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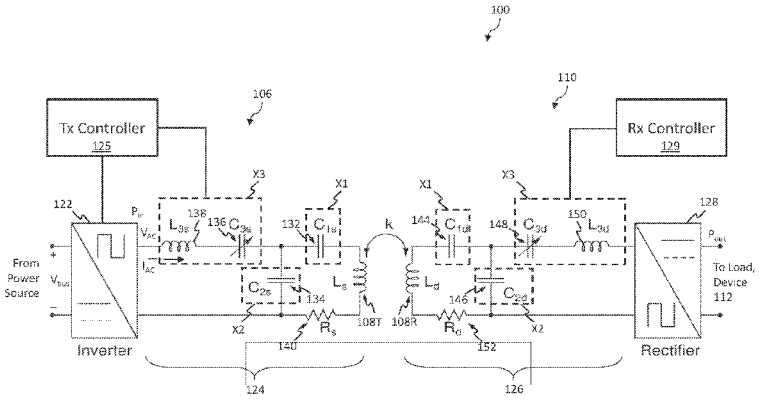

FIG. 1B

(57) Abstract: Methods, systems, and devices for operating wireless power transfer systems. One aspect features a wireless energy transfer system that includes a transmitter, and a receiver. The transmitter has a transmitter-IMN and is configured to perform operations including performing a first comparison between a characteristic of a power of the transmitter and a target power. Adjusting, based on the first comparison, a reactance of the transmitter-IMN to adjust the power of the transmitter. The receiver has a receiver-IMN and is configured to perform operations including determining an efficiency of the wireless energy transfer system at a second time based on power data from the transmitter. Performing a second comparison between the efficiency at the second time and an efficiency of the wireless energy transfer system at a first time, the first time being prior to the second time. Adjusting, based on the second comparison, a reactance of the receiver-IMN.

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CONTROLLING WIRELESS POWER TRANSFER SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. Provisional Patent Application Nos. 62/290,325, filed on February 2, 2016, and 62/379,618 filed on August 25, 2016, the entire contents of which are incorporated herein by reference.

BACKGROUND

[0001] Wireless power transfer systems operate over a wide range of coupling factors *k*, load conditions, and environmental conditions. Variations in these parameters affect the efficiencies of wireless power transfer systems. Wireless power transfer systems can include impedance matching networks to improve power transfer capability and efficiency. Obtaining good performance in a wireless power transfer system over such a wide range of conditions is challenging for traditional impedance matching networks.

SUMMARY

[0002] In general, the disclosure features wireless power transmission control systems that synchronously tune a wireless power transmitter and receiver to adapt to changing system, parameters, environmental parameters, or both. The wireless power transmission control systems described herein can be used in a variety of contexts, including implantable devices, cell phone and other mobile computing device chargers, and chargers for electric vehicles.

[0003] In a first aspect, the disclosure features a wireless energy transmitter that has a transmitter-impedance matching network (IMN). The transmitter is configured to perform operations including performing a first comparison between a characteristic of a power of the transmitter and a target power. Adjusting, based on the first comparison, a reactance of the transmitter-IMN to adjust the power of the transmitter. Transmitting power data that indicates the power of the transmitter to a wireless energy receiver.

[0004] In a second aspect, the disclosure features a wireless energy receiver that has a receiver- IMN. The receiver is configured to perform operations including determining an efficiency of a wireless energy transfer system at a second time based on power data from a wireless energy transmitter. Performing a second comparison

between the efficiency at the second time and an efficiency of the wireless energy transfer system at a first time, the first time being prior to the second time. Adjusting, based on the second comparison, a reactance of the receiver-IMN.

[0005] In a third aspect, the disclosure features a wireless energy transfer system that includes an energy transmitter, and an energy receiver. The transmitter has a transmitter- IMN. The transmitter is configured to perform operations including performing a first comparison between a characteristic of a power of the transmitter and a target power. Adjusting, based on the first comparison, a reactance of the transmitter-IMN to adjust the power of the transmitter. The receiver has a receiver-IMN. The receiver is configured to perform operations including determining an efficiency of the wireless energy transfer system at a second time based on power data from the transmitter. Performing a second comparison between the efficiency at the second time and an efficiency of the wireless energy transfer system at a first time, the first time being prior to the second time. Adjusting, based on the second comparison, a reactance of the receiver-IMN.

[0006] The first aspect and the second aspect can operate together in a system such as the system of the third aspect. Furthermore, these and the fourth through sevenths aspects can each optionally include one or more of the following features.

[0007] In some implementations, adjusting the reactance of the receiver-IMN includes adjusting the reactance of the receiver-IMN by a variable reactance adjustment value.

[0008] In some implementations, the first comparison and adjustment to the reactance of the transmitter-IMN occur iteratively until the characteristic of the power is within a threshold value of the target power.

[0009] In some implementations, adjusting the reactance of the receiver-IMN includes, in response to the efficiency at the second time being less than the efficiency at the first time, negating a reactance adjustment value. Adjusting the reactance of the receiver-IMN includes adjusting the reactance of the receiver-IMN by the negated reactance adjustment value.

[0010] In some implementations, adjusting the reactance of the transmitter-IMN includes, in response to the power being less than the target power, adjusting the reactance of the transmitter-IMN by a first reactance adjustment value. In response to

the power being greater than the target power, adjusting the reactance of the transmitter-IMN by a second, different reactance adjustment value.

