the present invention;

[0025] FIG. **6** is a diagram schematically showing a lumped circuit model of FIG. **4** and FIG. **5** according to the embodiments of the present invention; and

[0026] FIG. **7** is a diagram showing a process of calibrating a first resonant capacitor according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0027] The present invention proposes an RMC WPT system with calibration capabilities of its LC resonant frequencies, which can calibrate the resonant capacitors to achieve the maximal peak voltages in an appropriate calibration environment, whereby to realize the target of self-

calibration. The present invention may be a series-loaded RMC WPT system or a shunt-loaded RMC WPT system. No matter which type of system the present invention is applied to, the technical spirit thereof is identical.

[0028] Refer to FIG. **1**. One embodiment of the present invention proposes a series-loaded RMC WPT system with calibration capabilities of its LC resonant frequencies, which comprises at least one power transmitter **10**. The power transmitter **10** includes a power amplifier PA for driving an LC resonator **11**. The equivalent circuit of the LC resonator **11** at least includes a first resonant capacitor C_1 and a primary coil L_1 connected in series with each other. Two ends of the primary coil L_1 generate a primary-side observation (PSO) voltage V_{L1}. The PSO voltage V_{L1} may be defined as the voltage across the first resonant capacitor C_1, too. The power transmitter **10** transfers alternating-current (AC) power to at least one power receiver **20**. The power receiver **20** includes a secondary coil L_2 and a resonant load circuit connected in parallel. In this embodiment, the resonant load circuit is a series resonant load circuit **21**. The equivalent circuit of the series resonant load circuit **21** at least includes a second resonant capacitor C_2 and an equivalent load resistor R_L connected in series. Two switches S_S and S_O are electrically connected with the secondary coil L_2 and the series resonant load circuit **21**. The switch S_S is connected in parallel with the series resonant load circuit **21**. The switch S_O is connected in series with the series resonant load circuit **21**. An additional switch S_R is connected in parallel with the equivalent load resistor R_L. The switch S_S and the switch S_R are always off during normal WPT operation. The switch S_O is always on during normal WPT operation. The power receiver **20** generates a secondary-side-observation (SSO) voltage V_{L2}, which may be either the voltage across the secondary coil L_2 or the voltage across the second resonant capacitor C_2. A mutual inductance L_M exists between the primary coil L_1 and the secondary coil L_2. The mutual inductance can be expressed by a relationship involving a coupling coefficient k and the inductances (L_1 and L_2, respectively) of the two coils. During the first resonant capacitor C_1 is being calibrated (in a calibration mode), the first resonant capacitor C_1 is tuned until the peak voltage of the PSO voltage V_{L1} achieves its maximal value. In such a case, the calibrated capacitance of the first resonant capacitor C_1 has an optimal value for transferring the maximal power to the load in the designated power receiver **20**, no matter what values the parameters of the elements of the power receiver **20** are given. The power transmitter **10** further includes a peak voltage detector **12**. The peak voltage detector **12** is electrically connected with the primary coil L_1 or the first resonant capacitor C_1 and used to detect the peak voltages of the PSO voltage V_{L1}.

[0029] A primary-side controller **14** is electrically connected with the peak voltage detector **12**, receiving and storing the peak voltages, and tuning the first resonant capacitor C_1 according to the values of the peak voltages. The primary-side controller **14** also controls the equivalent output resistance of the power amplifier PA in the calibration mode. Similarly, the power receiver **20** also includes a peak voltage detector **22**. The peak voltage detector **22** is electrically connected with the secondary coil L_2 or the second resonant capacitor C_2 and used to detect the peak voltages of the SSO voltage V_{L2}. A secondary-side controller **24** is electrically connected with the peak voltage detector **22**, receiving and storing the peak voltages and tuning the second resonant capacitor C_2 according to the values of the peak voltages. The secondary-side controller **24** also controls the operations of the switches S_S, S_O, and S_R according to the operation mode.

[0030] The process to calibrate the first resonant capacitor C_1 comprises the steps shown in FIG. **2**. In Step S**1**, set the first resonant capacitor C_1 to have an arbitrary initial value, detect the peak voltage of the PSO voltage, and store the peak voltage as a first PSO peak voltage V_{P0}. In Step S**2**, add a predetermined FRCI step value ΔC_1 to the first resonant capacitor C_1. In Step S**3**, detect the peak voltage of the PSO voltage again, and store the peak voltage as a second PSO peak voltage V_{P1}. In Step S**4**, determine whether the absolute value of the difference of the first PSO peak voltage V_{P0} and the second PSO peak voltage V_{P1} is within a predetermined PSO tolerable range ΔV_{e1}. If the difference is within the predetermined PSO tolerable range ΔV_{e1}, undertake Step S**41**. In Step S**41**, stop the calibration process, and preserve the last capacitance of the first resonant capacitor C_1 as the calibration result. If the difference is not within the predetermined PSO tolerable range ΔV_{e1}, undertake Step S**5**. In Step S**5**, determine whether the second PSO peak voltage V_{P1} is greater than the first PSO peak voltage V_{P0}. If the second PSO peak voltage V_{P1} is greater than the first PSO peak voltage V_{P0}, undertake Step S**51**. In Step S**51**, add a predetermined FRCI step value ΔC_1 to the first resonant capacitor C_1. If the second PSO peak voltage V_{P1} is smaller than the first PSO peak voltage V_{P0}, undertake Step S**52**. In Step S**52**, subtract another predetermined FRCI step ΔC_1 from the first resonant capacitor C_1. The predetermined FRCI step ΔC_1 may be dynamically adjusted according to the difference of the first PSO peak voltage V_{P0} and the second PSO peak voltage V_{P1}. In Step S**6**, replace the value of the first PSO peak voltage V_{P0} with that of the second PSO peak voltage V_{P1}, return to Step S**3**, and undertake the steps in sequence. The abovementioned calibration process can acquire the optimal capacitance of the first capacitor C_1 for transferring the maximal power to the load. If the predetermined PSO tolerable range ΔV_{e1} is set to zero, the calibration process will be undertaken persistently to track any change of the parameters of the system.

[0031] Each of the first resonant capacitor C_1 and the second resonant capacitor C_2 is a digitally-controlled variable capacitor or a voltage-controlled variable capacitor. While the first resonant capacitor C_1 is being calibrated to have a specified value needed in calibrating the second resonant capacitor C_2, the secondary coil L_2 is in a short-circuit state or an open-circuit state.

[0032] In a non-short-circuit and non-open-circuit state, the calibration result of the first resonant capacitor C_1 is the optimal value for the load state at the time of calibration.