[0011] In some implementations, the first reactance adjustment value is equal in magnitude and opposite in sign to the second reactance adjustment value

[0012] In some implementations, the first comparison is between a power factor of the power of the transmitter and a target power factor. The operations of the transmitter can include a third comparison between a magnitude of the power and a target power magnitude, wherein the third comparison follows the first comparison, and adjusting, based on the third comparison, a bus voltage of the transmitter to adjust the power of the transmitter.

[0013] In some implementations, the power factor is represented by a phase relationship between a transmitter voltage and a transmitter current.

[0014] In some implementations, the first comparison and adjustment of the reactance of the transmitter-IMN based on the first comparison occur iteratively until the power factor of the power is within a threshold value of the target power factor.

[0015] In some implementations, the steps of performing the first comparison and adjusting the reactance of the transmitter-IMN are iterated at a faster rate than the steps of performing the third comparison and adjusting the bus voltage.

[0016] In some implementations, the transmitter is an electric vehicle charger and wherein the receiver is a coupled to a power system of an electric vehicle.

[0017] In some implementations, the operations of the transmitter include shutting down the wireless energy transfer system by reducing the target power to zero.

[0018] In some implementations, the operations of the transmitter include shutting down a power inverter in the transmitter.

[0019] In some implementations, the operations of the transmitter include starting up the transmitter by adjusting the reactance of the transmitter-IMN to a maximum value.

[0020] In some implementations, the operations of the transmitter include starting up the transmitter by adjusting a frequency of an inverter to a target frequency.

[0021] In some implementations, the operations of the receiver include starting up the receiver by adjusting the reactance of the receiver-IMN to a minimum value.

[0022] In some implementations, the operations of the receiver include starting up the receiver by adjusting the reactance of the receiver-IMN from a maximum value to a minimum value.

[0023] In some implementations, the transmitter-IMN includes a tunable reactive element electrically connected between an inverter and at least one fixed reactive element, and adjusting the reactance of the transmitter-IMN includes adjusting the tunable reactive element.

[0024] In some implementations, the receiver-IMN includes a tunable reactive element electrically connected between a rectifier and at least one fixed reactive element, and adjusting the reactance of the receiver-IMN includes adjusting the tunable reactive element.

[0025] In some implementations, the steps of performing the first comparison and adjusting the reactance of the transmitter-IMN are iterated at a faster rate than the steps of performing the second comparison and adjusting the reactance of the receiver-IMN.

[0026] In some implementations, determining the efficiency of the wireless energy transfer system includes receiving power data from the transmitter, determining an output power of the receiver, and calculating the efficiency of the wireless energy transfer system based on the power data from the transmitter and the output power of the receiver.

[0027] In some implementations, the operations of the transmitter include performing a plurality of checks that can include a check of a magnitude of the power, a check of a power factor of the power, and a check of a frequency of an inverter in the transmitter, and in response to the plurality checks, selectively adjusting the frequency of the inverter to adjust the power of the transmitter.

[0028] In some implementations, the operations of the transmitter include performing a plurality of checks that can include a check of a magnitude of the power and a check of a phase shift of an inverter of the transmitter, in response to the plurality checks, selectively adjusting the phase shift of the inverter to adjust the power of the transmitter.

[0029] In some implementations, the operations of the transmitter include, before adjusting the bus voltage, verifying that the bus voltage is greater than a minimum bus voltage.

[0030] In some implementations, the first comparison is between a power factor of the power of the transmitter and a target power factor. The operations of the transmitter can include performing a third comparison between a magnitude of the power and a target power magnitude, adjusting, based on the third comparison, the reactance of the transmitter-IMN to reduce the power of the transmitter.

[0031] In some implementations, the first comparison is between a power factor of the power of the transmitter and a target power factor. The operations of the transmitter can include performing a third comparison between a magnitude of the power and a target power magnitude, and adjusting, based on the third comparison, a frequency of an inverter of the transmitter to reduce the power of the transmitter.

[0032] In some implementations, the first comparison is between a power factor of the power of the transmitter and a target power factor. The operations of the can include performing a third comparison between a magnitude of the power and a target power magnitude, and adjusting, based on the third comparison, a phase shift of an inverter of the transmitter to reduce the power of the transmitter.

[0033] In some implementations, the transmitter includes an inductive coil coupled to at least portion of the transmitter-impedance matching network to form a transmitter resonator.

[0034] In some implementations, the receiver includes an inductive coil coupled to at least portion of the receiver-impedance matching network to form a receiver resonator.

[0035] In a fourth aspect, the disclosure features the subject matter described in this specification can be embodied in methods that include the actions of tuning, by a wireless energy transmitter, a transmitter-IMN of the wireless energy transmitter to achieve a target transmitter power characteristic. Sending, by the wireless energy transmitter, power data that indicates the power of the transmitter to a wireless energy receiver. Tuning, by the wireless energy receiver and based on the power data, the receiver-IMN to improve an efficiency of the wireless energy transfer system.

[0036] In a fifth aspect, the disclosure features a wireless energy transmitter that has a transmitter-IMN. The transmitter is configured to perform operations including tuning the transmitter-IMN to achieve a target transmitter power characteristic and sending power data that indicates the power of the transmitter to a wireless energy receiver.

[0037] In a sixth aspect, the disclosure features a features a wireless energy receiver that has a receiver- IMN. The receiver is configured to perform operations including tuning the receiver-IMN to improve an efficiency of the wireless energy transfer system based on power data received from a wireless energy transmitter.

[0038] In a seventh aspect, the disclosure features a wireless energy transfer system that includes an energy transmitter, and an energy receiver. The transmitter is configured to perform operations including tuning the transmitter-IMN to achieve a target transmitter power characteristic and sending power data that indicates the power of the transmitter to the wireless energy receiver. The receiver has a receiver-IMN. The receiver is configured to perform operations including tuning the receiver-IMN to improve an efficiency of the wireless energy transfer system based on power data received from the wireless energy transmitter.

[0039] The fifth aspect and the sixth aspect can operate together in a system such as the system of the seventh aspect. Furthermore, these and the first through third aspects can each optionally include one or more of the following features.

[0040] In some implementations, the target transmitter power characteristic is a target power factor and the target transmitter power characteristic is a target power factor.

[0041] In some implementations, the power factor is represented by a phase difference between a transmitter voltage and a transmitter current, and the target power factor is a target phase difference.

[0042] In some implementations, the operations include adjusting, by the transmitter, an inverter bus voltage to achieve a target power magnitude.

[0043] In some implementations, the operations include adjusting, by the transmitter, an inverter bus voltage to achieve a target power magnitude.

[0044] In some implementations, the operations include performing a safety check prior to adjusting the transmitter-IMN. In some implementations, the safety check is an over-voltage check or an over-current check.

[0045] In some implementations, the operations include performing, by the transmitter, a plurality of checks that can include a check of a magnitude of a transmitter power, a check of a transmitter power factor, and a check of a frequency of an inverter in the transmitter; and in response to the plurality checks, selectively adjusting the frequency of the inverter to adjust the power of the transmitter.

[0046] In some implementations, the operations include performing a plurality of checks that can include a check of a magnitude of a transmitter power and a check of a phase shift of an inverter of the transmitter; and in response to the plurality checks, selectively adjusting the phase shift of the inverter to adjust the power of the transmitter.

[0047] In some implementations, the transmitter is an electric vehicle charger and the receiver is a coupled to a power system of an electric vehicle.

[0048] In some implementations, the operations include adjusting, while starting up the transmitter, the reactance of the transmitter-IMN to a maximum value.

[0049] In some implementations, the operations include adjusting, while starting up the receiver, the reactance of the receiver-IMN to a minimum value.

[0050] In some implementations, the transmitter includes an inductive coil coupled to at least portion of the transmitter-impedance matching network to form a transmitter resonator.

[0051] In some implementations, the receiver includes an inductive coil coupled to at least portion of the receiver-impedance matching network to form a receiver resonator.

[0052] In an eighth aspect, the disclosure features a wireless power transmission system without bus voltage control configured to implement a control loop for tuning power transmission, where the control loop includes: a first sub-loop to control output power of a transmitter of the wireless power transmission system, and a second sub-loop to tune a combined reactance of an inductor and a capacitor that couple a tank circuit to a rectifier in a receiver of the wireless power transmission system, where the second sub-loop tunes the combined reactance by monitoring efficiency of wireless power transmission. Furthermore, this and other implementations can each optionally include one or more of the following features.

[0053] In some implementations, the second sub-loop employs a perturb-and-observe strategy to improve efficiency based on a previous point by tuning the combined reactance of an inductor and a capacitor that couple a tank circuit to a rectifier in a receiver of the wireless power transmission system.

[0054] In some implementations, the second sub-loop is dependent on a power comparison where output power is compared to target power at a start of the control loop.

[0055] In some implementations, the second sub-loop operates at the rate of communication, for example, 40 Hz.

[0056] In some implementations, the control loop is characterized by:

$$P_{inv} = \frac{\frac{8}{\pi^2} V_{bus}^2}{R_{inv}^2 + X_{inv}^2} R_{inv}$$

where P_{inv} is power out of an inverter of the transmitter of the wireless power transmission system, V_{bus} is bus voltage, R_{inv} is resistance seen by the inverter, and X_{inv} is reactance seen by the inverter, and where the tuning occurs at X_{inv} = the combined reactance of the inductor and the capacitor.

[0057] In some implementations, the first sub-loop is a local loop that does not communicate with another part of the wireless power transmission system.

[0058] In some implementations, the first sub-loop is faster than the second sub-loop where the first sub-loop is on order of 1 to 10 kHz.

[0059] In some implementations, the control loop includes preparing inputs, including: setting transmitter reactance to a maximum value, setting receiver reactance to a minimum value, and where the efficiency of wireless power transmission at time zero = 0 and receiver reactance is to be changed by a constant or variable value.

[0060] In some implementations, the control loop starts by comparing output power to target power. In some implementations, if the output power equals the target power within a tolerance, then: efficiency is measured at a time n, the efficiency at time n is compared to efficiency at a previous time n-1, if the efficiency at time n is greater than the efficiency at the previous time n-1, then a change in receiver reactance is added to the receiver reactance and the output power is compared to the target power; whereas if efficiency at time n is equal to or less than the efficiency at the previous time n-1, then a change in receiver reactance is negated, the negated change is added to the receiver reactance, and the output power is compared to the target power.

[0061] In some implementations, if the output power does not equal the target power within a tolerance, then: it is determined whether the output power is less than the target power, if the output power is less than the target power, then a change in transmitter reactance is set to $-\delta$, the change in transmitter reactance is added to the

transmitter reactance, and the output power is compared to the target power; if the output power is greater than the target power, then the change in transmitter reactance is set to δ, the change in transmitter reactance is added to the transmitter reactance, and the output power is compared to the target power.

[0062] In a ninth aspect, the disclosure features a wireless power transmission system with bus voltage control configured to implement a control loop for tuning power transmission, where the control loop includes: a first sub-loop to control phase as defined: $\varphi = \arctan(X_{inverter}/R_{inverter})$, a second sub-loop to control output power, and a third sub-loop to tune a combined reactance of an inductor and a capacitor that couple a tank circuit to a rectifier in a receiver of the wireless power transmission system by monitoring efficiency. Furthermore, this and other implementations can each optionally include one or more of the following features.