[0033] Refer to FIG. **1** again for the detailed demonstration of the abovementioned statement. While the control switch S_S is turned on, the secondary coil L_2 is in a short-circuit state, whereby the first resonant capacitor C_1 is ready for calibration. At the same time, the switches S_O and S_R may be turned on or off. Alternatively, the control switch S_S is turned off and the switch S_O is turned off, whereby the secondary coil L_2 is in an open-circuit state and ready for calibration. At the same time, the switch S_R may be turned on or off. For the power transmitter, driving the secondary coil L_2 in an open-circuit state is the same as driving without the entire power receiver **20**. Therefore, the switch S_O is not a necessary but an optional element.

[0034] For the RMC WPT system with calibration capabilities of its LC resonant frequencies shown in FIG. **1**, in addition to the first resonant capacitor C_1, the second resonant capacitor C_2 of the series-loaded power receiver **20** can also be calibrated in a calibration mode to achieve a high (sub-optimal) PTE. When calibrating the second resonant capacitor C_2, the second resonant capacitor C_2 is tuned until the peak voltage of the SSO voltage reaches its maximal value. The SSO voltage is the voltage across the secondary coil L_2 or that across the second resonant capacitor C_2.

[0035] The process to calibrate the second resonant capacitor C_2 in FIG. **1** is essentially identical to the process to calibrate the first resonant capacitor C_1 shown in FIG. **2** except that the SSO voltage is detected during calibrating the second resonant capacitor C_2 and a first SSO peak voltage V_{R0} and a second SSO peak voltage V_{R1} are sequentially detected as the first PSO peak voltage V_{P0} and the second PSO peak voltage V_{P1} are respectively for the succeeding calibration process. Further, in Step S**4**, it is determined whether the absolute value of the difference of the first SSO peak voltage V_{R0} and the second SSO peak voltage V_{R1} is within a predetermined SSO tolerable range Δ_{e2}. Therefore, the process to calibrate the second resonant capacitor C_2 will not be repeated herein. When calibrating the second resonant capacitor C_2, the resistance of the equivalent load resistor R_L of the power receiver **20** can be set to be zero via controlling the parallel switch S_R. It is premised that before calibrating the second resonant capacitor C_2, the first resonant capacitor C_1 has been calibrated under the condition that the secondary coil L_2 is in a short-circuit state or an open-circuit state. In order to further reduce the error of the calibration result of the second resonant capacitor C_2 and to acquire the optimal capacitance of the second resonant capacitor C_2, the coupling coefficient k of the primary coil L_1 and the secondary coil L_2 can be set to a sufficiently-small value, and/or the equivalent output resistance of the power amplifier PA can be increased during the calibration.

[0036] Refer to FIG. **3**. Another embodiment of the present invention proposes a shunt-loaded RMC WPT system with calibration capabilities of its LC resonant frequencies, which comprises at least one power transmitter **30**. The power transmitter **30** includes a power amplifier PA and an LC resonator **31**. The equivalent circuit of the LC resonator **31** at least includes a first resonant capacitor C_1 and a primary coil L_1 connected in series with each other. The primary coil L_1 generates a PSO voltage V_{L1} across itself. The PSO voltage V_{L1} can be the voltage across the first resonant capacitor C_1 as well. The power transmitter **30** transfers AC power to at least one power receiver **40**. The power receiver **40** includes a secondary coil L**2** and a resonant load circuit which is a shunt resonant load circuit **41**. The equivalent circuit of the shunt resonant load circuit **41** at least includes a second resonant capacitor C_2 and an equivalent load resistor R_L connected in parallel. Two switches S_S and S_O are electrically connected with the secondary coil L_2 and the shunt resonant load circuit **41**. The switch S_S is connected in parallel with the second resonant capacitor C_2 and the equivalent load resistor R_L. The switch S_O is an optional element and connected in series with the shunt resonant load circuit **41**. The switch S_S is always off and the switch S_O is always on during normal WPT operation. Two ends of the secondary coil L_2 generate a SSO voltage V_{L2}. A coupling coefficient k (representing the mutual inductance L_M) exists between the primary coil L_1 and the secondary coil L_2. While the first resonant capacitor C_1 is being calibrated, the first resonant capacitor C_1 is tuned until the peak voltage of the PSO voltage V_{L1} achieves its maximal value. In such a case, the calibrated first resonant capacitor C_1 has the optimal value for transferring the maximal power to the load in the designated power receiver **40** no matter what values the parameters of the components of the power receiver **40** have.

[0037] The power transmitter **30** further includes a peak voltage detector **32**. The peak voltage detector **32** is electrically connected with the primary coil L_1 or the first resonant capacitor C_1 and used to detect the peak voltage of the PSO voltage V_{L1}. A primary-side controller **34** is electrically connected with the peak voltage detector **32**, receiving and storing the peak voltages and tuning the first resonant capacitor C_1 according to the values of the peak voltages. The primary-side controller **34** also controls the equivalent output resistance of the power amplifier PA in the calibration mode. Similarly, the power receiver **40** also includes a peak voltage detector **42**. The peak voltage detector **42** is electrically connected with the secondary coil L_2 or the second resonant capacitor C_2 and used to detect the peak voltages of the SSO voltage V_{L2}. A secondary-side controller **44** is electrically connected with the peak voltage detector **42**, receiving and storing the peak voltages of the SSO voltage V_{L2} and tuning the second resonant capacitor C_2 according to the peak voltages of the SSO voltage V_{L2}. The secondary-side controller **44** also controls the operations of the switches S_S and So according to the operation mode.

[0038] In the system architecture shown in FIG. **3**, although the connections of the circuits in the power receiver **40** are different from that of the power receiver **20** shown in FIG. **1**, the operation and the calibration process of the first resonant capacitor C_1 and the second resonant capacitor C_2 in FIG. **3** are identical to those described above. Therefore, it may refer to the descriptions made herein before and will not be repeated herein. However, there is an exception: while the second resonant capacitor is being calibrated, the resistance of the equivalent load resistor R_L of the power receiver **40** is not set to be zero but maintained in its original state in the normal WPT operation mode.

[0039] After the description of the technical characteristics of the present invention, the theoretical principles of the present invention will be described in detail below, so as to prove that the present invention can achieve the optimal performance of the RMC WPT system via automatically calibrating the resonant capacitors of the power transmitter and the power receiver to optimize the resonant frequencies of the LC resonators thereof (the optimal frequency is not necessarily the carrier wave frequency fc).