[0063] In some implementations, the third sub-loop employs a perturb-and-observe strategy to improve efficiency based on a previous point by tuning the combined reactance of an inductor and a capacitor.

[0064] In some implementations, the third sub-loop is dependent on a power comparison and thus on the second sub-loop.

[0065] In some implementations, the third sub-loop operates at a rate of communication, for example, 40 Hz (speed of WiFi).

[0066] In some implementations, the control loop can be characterized by:

$$P_{inv} = \frac{\frac{8}{\pi^2}V_{bus}^2}{R_{inv}^2 + X_{inv}^2}R_{inv}$$

where P_{inv} is power output from an inverter of the transmitter of the wireless power transmission system, V_{bus} is bus voltage, R_{inv} is resistance seen by the inverter, and X_{inv} is the reactance seen by the inverter, and where tuning occurs at both V_{bus} and X3 = X_{inv}.

[0067] In some implementations, the first sub-loop is adjusted first, the second sub-loop is then adjusted, and the third sub-loop is then adjusted.

[0068] In some implementations, the first sub-loop runs on the order of 1 to 10 kHz.

[0069] In some implementations, the first sub-loop is a local loop and does not communicate with another part of the wireless power transmission system.

[0070] In some implementations, the second sub-loop is a local loop and does not communicate with another part of the wireless power transmission system.

[0071] In some implementations, the second sub-loop runs on the order of 1 to 10 kHz.

[0072] In some implementations, the control loop includes preparing inputs, including: setting transmitter reactance to a maximum value, setting receiver reactance to a minimum value, where the efficiency of wireless power transmission at time zero = 0, the receiver reactance is to be increased, the transmitter reactance is to be increased, the bus voltage is to be increased, and phase is to be increased.

[0073] In some implementations, the control loop includes: comparing a phase measured at the inverter to a target phase, and if the phase measured at the inverter equals the target phase, then output power is compared to target power.

[0074] In some implementations, the third sub-loop occurs if the output power equals the target power and includes: measuring efficiency at a time n, comparing efficiency at the time n to efficiency at a previous time n-1, if the efficiency at the time n is greater than the efficiency at the previous time n-1 then receiver reactance is incremented; whereas if the efficiency at the time n is less than or equal to the efficiency at the previous time n-1, then change in the receiver reactance is negated and the negated value is added to the receiver reactance.

[0075] In some implementations, the second sub-loop occurs if the output power does not equal the target power and includes: if the output power is less than the target power, increasing the bus voltage, and if the output power is greater than the target power, reducing the bus voltage.

[0076] In some implementations, the first sub-loop occurs if a phase measured at inverter is not equal to a target phase and includes: if the phase measured at inverter is greater than a target phase, comparing receiver reactance to a minimum receiver reactance and if the receiver reactance equals the minimum receiver reactance, then comparing the output power to the target power; whereas if the receiver reactance does not equal the minimum receiver reactance, decreasing the transmitter reactance; and if the phase measured at the inverter is less than the target phase, then comparing the receiver reactance to a maximum receiver reactance and if the receiver reactance equals maximum receiver reactance then comparing the output power to the target power

whereas if the receiver reactance does not equal the maximum receiver reactance then increasing the transmitter reactance.

[0077] Particular implementations of the subject matter described in this specification can be implemented so as to realize one or more of the following advantages. Implementations may improve the efficiency of operating wireless power transfer systems. Implementations may improve the dependability of wireless power transfer systems. Implementations may improve robustness of wireless power transfer systems to operate over many conditions. Implementations may improve ability to achieve higher levels of power transfer over many conditions.

[0078] Embodiments of the devices, circuits, and systems disclosed can also include any of the other features disclosed herein, including features disclosed in combination with different embodiments, and in any combination as appropriate.

[0079] The details of one or more implementations of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages of the subject matter will be apparent from the description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0080] FIGS. 1A and 1B depict diagrams of an exemplary wireless power transmission system.

[0081] FIGS. 2A – 2D depict plots related to the effects of receiver X3 tuning in an exemplary wireless power transmission system.

[0082] FIG. 3 depicts a flowchart of an exemplary control process for operating a wireless power transmission system.

[0083] FIGS. 4 depicts a flowchart of another exemplary control process for operating a wireless power transmission system.

[0084] FIGS. 5A-5C depict more detailed flowcharts of exemplary control processes for operating control loop for tuning a wireless power transmission system.

[0085] FIG. 6A depicts a flowchart of an exemplary startup process for a wireless power transmission control system.

[0086] FIG. 6B depicts a flowchart of an exemplary shutdown process for a wireless power transmission control system.

[0087] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0088] Wireless energy transfer systems described herein can be implemented using a wide variety of resonators and resonant objects. As those skilled in the art will recognize, important considerations for resonator-based power transfer include resonator quality factor and resonator coupling. Extensive discussion of such issues, e.g., coupled mode theory (CMT), coupling coefficients and factors, quality factors (also referred to as Q-factors), and impedance matching is provided, for example, in U.S. Patent Application No. 13/428,142, published on July 19, 2012 as US 2012/0184338, in U.S. Patent Application No. 13/567,893, published on February 7, 2013 as US 2013/0033118, and in U.S. Patent Application No. 14/059,094, published on April 24, 2014 as US 2014/0111019. The entire contents of each of these applications are incorporated by reference herein.

[0089] In some applications such as wireless power transfer, impedances seen by the wireless power supply source and device may vary dynamically. In such applications, impedance matching between a device resonator coil and a load, and a source resonator coil and the power supply, may be required to prevent unnecessary energy losses and excess heat. The impedance experienced by a resonator coil may be dynamic, in which case, a dynamic impedance matching network can be provided to match the varying impedance to improve the performance of the system. In the case of the power supply in a wireless power system, the impedances seen by the power supply may be highly variable because of changes in the load receiving power (e.g., battery or battery charging circuitry) and changes in the coupling between the source and device (caused, for example, by changes in the relative position of the source and device resonators). Similarly, the impedance experienced by the device resonator may also change dynamically because of changes in the load receiving power. In addition, the desired impedance matching for the device resonator may be different for different coupling conditions and/or power supply conditions. Accordingly, power transfer systems transferring and/or receiving power via highly resonant wireless power transfer, for example, may be required to configure or modify impedance matching networks to maintain efficient power transfer. Implementations of the present

disclosure provide startup, shutdown, and steady state operation processes that allow for efficient operation over the entire range of conditions encountered in highly-resonant wireless power transfer systems (HRWPT) system such as high-power vehicle charging systems, for example.

[0090] FIGS. 1A and 1B depict diagrams of an exemplary a wireless power transfer system 100. Referring first to FIG. 1A, the system 100 includes a wireless power transmitter 102 and a wireless power receiver 104. A wirelessly powered or wirelessly charged device 112 is coupled to receiver 104. Wirelessly powered or wirelessly charged devices 112 can include, for example, high-power devices such as electric vehicles or electronic devices such as laptops, smartphones, tablets, and other mobile electronic devices that are commonly placed on desktops, tabletops, bar tops, and other types of surfaces.

[0091] For purposes of illustration, wireless power transfer system 100 will be discussed in the context of a wireless charging system for an electric vehicle. For example, system 100 can be a HRWPT system which is required to operate over a wide range of coupling factors k, load conditions (such as a battery voltage), and environmental conditions that detune the inductances of the resonators (e.g., due to spatial variations and interfering objects). Furthermore, in order to perform wireless charging of electric vehicles, system 100 may be required to operate with high voltages (e.g., between 360V and 800V) and high currents (e.g., between 26A and 40A) to achieve a suitable range of power (e.g., 0 to 3.7 kW, 0 to 7.7 kW, 0 to 11 kW, or 0 to 22 kW).

[0092] Wireless power transmitter 102 converts power from an external power source (e.g., power grid or generator) to electromagnetic energy which is transmitted between resonators 108T and 108R to wireless power receiver 104. Receiver 104 converts the oscillating energy received by resonator 108R to an appropriate form for use by device 112 (e.g., charging an electric vehicle battery). More specifically, the receiver power and control circuitry 110 can convert AC voltage and current from resonator 108R to DC power within appropriate voltage and current parameters for device 112.

[0093] The transmitter power and control circuitry 106 can include circuits and components to isolate the source electronics from the power supply, so that any reflected power or signals are not coupled out through the source input terminals. The

source power and control circuitry 106 can drive the source resonator 108S with alternating current, such as with a frequency greater than 10 kHz and less than 100 MHz (e.g., 85 kHz). The source power and control circuitry 106 can include, for example, power factor correction (PFC) circuitry, a transmitter controller, impedance matching circuitry, a power inverter, a DC-to-DC converter, an AC-to-DC converter, a power amplifier, or any combination thereof.

[0094] The receiver power and control circuitry 110 can be designed to transform alternating current power from the receiver resonator 108R to stable direct current power suitable for powering or charging one or more devices 112. For example, the receiver power and control circuitry 110 can be designed to transform an alternating current power at one frequency (e.g., 85 kHz) from resonator 108R to alternating current power at a different frequency suitable for powering or charging one or more devices 112. The receiver power and control circuitry 110 can include, for example, a receiver controller, impedance matching circuitry, rectification circuitry, voltage limiting circuitry, current limiting circuitry, AC-to-DC converter circuitry, DC-to-DC converter circuitry, DC-to-AC circuitry, AC-to-AC converter circuitry, and battery charge control circuitry.

[0095] Transmitter 102 and receiver 104 can have tuning capabilities, for example, dynamic impedance matching circuits, that allow adjustment of operating points to compensate for changing environmental conditions, perturbations, and loading conditions that can affect the operation of the source and device resonators and the efficiency of the energy transfer. The tuning capability can be controlled automatically, and may be performed continuously, periodically, intermittently or at scheduled times or intervals. In some implementations, tuning is performed synchronously between the transmitter 102 and the receiver 104 as described in more detail below.

[0096] FIG. 1B shows the power and control circuitry 106 and 110 of transmitter 102 and receiver 104 in more detail. Referring to both FIGS. 1A and 1B, transmitter 102 includes an inverter 122 powering a transmitter impedance matching network (IMN) 124 and a controller 125 that controls the operation of inverter 122 and tunes transmitter IMN 124. Transmitter IMN 124 is coupled to resonator coil 108T. Receiver 104 includes a receiver IMN 126 coupled to resonator 108R, a rectifier 128 and a controller 129 that can tune the receiver IMN 126. In operation, inverter 122 provides power through transmitter IMN 124 to resonator 108T. Resonator 108T

couples oscillating electromagnetic energy to resonator 108R, with a coupling constant *k*. The energy received by resonator 108R is transferred through receiver IMN 126 to rectifier 108 which converts the energy into an appropriate form for use by device 112.