[0040] As shown in FIG. **1** and FIG. **3**, the first resonant capacitor C_1 and the primary coil L_1 are interchangeable. The switches S_S and S_R are maintained in an off state, and the switch S_O is maintained in an on state in the normal WPT operation mode. The abovementioned switches are for the calibration process only. In the power transmitter, the power amplifier PA drives the primary coil carrying an inductance L_1. The equivalent output resistor of the power amplifier PA is adjustable. In the power transmitter, C_1 and L_1 jointly form an LC resonator. In the power receiver, the secondary coil carrying an inductance L_2 receives the AC power via the mutual inductance L_M between L_1 and L_2 and transfers the received power to the equivalent load resistor R_L; C_2 and L_2 jointly form another LC resonator. While the resonant frequencies of the two LC resonators approach specified frequencies, the RMC WPT system achieves its optimal performance. The mutual inductance L_M can be expressed as $L_M=k\sqrt{L_1L_2}$, wherein k is defined as the coupling coefficient.

[0041] FIG. **4** and FIG. **5** respectively show the equivalent circuits of the systems shown in FIG. **1** and FIG. **3**. The symbols ω_c, R_{PA}, R_L, R_1 and R_2 respectively denote the radian frequency of the carrier wave, the equivalent output resistor of the PA, the equivalent load resistor, the parasitic series resistor of the primary coil, and the parasitic series resistor of the secondary coil. The values of ω_c, R_{PA}, R_L, R_1 and R_2 are set to be constants in the normal WPT operation mode. Generally speaking, the series-loaded RMC system can transfer power to the load R_L of the power receiver more efficiently when R_L is relatively small, while the shunt-loaded RMC system can transfer power to the load R_L of the power receiver more efficiently when R_L is larger.

[0042] Both the RMC WPT systems shown in FIG. **4** and FIG. **5** can be expressed by the same lumped circuit model shown in FIG. **6**. The parameters of the circuit model in FIG. **6** are listed in Table. 1.

TABLE 1

	Series-loaded	Shunt-loaded
Z_{11}	$j\omega_cL_1$	
Z_{22}	$j\omega_cL_2$	
$Z_{21/12}$	$j\omega_cL_M = j\omega_ck\sqrt{L_1L_2}$	
Z_S	$R_{PA}+R_1+\frac{1}{j\omega_cC_1}$	
Z_L	$R_L+\frac{1}{j\omega_cC_2}$	$\frac{R_L}{1+j\omega_cC_2R_L}$
Z_{2L}	$R_2+R_L+\frac{1}{j\omega_cC_2}$	$R_2+\frac{R_L}{1+j\omega_cC_2R_L}$

[0043] In the following analysis, the quality factors defined in Table. 2 will be used to express the results of the analysis.

TABLE 2

Symbol	Definition	Value in a design example and explanations
Q_1	$\frac{\omega_cL_1}{R_1}$	150, the quality factor of L_1
Q_2	$\frac{\omega_cL_2}{R_2}$	110, the quality factor of L_2
Q_S	$\frac{\omega_cL_1}{R_{PA}+R_1}$	131, the primary-side quality factor.
Q_L	$\frac{\omega_cL_2}{R_L}$	—
Q_{2L}	$\frac{\omega_cL_2}{R_2+R_L}$	—

[0044] Usually, the RMC WPT system cannot achieve good performance unless the quality factors of the two inductors L_1 and L_2 are much larger than 1. In practical applications, it is demanded: $k^2Q_SQ_2>>1$.

[0045] As will be shown in the following, analyzing the lumped circuit model in FIG. **6** results in: C_1 is the only factor to determine the MTP in the condition that k, C_2, and R_L are given and remained unchanged. Therefore, the maximal load power (P_L) can be achieved via tuning C_1 to its optimal value. On the other hand, the analysis results also show: the PTEs of both the RMC WPT systems depend on their C_2 and R_L and are independent of their C_1. Therefore, the system can achieve the maximal PTE via tuning C_2 to the optimal value given that R_L is kept at a fixed value. Table. 3 lists the optimal design values of the RMC WPT system according to the analysis.

TABLE 3

	Optimal C_2 for the maximal PTE, denoted as $C_{2,opt}$	Optimal R_L for the maximal PTE given $C_2=C_{2,opt}$, denoted as $R_{L,opt}$	Optimal C_1 for the maximal P_L given $C_2=C_{2,opt}$ and $R_L=R_{L,opt}$, denoted as $C_{1,opt}$
Series-loaded RMC	$\frac{1}{\omega_c^2L_2}$	$\omega_cL_2\left(\frac{k^2Q_S}{\sqrt{1+k^2Q_SQ_2}}-\frac{1}{Q_2^2}\right)$	$\frac{1}{\omega_c^2L_1}$
Shunt-loaded RMC	$\frac{1}{1+k^2\frac{Q_S}{Q_2}+\frac{1}{Q_2^2}}\frac{1}{\omega_c^2L_2}$	$\omega_cL_2\frac{k^2Q_S+Q_2+\frac{1}{Q_2}}{\sqrt{1+k^2Q_SQ_2}}$	$\frac{1}{\omega_c^2L_1}$

[0046] It can be observed in Table. 3 that the $C_{2,opt}$ of the series-loaded RMC system is independent of R_L, k, and the design parameters of the power transmitter. Therefore, C_2 can be calibrated in the environment that these parameters have the values different from the values these parameters have in the normal WPT operation environment. The calibration result of C_2 is then stored and used in the normal WPT operation mode. In other words, no matter whether the values of R_L, k, and the design parameters of the power transmitter are the same as those in the normal WPT operation environment, the correctness of the calibration results would not be affected.

[0047] Below will describe a preferred embodiment of calibrating the first resonant capacitor C_1 of the RMC WPT system.

[0048] In addition to a high PTE, the WPT system also demands a high MTP. The analysis results of the lump model shown in FIG. **6** show that the load power P_L received by the load R_L can be expressed by

$$P_L = H_{PL} \times |V_{L1}(C_1)|^2 \tag{1}$$

wherein

$$H_{PL} = \frac{k^2 Re\{Z_L\}}{2\omega_c^2 L_1 L_2 \left|\left(\frac{Z_{2L}}{Z_{22}}+1\right)\left(1-j\frac{1}{Q_1}\right)-k^2\right|^2} \tag{2}$$

[0049] Equations (1) and (2) are applicable to both the series-loaded and shunt-loaded RMC WPT systems. Equation (2) depicts that H_{PL} is independent of C_1. As a result, the maximal $|V_{L1}(C_1)|$ also generates the maximal P_L according to Equation (1). Therefore, the present invention proposes: automatically tuning C_1 to acquire the maximal $|V_{L1}|$. Once the optimal C_1 is found, it is denoted by $C_{1,opt}$ and used to provide the maximal power for the R_L.

[0050] Define

$$\frac{Z_S}{Z_{11}} + 1 = m_1 - j\frac{1}{Q_S} \tag{3}$$

$$\frac{Z_{2L}}{Z_{22}} + 1 = m_2 - jb \tag{4}$$

wherein

$$m_1 = 1 - \frac{1}{\omega_c^2 L_1 C_1}, \tag{5}$$

$$m_2 = 1 - \frac{\omega_c^2 L_2 C_2}{Q_L^2 + (\omega_c^2 L_2 C_2)^2}, \quad b = \frac{Q_L}{Q_L^2 + (\omega^2 L_2 C_2)^2} + \frac{1}{Q_2} \tag{6}$$

for the shunt-loaded RMC system, and

$$m_2 = 1 - \frac{1}{\omega_c^2 L_2 C_2}, \; b = \frac{1}{Q_{2L}} \tag{7}$$

for the series-loaded RMC system.

[0051] In order to understand the relationship between C_1 and $|V_{L1}|$, Detailed analysis shows that

$$\frac{\partial}{\partial C_1}\left|\frac{V_{L1}(C_1)}{V_S}\right| = \frac{H_{dVL1}}{\omega_c^2 L_1 C_1^2} \times (m_1 - m_{10}) \tag{8}$$

wherein

$$H_{dVL1} = \left|\frac{V_{L1}(C_1)}{V_S}\right|^4 \frac{-(m_2^2+b^2)}{(m_2-k^2)^2 + \frac{m_2^2}{Q_1^2} + b\left(b+\frac{2}{Q_1}k^2\right)} \tag{9}$$

$$m_{10} = \frac{m_2}{m_2^2+b^2}k^2. \tag{10}$$

[0052] Simultaneously define

$$C_{10} = \frac{1}{\omega_c^2 L_1\left(1-\frac{m_2}{m_2^2+b^2}k^2\right)}. \tag{11}$$

[0053] The two kinds of the RMC WPT systems both have the conditions: $H_{dVL1}<0$ and $b>0$. By Equations (8), (9), (10), and the two conditions $H_{dVL1}<0$ and $b>0$, we have

$$\begin{cases} \frac{\partial}{\partial C_1}\left|\frac{V_{L1}(C_1)}{V_S}\right| > 0 \text{ for } C_1 < C_{10} \\ \frac{\partial}{\partial C_1}\left|\frac{V_{L1}(C_1)}{V_S}\right| < 0 \text{ for } C_1 > C_{10} \end{cases} \tag{12}$$

wherein when

$$\frac{\partial}{\partial C_1}\left|\frac{V_{L1}(C_1)}{V_S}\right| = 0, \; C_1 = C_{10}.$$

Equation (12) indicates that C_{10} is the optimal value corresponding to the maximal $|V_{L1}|$, i.e. $C_{10}=C_{1,opt}$. Equation (12) also indicates that when C_1 is larger than the optimal value C_{10}, the derivative of $|V_{L1}|$ with respect to C_1 is negative and if C_1 is smaller than the optimal value, the derivative of $|V_{L1}|$ with respect to C_1 is positive.

[0054] The calibration method of the present invention is based on Equation (12): Varying C_1 to detect the slope of $|V_{L1}(C_1)|$ with respect to the C_1 and adjust C_1 according to the detected slope until the tuned C_1 is close to C_{10} which corresponds to the peak value of

$$\left|\frac{V_{L1}(C_1)}{V_S}\right|.$$

The detailed process of calibrating C_1 is as follows:

[0055] 1. Set C_1 to an arbitrary initial value, detect the peak value of $|V_{L1}(C_1)|$, and store the peak value as V_{p0}.

[0056] 2. Increase the value of C1 by a predetermined FRCI step value ΔC_1, ΔC_1 is assumed to be positive herein to simplify the discussion though it can be negative.

[0057] 3. Detect the current peak value of $|V_{L1}(C_1)|$, and store the peak value as V_{p1}.

[0058] 4. If the absolute value of the difference of V_{p1} and V_{p0} is smaller than a predetermined PSO tolerable range

ΔV_{e1}, the calibration is completed. Store the current value of C_1 as the calibration result. If the absolute value is not smaller than the predetermined PSO tolerable range ΔV_{e1}, go to the next step.

[0059] 5. If $V_{p1}>V_{p0}$, the slope of $|V_{L1}(C_1)|$ with respect to C_1 is positive. By Equation (12), it means $C_1<C_{10}$. Thus, the calibration process increases C_1 by another FRCI step having the same sign as ΔC_1, wherein the another FRCI step may be identical to the predetermined FRCI step ΔC_1 or dynamically adjusted according to the difference of V_{p1} and V_{p0} to accelerate the calibration process. If $V_{p1}<V_{p0}$, the slope of $|V_{L1}(C_1)|$ with respect to C_1 is negative. It means $C_1>C_{10}$ by Equation (12). Thus, the calibration process decreases C_1 by another FRCI step having the same sign as ΔC_1, wherein the another FRCI step is either identical to the predetermined FRCI step ΔC_1 or dynamically adjusted according to the difference of V_{p1} and V_{p0} to accelerate the calibration process.

[0060] 6. Update the value of V_{p0} to be V_{p1}; return to Step 3, and repeat the steps in sequence.

[0061] As have been mentioned in the Step 2 above, ΔC_1 may also be a negative value. While ΔC_1 is negative, increasing a negative value of ΔC_1 is equal to decreasing $|\Delta C_1|$ in the abovementioned Step 2 or Step 5. Similarly, decreasing a negative value of ΔC_1 is equal to increasing $|\Delta C_1|$ in the abovementioned Step 5. Accordingly, the slopes of $|V_{L1}(C_1)|$ with respect to ΔC_1 are also changed in the abovementioned statements. For example, while $V_{p1}>V_{p0}$, the slope of $|V_{L1}(C_1)|$ with respect to ΔC_1 is changed to be a negative value, it indicates that $C_1>C_{10}$; if $V_{p1}<V_{p0}$, the slope of $|V_{L1}(C_1)|$ with respect to ΔC_1 is changed to be a positive value, it indicates that $C_1<C_{10}$.

[0062] FIG. **7** shows two example processes of calibrating C_1 using two different initial C_1 values. At the end of both calibration processes, the slope of $|V_{L1}(C_1)|$ with respect to C_1 approaches zero, whereby the maximal $|V_{L1}(C_1)|$ is acquired. If Δ_{e1} is set to be zero, the calibration process will be an infinite loop, and the C_1, which is being calibrated, will be shifted back and forth within the range of $C_{10}\pm\Delta C_1$ in the long run. It is due to the intrinsic quantization error (ΔC_1) of the variable capacitor. However, using a smaller ΔC_1 can make the calibration result accurate enough.

[0063] It is noteworthy that the optimal C_{10} tracks the variation of the coupling coefficient k according to Equation (11), so does the C_1 being calibrated in this scenario. Consequently, the power transmitter can persistently provide maximal power to the load R_L against environmental variations.