[0097] Transmitter controller 125 and receiver controller 129 can be implemented as processors or microcontrollers. In some implementations, transmitter controller 125 and receiver controller 129 can be implemented as ASIC or FPGA controllers. Transmitter controller 125 and receiver controller 129 need not be implemented in the same form. For example, transmitter controller 125 can be implemented as a microcontroller and receiver controller 129 can be implemented as an ASIC controller.

[0098] Transmitter 102 also includes a plurality of sensors such as voltage, current, and power sensors to measure transmitter operating parameters. Transmitter controller 125 can use measurements from the sensors to control the operation of the transmitter 102 and to tune the transmitter IMN 124. Transmitter operating parameters measured by the sensors can include, but is not limited to, inverter bus voltage (V_{bus}), transmitter input power, inverter AC voltage (V_{AC}), inverter AC current (I_{AC}), transmitter power factor (pf), and other voltages and currents as needed for safety checks. In some implementations, the transmitter input power is measured at an AC input to a transmitter PFC circuit. In some implementations, the transmitter input power is measured as an inverter power (P_{in}), as shown in FIG. 1B. In some implementations, the inverter power (P_{in}) is measured at the DC input of inverter 122. In some implementations, inverter power (P_{in}) is measured at the AC output of inverter 122. Transmitter power factor can be measured as the phase difference (φ) between the inverter AC voltage (V_{AC}) and inverter AC current (I_{AC}), where the power factor is the cosine of the phase difference (φ). In some implementations, the phase difference (φ) can be used as a proxy for power factor. That is, transmitter controller 125 can perform operations based on the phase difference (φ) instead of calculating an actual power factor value. In some implementations, transmitter power factor (pf) can be calculated based on equivalent resistance and reactance values as seen at the output of the inverter. For example, the phase difference (φ) can be represented by:

$$\varphi = \arctan(X_{inverter}/R_{inverter}).$$

[0099] Receiver 104 also includes a plurality of sensors such as voltage, current, and power sensors to measure receiver operating parameters. Receiver controller 129 can use measurements from the sensors to control the operation of the receiver 104 and

to tune the receiver IMN 126. Receiver operating parameters measured by the sensors can include, but is not limited to, receiver output power (P_{out}), rectifier AC voltage, rectifier AC current, rectifier DC voltage, rectifier DC current, and other voltages and currents as needed for safety checks.

[0100] Transmitter IMN 124 and receiver IMN 126 can each include a plurality of fixed and variable impedance matching components such as resistors, capacitors, inductors, or combinations thereof. Variable impedance components can be tunable reactive impedance components including, but not limited to, PWM-switched capacitors, radio frequency (RF) controlled capacitors whose effective capacitance at RF is controlled by a DC bias field, temperature-controlled capacitors, PWM-switched inductors, DC controlled inductors whose effective inductance is controlled by a bias DC field (e.g., a saturable core), temperature-controlled inductors, arrays of reactive elements switched in and out of the circuit by switches, or a combination thereof.

[0101] In the illustrated example, transmitter IMN 124 includes series capacitor 132, parallel capacitor 134, and the combination of capacitor 136 and inductor 138 at the output of inverter 122. Capacitor 136 is a variable capacitor and can include one or more variable capacitors. A resistive component of the transistor resonator coil 108T is represented by resistor 140.

[0102] Receiver IMN 126 includes series capacitor 144, parallel capacitor 146, and the combination of capacitor 148 and inductor 150 at the input to rectifier 128. Capacitor 148 is a variable capacitor and can include one or more variable capacitors. A resistive component of the receiver resonator coil 108R is represented by resistor 152.

[0103] IMNs 124 and 126 can have a wide range of circuit implementations with various components having impedances to meet the needs of a particular application. For example, U.S. Patent No. 8,461,719 to Kesler et al., which is incorporated herein by reference in its entirety, discloses a variety of tunable impedance network configurations, such as in FIGS. 28a-37b. In some implementations, each of the components shown in FIG. 1B may represent networks or groups of components.

[0104] Each of the IMNs 124 and 126 include three reactances: series reactance X1 (e.g., capacitor 132 or 144), parallel reactance X2 (e.g., capacitor 134 or 146), and inverter output/rectifier input reactance X3 (combined reactance of inductor 138 or 150 with capacitor 136 or 148, respectively). The reactances X1-X3 of receiver IMN 126

mirror the corresponding reactances X1-X3 of transmitter IMN 124. Although reactance X3 is the only reactance illustrated as including a tunable reactance component, namely, capacitors 136 and 148, in other implementations, reactances X1 and X2 can include tunable reactance components in addition to or in place of the tunable reactance component in reactance X3. In other words, IMNs 124 and 126 can be tuned by tuning any one or more of reactances X1-X3. In some implementations, components that make up reactances X1 and X3 can be balanced.

[0105] While any of reactances X1, X2, X3, or combinations thereof can be tuned, in some implementations, it can be advantageous to tune reactance X3. For example, by tuning reactance X3, it may be possible to reduce system complexity and cost if tuning a single component in IMN is sufficient. By tuning reactance X3, the current through the X3 elements can be significantly lower than that through the tank circuit formed by X1, X2, and the resonator coil. This lower current may make implementation of tunable components more cost-effective by, for example, reducing current ratings that may be required for such components. Additionally, lower currents may reduce losses by tuning elements at X3.