[0064] In addition to calibrating C_1 to achieve the highest MTP, the present invention also sets Z_L=0 or Z_L=00 during calibrating C_1, so as to set C_1 to have a specified value for calibrating C_2. The present invention sets Z_L=0 via turning on the switch S_S in FIG. **1** and FIG. **3** and leaving the switch S_O being turned on or turned off. The present invention sets Z_L=00 via turning off the switches S_O and S_S in FIG. **1** and FIG. **3**. Alternatively, the present invention can set $Z_L=\infty$ by directly removing the whole power receiver 20⁄40. This is the reason why the switch S_O is optional. Table. 4 shows the calibration results according to Equation (11).

TABLE 4

S_S	S_O	Calibration result C_{10}	Comments of C_{10}
off	on	$\frac{1}{\omega_c^2 L_1\left(1-\frac{m_2}{m_2^2+b^2}k^2\right)}$	Optimal C_1 for the maximal P_L (MTP) in the normal WPT operation mode.
on	on or off	$\frac{1}{\omega_c^2 L_1\left(1-\frac{1}{1+\frac{1}{Q_2^2}}k^2\right)}$	calibration result of C_1 with Z_L = 0, which will be used in calibrating C_2.
off	off	$\frac{1}{\omega_c^2 L_1}$	calibration result of C_1 with $Z_L=\infty$, which will be used in calibrating C_2.

[0065] A preferred embodiment of calibrating the second resonant capacitor C_2 of a shunt-loaded RMC WPT system is described in the following.

[0066] For a shunt-loaded RMC system, define

$$y=\omega_c^2 L_2 C_2-1. \tag{13}$$

[0067] Equation (13) is applicable to a shunt-loaded RMC system. In order to understand the relationship between C_2 and $|V_{L2}|$. Detailed analysis leads to

$$\frac{\partial}{\partial C_2}\left|\frac{V_{L2}}{V_S}\right| = H_{dVL2}\times(y-y_0) \tag{14}$$

wherein

$$H_{dVL2} = -\left|\frac{V_{L2}}{V_S}\right|^4 \frac{\omega_c^2 L_1^2}{k^4 L_2}\left((m_1-k^2)^2+\frac{1}{Q_S^2}+\frac{2k^2}{Q_S Q_2}+\frac{m_1^2+\frac{1}{Q_S^2}}{Q_2^2}\right) \tag{15}$$

$$y_0 = \frac{k^2(m_1-k^2)-\left(\left(k^2+\frac{1}{Q_S Q_2}\right)^2-k^4+\frac{m_1^2}{Q_2^2}\right)}{(m_1-k^2)+\frac{1}{Q_S^2}+\left(k^2+\frac{1}{Q_S Q_2}\right)^2-k^4+\frac{m_1^2}{Q_2^2}}. \tag{16}$$

[0068] Simultaneously, define

$$C_{20} = \frac{y_0+1}{\omega_c^2 L_2} \tag{17}$$

[0069] Since $H_{dVL2}<0$, $Q_S>0$, and $Q_2>0$, we have

$$\begin{cases} \frac{\partial}{\partial C_2}\left|\frac{V_{L2}}{V_S}\right| > 0 \text{ for } C_2 < C_{20} \\ \frac{\partial}{\partial C_2}\left|\frac{V_{L2}}{V_S}\right| < 0 \text{ for } C_2 > C_{20} \end{cases} \tag{18}$$

according to Equations (14) to (17). While $C_2=C_{20}$,

$$\frac{\partial}{\partial C_2}\left|\frac{V_{L2}}{V_S}\right| = 0.$$

Equation (18) indicates that C_{20} is the optimal value corresponding to the maximal $|V_{L2}|$. Equation (18) also indicates

that while C_2 is larger than the optimal value C_{20}, the derivative of $|V_{L2}|$ with respect to C_2 is negative, and if C_2 is smaller than the optimal value C_{20}, the derivative of $|V_{L2}|$ with respect to C_2 is positive. Because Equation (18) is similar to Equation (12), the method of calibrating C_2 is similar to the aforementioned calibration method of C_1.

[0070] The present invention uses Equation (18) to calibrate C_2 to be C_{20} by: Varying C_2 and detecting the slope of $|V_{L2}|$ with respect to C_2 and tuning C_2 according to the detected slope of $|V_{L2}|$ with respect to C_2 until C_2 is close enough to C_{20} which corresponds to the peak value of

$$\left|\frac{V_{L2}}{V_S}\right|.$$

The detailed process of calibrating C_2 is as follows:

[0071] 1. Set C_2 to an initial value, detect the peak value of $|V_{L2}|$, and store the peak value as V_{R0}.

[0072] 2. Increase the value of C_2 by a predetermined SRCI step value ΔC_2, ΔC_2 is assumed to be positive herein to simplify the discussion though it can be negative.

[0073] 3. Detect the current peak value of $|V_{L2}|$, and store the peak value as V_{R1}.

[0074] 4. If the absolute value of the difference of V_{R1} and V_{R0} is smaller than a predetermined SSO tolerable range ΔV_{e2}, the calibration is completed. Store the current value of C_2 as the calibration result. If the absolute value is not smaller than the predetermined SSO tolerable range ΔV_{e2}, go to the next step.

[0075] 5. If $V_{R1}>V_{R0}$, the slope of $|V_{L2}|$ with respect to C_2 is positive. By Equation (18), it means $C_2<C_{20}$. Thus, the calibration process increases C_2 by another SRCI step having the same sign as ΔC_2, wherein the another SRCI step may be identical to the predetermined SRCI step ΔC_2 or dynamically adjusted according to the difference of V_{R1} and V_{R0} to accelerate the calibration process. If $V_{R1}<V_{R0}$, the slope of $|V_{L2}|$ with respect to C_2 is negative. It means $C_2>C_{20}$ by Equation (18). Thus, the calibration process decreases C_2 by another SRCI step having the same sign as ΔC_2, wherein the another SRCI step is either identical to the predetermined SRCI step ΔC_2 or dynamically adjusted according to the difference of V_{R1} and V_{R0} to accelerate the calibration process.

[0076] 6. Update the value of V_{R0} to be V_{R1}; return to Step 3, and repeat the steps in sequence.

[0077] As have been mentioned in the Step 2 above, ΔC_2 may also be a negative value. While ΔC_2 is negative, increasing a negative value of ΔC_2 is equal to decreasing $|\Delta C_2|$ in the abovementioned Step 2 or Step 5. Similarly, decreasing a negative value of ΔC_2 is equal to increasing $|\Delta C_2|$ in the abovementioned Step 5. Accordingly, the slopes of $|V_{L2}|$ with respect to ΔC_2 are also changed in the abovementioned statements. For example, if $V_{R1}>V_{R0}$, the slope of $|V_{L2}|$ with respect to ΔC_2 is changed to be a negative value, it indicates that $C_2>C_{20}$; if $V_{R1}<V_{R0}$, the slope of $|V_{L2}|$ with respect to ΔC_2 is changed to be a positive value, it indicates that $C_2<C_{20}$.

[0078] According to Table. 3, in a shunt-loaded RMC WPT system, the optimal C_2 that achieves the maximal PTE is

$$C_{2,opt}=\frac{1}{1+k^2\frac{Q_S}{Q_2}+\frac{1}{Q_2^2}}\frac{1}{\omega_c L_2} \tag{19}$$

which is independent of R_L. As the intended calibration result of C_2 is $C_{2,opt}$, C_1 must be set to be a specified value during calibration so that $C_{2,opt}=C_{20}$. After the calibration of C_2 is completed, C_2 will keep the calibrated value in the normal WPT operation mode. As the PTE is independent of C_1, the value of C_1 in the normal WPT operation mode can be different from the value of C_1 used during calibrating C_2. Therefore, the two parameters C_1 and R_L can be set to any fixed values during calibration. However, for the shunt-loaded RMC WPT system, the parameter k must be the same as that in the application. Consequently, on-line calibration is required.

[0079] By equaling Equation (17) and Equation (19), we can set C_1 to be

$$C_1\cong\frac{1}{\omega_c^2 L_1(1-k^2)}\text{ or }C_1=\frac{1}{\omega_c^2 L_1\left(1+\frac{Q_S}{Q_2}\right)} \tag{20}$$

during calibrating C_2 to make $C_{2,opt}=C_{20}$.

[0080] The second solution in Equation (20) is not preferred because of the difficulties of accurately measuring Q_S and Q_2, accurately setting C_1, and the need of a larger varactor to implement C_1. On the other hand, Table. 4 indicates that calibrating the C_1 with $Z_L=0$ results in a value very close to the first solution in Equation (20) without troublesome setup. Given the calibrated C_1 and perform the proposed calibration of C_2, the error of the calibration result C_{20} normalized to $C_{2,opt}$, can be expressed as

$$\frac{C_{20}-C_{2,opt}}{C_{2,opt}}=\frac{-k^2Q_SQ_2}{Q_2^2+1}. \tag{21}$$

[0081] Equation (21) indicates we can further reduce the calibration error by reducing Q_S to a smaller value Q_{SS} during calibrating C_2. It can be achieved by increasing R_{PA}. There are two simple ways to increase R_{PA} without changing the connections of the circuit: reducing the effective sizes of the output transistor of the PA (the driving capability) or the supply voltage of the PA. Alternatively, interposing an additional resistor to connect in series with the PA and the LC resonator in the primary side during calibration can also reduce Q_S.

[0082] Firstly, let's define

$$Q_{SS}=\lambda Q_S,\text{ wherein }0<\lambda<1. \tag{22}$$

[0083] Thus, the normalized calibration error becomes

$$\frac{C_{20}-C_{2,opt}}{C_{2,opt}}=\frac{-k^2Q_SQ_2}{Q_2^2+1}\times G_{e2cal} \tag{23}$$

wherein the error gain G_{e2cal}

$$G_{e2cal} = \frac{2\lambda(1-\lambda)}{\frac{Q_2}{k^2Q_S} + \frac{1}{k^2Q_SQ_2} + \lambda} + 2\lambda - 1. \quad (24)$$

[0084] According to Equation (24), setting λ to be λ_{opt} can completely vanish the calibration error, wherein

$$\lambda_{opt} = \frac{Q_2^2 + 1}{2(Q_2^2 + 1) + k^2Q_SQ_2} \quad (25)$$

Even though we do not accurately set λ to be λ_{opt}, the error gain is still less than 1 as long as $\lambda<1$. In other words, the acquired calibration error is still smaller than the calibration error in the case that Q_S is not reduced.

[0085] Table. 4 also indicates that calibrating the C_1 with $Z_L=\infty$ results in a C1 whose value close to Equation (20) for loose coupling cases without troublesome setup. Given the calibrated C_1 under $Z_L=\infty$ and performing the proposed calibration of C_2, the error of the calibration result C_{20} normalized to $C_{2,opt}$ can be expressed by

$$\frac{C_{20} - C_{2,opt}}{C_{2,opt}} \cong \frac{-(k^2Q_S)^2}{1 + (k^2Q_S)^2}. \quad (26)$$

[0086] The calibration error is negligible for the loose coupling applications where $k^2Q_S<<1$.

[0087] For stronger coupling applications, the calibration error can be further reduced by reducing Q_S to a smaller value Q_{SS} which can be achieved by increasing R_{P4} during calibration. The normalized calibration error of the calibration result C_{20} with respect to $C_{2,opt}$ can be expressed by

$$\frac{C_{20} - C_{2,opt}}{C_{2,opt}} = \frac{-k^2Q_SQ_2(k^2Q_SQ_2 + 1)}{Q_2^2 + (k^2Q_SQ_2 + 1)^2} \times G_{e2cal} \quad (27)$$

wherein the error gain G_{e2cal} is expressed by

$$G_{e2cal} = \frac{(k^2Q_SQ_2\lambda^2 + 2\lambda - 1)\left(Q_2^2 + (k^2Q_SQ_2 + 1)^2\right)}{(k^2Q_SQ_2 + 1)(Q_2^2 + (\lambda k^2Q_SQ_2 + 1)^2)}. \quad (28)$$

[0088] The calibration error vanishes while λ is equal to the λ_{opt} expressed by Equation (29)

$$\lambda_{opt} = \frac{\sqrt{k^2Q_SQ_2 + 1} - 1}{k^2Q_SQ_2}. \quad (29)$$

Even though we cannot accurately set λ to be λ_{opt}, the error gain G_{e2cal} is still less than 1 as long as $\lambda<1$. In other words, the acquired calibration error is still smaller than the calibration error in the case that Q_S is not reduced.

[0089] Next describes a preferred embodiment of calibrating the second resonant capacitor C_2 of a series-loaded RMC WPT system.

[0090] The methods of calibrating the second resonant capacitors C_2 of the series-loaded RMC WPT system are similar to those of the shunt-loaded RMC WPT system. However, they are different in that the calibration target $C_{2,opt}$ becomes

$$\frac{1}{\omega_c^2 L_2}$$

in the series-loaded system, which has been shown in Table. 3 and is independent of k, R_L, and all the design parameters of the power transmitter. Therefore, we can assign k to whatever value during the calibration. The calibration result is stored and applied to practical applications where these parameters may have different values.