[0106] In some implementations, tunable reactive elements (e.g., PWM controlled capacitors) can inject harmonic noise into a HRWPT system. To help with EMI compliance, may be preferable to keep this harmonic noise away from the main HRWPT resonator coils (e.g., 108T and 108R). Higher-harmonics injected by a tunable element at X3 may be more suppressed than those that can be generated by the inverter and rectifier and may be significantly suppressed by the rest of the HRWPT circuit before reaching the resonator coil 108T or 108R.

[0107] In some implementations with tunable elements at X3 (e.g., PWM controlled capacitors), the tunable element dissipates the least amount of power (theoretically zero) when the overall efficiency of the rest of the system is lowest, and the highest amount of power when the overall efficiency of the rest of system is highest. This has the desirable effect of optimizing the minimum and average efficiencies of the system while only slightly affecting the maximum efficiency. However, tuning elements at X1 or X2 can have the opposite, less desirable, effect.

[0108] Fixed reactances of X1 and X2, and the base reactance value of X3 can be selected to achieve the results shown in FIGS. 2A-2D and discussed below. For example, values for X1 and X2 can be determined by: 1) Determining the maximum

range of reactive tuning that can be achieved based on the maximum current that flows through the circuit branches containing X3 and the current and voltage ratings of the components used in the implementation of the tunable reactive elements. For example, one may conclude that a single-stage reactive element can affect 20 Ω of reactive tuning. 2) Optimizing, for the receiver-side IMN, X1, X2, and the base value of X3 so as to optimize the coil-to-coil efficiency over the range of relative positions of the resonators (and of load conditions) and/or ensure that the amount of power dissipated in the resonators stays below a specified limit based on the range of reactive determined in step 1. 3) Optimizing, for the transmitter-side IMN, X1, X2, and the base value of X3 so as to present a desirable effective impedance to the inverter (e.g., sufficiently inductive to achieve zero-voltage-switching in a Class D inverter, but not too inductive that there's excessive reactive current, and with a magnitude that falls within the range of bus voltages that can be practically achieved).

[0109] FIGS. 2A – 2D illustrate plots related to the effects of tuning receiver X3. FIG. 2A shows source (transmitter) resonator power losses (in W per kW to the load) as a function of quality factor ratio Q_d^U/Q_d^L, where Q_d^U is the quality factor of the unloaded device (receiver) resonator and Q_d^L is the quality factor of the loaded device resonator (loading includes the loading of the remaining device circuitry and load) and figure of merit $F_{oM} = U = k\sqrt{Q_s Q_d}$. FIG. 2A illustrates that figure of merit plays a dominate role in losses at the transmitter resonator.

[0110] FIG. 2B shows device resonator power losses (in W per kW to the load) as a function of quality factor ratio Q_d^U/Q_d^L where Q_d^U is the quality factor of the unloaded device resonator and Q_d^L is the quality factor of the loaded device resonator (loading includes the remaining device circuitry and load) and figure of merit $F_{oM} = U = k\sqrt{Q_s Q_d}$. FIG. 2B illustrates that quality factor ratio plays a dominate role in losses at the receiver resonator.

[0111] FIG. 2C shows device figure of merit U_d at an operating frequency of 84 kHz as a function of the change in reactance dX (in ohms) at position X3 and load resistance R_L (in ohms). Figure of merit U_d is defined through:

$$\frac{R_{L,eq}}{R_d} = \sqrt{1 + U_d^2}$$

where $R_{L,eq}$ is the loaded equivalent series resistance (ESR) (due to device electronics, such as the rectifier, and battery) of the device resonator and R_d is the unloaded ESR of the device resonator. When U_d is set to equal figure of merit U of the system, then the coil-to-coil efficiency can be maximized.

[0112] FIG. 2D shows phase ψ (in degrees) at an operating frequency of 84 kHz as a function of the change in reactance (in ohms) and load resistance (in ohms). Phase ψ is defined by:

$$\psi = \arctan\left(\frac{\Delta X_L}{R_{L,eq}}\right)$$

where ΔX_L is the residual reactance of the loaded device resonator at the operating frequency. A phase $\psi = 0$ means the loaded device resonator is at resonance.

[0113] The trapezoidal dotted outline 202 in FIGS. 2C and 2D shows an operating range for a wireless power transfer receiver. Outline 202 in FIG. 2D shows a range of R_L that would be seen for a wireless power transmission system operating at 11 kW output. For example, for R_L = 10 Ω, there is a significant ability to tune X3, as shown in FIG. 2C by range of dX at R_L = 10 Ω, while maintaining near resonance (or avoiding detuning the resonator), as shown in FIG. 2D by the proximity of $\psi = 0$ curve to R_L = 10 Ω.

[0114] Referring again to FIG. 1B, controllers 125 and 129 can synchronously tune the IMNs 124 and 126, respectively, to maintain system 100 operations within desired operating ranges such as outline 202. In the illustrated implementations, controllers 125 and 129 perform the processes described below to synchronously tune reactance X3 of the transmitter and receiver IMNs 124 and 126 in order to safely and efficiently transfer power to a device 112 such as an electric vehicle. In order to synchronously control the IMNs 124 and 126, transmitter 102 and receiver 104 can communicate control data between each other. For example, controllers 125 and 129 can include wireless communication interfaces to conduct electronic communications in an out-of-band communications channel. Communications between controllers 125 and 129 can include, but are not limited to, RF communications (e.g., WiFI, Bluetooth, Zigbee), optical communication, infrared communications, ultrasonic communications, or a combination thereof.