[0091] The analysis of the series-loaded RMC WPT system using the lumped model shown in FIG. **6** results in

$$\frac{\partial}{\partial C_2}\left|\frac{V_{L2}}{V_S}\right| = H_{dVL2} \times (m_2 - m_{21})(m_2 - m_{22}) \quad (30)$$

wherein

$$m_{21} < m_{22}, \text{ and} \quad (31)$$

$$H_{dVL2} = \left|\frac{V_{L2}}{V_S}\right|^4 \frac{\omega_c^2 L_1}{k^2\omega_c^2 L_2^2 C_2^2} \frac{\left(m_1 - \frac{k^2}{2}\right)^2 + \frac{1}{Q_S^2} - \frac{k^4}{4}}{\left((m_2 - 1)^2 + \frac{1}{Q_L^2}\right)^2}.$$

[0092] Then, define

$$C_{21} = \frac{1}{\omega_c^2 L_2(1 - m_{21})} \quad (32)$$

and

$$C_{22} = \frac{1}{\omega_c^2 L_2(1 - m_{22})}. \quad (33)$$

[0093] For the loose coupling cases,

$$k < \sqrt{\frac{2}{Q_S}},$$

and $H_{dvL2}<0$. Therefore,

[0094]

$$\begin{cases} \frac{\partial}{\partial C_2}\left|\frac{V_{L2}}{V_S}\right| < 0 \text{ for } C_{22} > C_2 > C_{21} \\ \frac{\partial}{\partial C_2}\left|\frac{V_{L2}}{V_S}\right| > 0 \text{ for } C_2 < C_{21} \text{ or } C_2 > C_{22} \end{cases} \quad (34)$$

[0095] If the calibration range of C_2 does not cover C_{22}, i.e. the initial value of C_2 is less than C_{22}, Equation (35) is obtained

$$\begin{cases} \frac{\partial}{\partial C_2}\left|\frac{V_{L2}}{V_S}\right| < 0 \text{ for } C_2 > C_{21} \\ \frac{\partial}{\partial C_2}\left|\frac{V_{L2}}{V_S}\right| > 0 \text{ for } C_2 < C_{21} \end{cases} \quad (35)$$

[0096] Equation (35) is similar to Equation (18). The same calibration procedure can be used to calibrate the second resonant capacitor C_2 of the series-loaded RMC system. The calibration result is C_{21}. In fact, the only requirement for successfully calibrating C_2 to C_{21} is to assign the initial value C_2 of the calibration procedure to be less than C_{22} which is an easy task.

[0097] In order to achieve

$$C_{21} = C_{2,opt} = \frac{1}{\omega_c^2 L_2},$$

C_1 needs to be set to Equation (36):

$$\frac{1}{\omega_c^2 L_2\left(1-\frac{k^2Q_{2L}^2}{2}\left(1+\frac{1}{Q_L^2}\right)\left(1\pm\sqrt{1-4\left(\frac{1+\frac{1}{k^2Q_SQ_{2L}}}{1+\frac{1}{Q_L^2}}\right)^2}\right)\right)}, \quad (36)$$

and R_L is needed to be set to a value that fulfills following equation:

$$0 \le Q_L < \frac{\sqrt{1+k^4Q_S^2}-1}{k^2Q_S}. \quad (37)$$

[0098] However, it is hard to precisely set the required C_1 and R_L in practice.

[0099] A simpler calibration setup for calibrating C_2 of the series-loaded RMC system is to set R_L=0 by turning on the switch S_R in FIG. **1** and setting C_1 to the calibrated C_1 with Z_L=0. This setup leads to C_{22}=∞, which means there is no limit for the initial value of C_2. The normalized calibration error of the calibrated C_2 with respect to $C_{2,opt}$ using this setup is expressed as

$$\frac{C_{21}-C_{2,opt}}{C_{2,opt}} \cong \frac{1}{\left(k^2\frac{Q_S}{Q_2}+1\right)^2}-1. \quad (38)$$

[0100] By setting a k satisfying

$$k^2 << \frac{Q_2}{Q_S}$$

during the calibration of C_2, the calibration error becomes negligible.

[0101] Similar to the calibration of the shunt-loaded RMC system, the calibration error of C_2 can be further reduced via decreasing Q_S to a smaller value Q_{SS}. The normalized calibration error with the Q_{SS} becomes

$$\frac{C_{21}-C_{2,opt}}{C_{2,opt}} \cong -2k^2\frac{Q_{SS}}{Q_2} \quad (39)$$

wherein $k^2 << \frac{Q_2}{Q_{SS}}$.

[0102] Another convenient setup for calibrating C_2 of the series-loaded RMC system is to set R_L=0 and set C_1 to the calibrated C_1 under Z_L=∞. The calibration setup also leads to C_{22}=∞, which means there is no limit for the initial value of C_2. The normalized calibration error of the calibrated C_2 with respect to $C_{2,opt}$ is expressed by

$$\frac{C_{21}-C_{2,opt}}{C_{2,opt}} = \frac{-1}{1+\left(\frac{1}{\frac{1}{Q_2}+k^2Q_S}\right)^2}. \quad (40)$$

[0103] It is learned from Equation (40): by setting a small enough k that satisfying k^2Q_S<<1 during the calibration of C_2, the calibration error also becomes negligible.

[0104] The calibration error shown in Equation (40) can be further reduced by reducing Q_S to a smaller value Q_{SS} during the calibration of C_2. Thereby, the normalized calibration error is

$$\frac{C_{21}-C_{2,opt}}{C_{2,opt}} = \frac{-1}{1+\left(\frac{1}{\frac{1}{Q_2}+k^2Q_{SS}}\right)^2}, \quad (41)$$

which is always smaller than Equation (40).

[0105] Therefore, the present invention can automatically calibrate the resonant capacitors of the power transmitter and the power receiver in an appropriate environmental setting to achieve the maximal peak voltages of the PSO voltage and the SSO voltage so as to achieve the optimal MTP and the sub-optimal PTE, respectively. By further setting the equivalent load resistor to its optimal value listed in Table. 3, the present invention can also achieve the optimal PTE.

[0106] Further, the technical characteristics of the present invention can also be applied to the WPT systems using a capacitor/inductor matching network. As long as the circuit architecture is equivalent to the resonant load circuit and the LC resonator, the present invention can be used to tune the capacitances of the equivalent resonant capacitors and calibrate the resonant frequencies of the power transmitter and receiver.

[0107] The embodiments described above are only to demonstrate the technical thoughts and characteristics of the present invention to enable the persons skilled in the art to understand, make, and use the present invention but not to

limit the scope of the present invention. Any equivalent modification or variation according to the spirit of the present invention is to be also included by the scope of the present invention.

What is claimed is:

1. A resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies, comprising

at least one power receiver each at least including a secondary coil and a resonant load circuit; and

at least one power transmitter transmitting an alternating-current power using a carrier wave to said at least one power receiver, and said power transmitter at least including a power amplifier and an inductor-capacitor (LC) resonator driven by said power amplifier, wherein said LC resonator equivalently includes at least a first resonant capacitor and a primary coil connected in series; said primary coil generates a primary-side-observation (PSO) voltage; during calibrating said first resonant capacitor, said first resonant capacitor is tuned until said PSO voltage's peak voltage reaches its maximal value, and thus said first resonant capacitor achieves its optimal capacitance value.

2. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **1**, wherein said PSO voltage is the voltage across said first resonant capacitor.

3. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **1**, wherein said resonant load circuit of said power receiver is selected from:

a series resonant load circuit equivalently including at least a second resonant capacitor and a resistive load connected in series, wherein said secondary coil generates a secondary-side-observation (SSO) voltage; said primary coil and said secondary coil have a coupling coefficient there between; and

a shunt resonant load circuit equivalently including at least a second resonant capacitor and a resistive load connected in parallel, wherein said secondary coil generates said SSO voltage; said primary coil and said secondary coil have a coupling coefficient there between.

4. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **3**, wherein a calibration process of said first resonant capacitor includes steps:

(S**1**) setting said first resonant capacitor to an initial value, detecting a peak voltage of said PSO voltage, and storing said peak voltage as a first PSO peak voltage;

(S**2**) adding a predetermined first-resonant-capacitor-incremental (FRCI) step value to the capacitance of said first resonant capacitor;

(S**3**) detecting said peak voltage of said PSO voltage again, and storing said detected PSO voltage's peak voltage as a second PSO peak voltage;

(S**4**) determining whether an absolute value of the difference of said first PSO peak voltage and said second PSO peak voltage is within a predetermined PSO tolerable range; if yes, stopping said calibration process, and preserving the last value of said first resonant capacitor as a calibration result; if no, undertaking the next step;

(S**5**) if said second PSO peak voltage is greater than said first PSO peak voltage, adding another predetermined FRCI step value to said first resonant capacitor; if said second PSO peak voltage is smaller than said first PSO peak voltage, subtracting another predetermined FRCI step value from said first resonant capacitor; and

(S**6**) replacing the value of said first PSO peak voltage with the value of said second PSO peak voltage, returning to Step (S**3**), and undertaking said steps again in sequence.

5. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **4**, wherein in Step (S**5**), said another predetermined FRCI step value is dynamically adjusted according to said difference of said first PSO peak voltage and said second PSO peak voltage and has the same sign as said predetermined FRCI step value in Step (S**2**).

6. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **1**, wherein said first resonant capacitor is a digitally-controlled variable capacitor or a voltage-controlled variable capacitor.

7. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **4**, wherein while said first resonant capacitor is being calibrated, said secondary coil is in a short-circuit state or an open-circuit state.

8. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **4**, wherein while said first resonant capacitor is being calibrated, said power receiver is removed beforehand.

9. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **4** further comprising a peak voltage detector electrically connected with said primary coil or said first resonant capacitor and used to detect said peak voltage of said PSO voltage.

10. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **9** further comprising a primary-side controller electrically connected with said peak voltage detector, receiving and storing said peak voltages of said PSO voltage, and tuning said first resonant capacitor according to said calibration process of said first resonant capacitor.

11. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **3**, wherein said second resonant capacitor of said power receiver is calibrated to achieve a maximal PTE; while said second resonant capacitor is being calibrated, said first resonant capacitor is set beforehand to have a value obtained by said calibration process of said first resonant capacitor under a condition that said secondary coil is in an open-circuit or a short-circuit state or a condition that said power receiver is removed, and then said second resonant capacitor is tuned

until said SSO voltage's peak voltage reaches its maximal value, and thus said second resonant capacitor achieves its optimal value.

12. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **11**, wherein said second resonant capacitor is a digitally-controlled variable capacitor or a voltage-controlled variable capacitor.

13. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **11**, wherein a calibration process of said second resonant capacitor includes steps:

(S**1**) setting said second resonant capacitor to an initial value, detecting a peak voltage of said SSO voltage, and storing said peak voltage as a first SSO peak voltage;

(S**2**) adding a predetermined second-resonant-capacitor-incremental (SRCI) step value to the capacitance of said second resonant capacitor;

(S**3**) detecting said SSO voltage's peak voltage again, and storing said detected SSO voltage's peak voltage as a second SSO peak voltage;

(S**4**) determining whether an absolute value of the difference of said first SSO peak voltage and said second SSO peak voltage is within a predetermined SSO tolerable range; if yes, stopping said calibration process, and preserving the last value of said second resonant capacitor as a calibration result of said second resonant capacitor; if no, undertaking the next step;

(S**5**) if said second SSO peak voltage is greater than said first SSO peak voltage, adding another predetermined SRCI step value to the capacitance of said second resonant capacitor; if said second SSO peak voltage is smaller than said first SSO peak voltage, subtracting another predetermined SRCI step value from said second resonant capacitor; and

(S**6**) replacing the value of said first SSO peak voltage with the value of said second SSO peak voltage, returning to Step (S**3**), and undertaking said steps again in sequence.

14. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **13**, wherein in Step (S**5**), said another predetermined SRCI step value is dynamically adjusted according to said difference of said first SSO peak voltage and said second SSO peak voltage and has the same sign as said predetermined SRCI step value in Step (S**2**).

15. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **11**, wherein while said resonant load circuit is said series resonant load circuit, said series resonant load circuit's equivalent resistive load has zero resistance during said second resonant capacitor is being calibrated.

16. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **11**, wherein said coupling coefficient (k) is a sufficiently small value and satisfies $k^2 \ll 1/Q_S$, and wherein Q_S is a quality factor expressed by

$$Q_S = \frac{\omega_c L_1}{R_{PA} + R_1},$$

and wherein ω_c denotes said carrier wave's radian frequency; L_1 denotes said primary coil's inductance; R_{PA} denotes said power amplifier's equivalent output resistance; R_1 denotes said primary coil's parasitic series resistance.

17. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **11**, wherein while said second resonant capacitor is being calibrated, said power amplifier's equivalent output resistance is increased.

18. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **13** further comprising a peak voltage detector electrically connected with said secondary coil or said second resonant capacitor and used to detect said first and said second peak voltages of said SSO voltage.

19. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **18** further comprising a secondary-side controller electrically connected with said peak voltage detector, receiving and storing said peak voltages of said SSO voltage, and tuning said second resonant capacitor according to said calibration process of said second resonant capacitor.

20. The resonant magnetic coupling wireless power transfer system with calibration capabilities of its inductor-capacitor resonant frequencies according to claim **13**, wherein while said resonant load circuit of said power receiver is said series resonant load circuit, said initial value of said second resonant capacitor is smaller than said calibration result of said second resonant capacitor.

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