[0115] For example, as described in more detail below in reference to FIGS. 3-5C, controller 125 can tune transmitter IMN 124 to achieve a target power characteristics of

transmitter 102, while controller 129 can tune receiver IMN 126 to achieve a target system efficiency. Transmitter controller 125 adjusts IMN 124 to achieve and maintain target power characteristics of the transmitter 102. Transmitter controller 125 sends input power data to receiver controller 129. Receiver controller 129 measures output power of the receiver 104 and, together with the input power data, calculates the efficiency of the system 100. Receiver controller 129 tunes the receiver IMN 126 to maximize the system efficiency. For example, receiver controller 129 can determine appropriate adjustments to receiver IMN 126 based on comparing a calculated efficiency values at two different times.

[0116] In some implementations, transmitter controller 125 operates at a faster rate than receiver controller 129. That is, transmitter controller 125 can tune the transmitter IMN 124 at a faster rate than receiver controller 129 can tune the receiver IMN 126. For example, receiver controller 129 may only be permitted to tune receiver IMN 126 as fast as it receives new input power data from transmitter controller 125.

[0117] FIG. 3 depicts a flowchart of an exemplary control process 300 for operating a wireless power transmission system. In some examples, the example process 300 can be provided as computer-executable instructions executed using one or more processing devices (e.g., processors or microcontrollers) or computing devices. In some examples, the process 300 may be executed by hardwired electrical circuitry, for example, as an ASIC or an FPGA controller.

[0118] Portions of process 300 are be performed by a wireless power transmitter 102 (e.g., transmitter controller 125) and portions of process 300 are performed by a wireless power receiver 104 (e.g., receiver controller 129). Process 300 includes two control loops 303 and 305. Loop 303 is performed by a transmitter 102 to tune a transmitter IMN 124 by adjusting reactance X3 to control the transmitter power. In some implementations, loop 303 is a local loop that does not require communication with other devices (e.g., receiver 104) to be performed. In some implementations, loop 303 is executed by a transmitter at between 1 – 10 kHz. Loop 303 can be characterized by:

$$P_{in} = \frac{\frac{8}{\pi^2} V_{bus}^2}{R_{inv}^2 + X_{inv}^2} R_{inv}$$

where P_{in} is the power of the inverter, V_{bus} is the DC bus voltage of the inverter 122, R_{inv} is the effective resistance as seen by the inverter, and X_{inv} is the effective reactance as seen by the inverter.

[0119] Loop 305 is performed by a receiver 104 to tune a receiver IMN 126 based on system efficiency. For example, loop 305 can employ a "perturb-and-observe" strategy to improve efficiency by adjusting reactance X3 of a receiver IMN 126 to continually improve efficiency over consecutive iterations. Loop 305 depends on input power data from transmitter 102 to calculate system efficiency at each iteration. In some implementations, loop 305 operates at the rate of communication between transmitter 102 and receiver 104, for example, 40 Hz.

[0120] Block 302 lists the inputs and initial conditions for process 300 which include a variable transmitter reactance X_{tx} (e.g., X3 of transmitter IMN 124), set to a maximum reactance value $X_{tx,max}$; a variable receiver reactance Xrx (e.g., X3 of receiver IMN 126), set to a minimum reactance value $X_{rx,min}$; a system efficiency η, initially set to zero; a transmitter reactance step size ΔX_{tx}, set to an adjustment value of δ; and a receiver reactance step size ΔX_{rx}, set to an adjustment value of ε. In some implementations, the reactance step sizes ΔX_{tx} and ΔX_{rx} are constant values. In some implementations, the reactance step sizes ΔX_{tx} and ΔX_{rx} can be variable. For example, controller 125 or controller 129 can increase or decrease the magnitude of the respective step sizes dynamically during process 300.

[0121] Process 300 starts at step 304. At step 306 the power of the transmitter 102 is measured. Transmitter controller 125 measures the input power P_{in}, and, at step 306, compares the input power P_{in} to a target power level P_{target}. If P_{in} equals P_{target} the process 300 proceeds to step 308 of loop 305. If P_{in} does not equal P_{target}, process 300 proceeds to step 316 of loop 303. In some implementations or some operation modes, the target power level is set by the transmitter 102. In some implementations or some operation modes, the target power level is set by the receiver 104. For example, when in steady-state operations (e.g., normal operations apart from startup or shutdown sequences), system 100 can operate as a demand based system. For example, receiver 104 can request power levels from the transmitter 102. Transmitter controller 125 can calculate a target input power level based on the demanded power level from the receiver 104. For example, transmitter controller 125 can convert the demanded power to a target input power level that would be required to transmit the demanded power

level by accounting for expected losses in the transmitter (e.g., IMN losses and inverter losses).

[0122] Referring first to the transmitter-side loop, loop 303, if the input power of the transmitter (e.g., the inverter power) is not equal to the target power, at step 316 transmitter controller 125 compares the input power to the target power level to determine whether the input power is less than the target power level. If P_{in} is less than P_{target}, then, at step 318, transmitter controller 125 sets the transmitter reactance step size ΔX_{tx}, to a negative adjustment value to decrease the variable transmitter reactance X_{tx} in step 320. If P_{in} is not less than P_{target}, then, at step 322, transmitter controller 125 sets the transmitter reactance step size ΔX_{tx}, to a positive adjustment value to increase the variable transmitter reactance X_{tx} in step 320. In some implementations, the magnitude of the reactance adjustment value δ can be varied. For example, if the difference between P_{in} and P_{target} is large, for example, greater than a coarse adjustment threshold value, then the transmitter controller 125 can increase the magnitude of the reactance adjustment value δ. Correspondingly, if the difference between P_{in} and P_{target} is small, for example, less than a fine adjustment threshold value, then the transmitter controller 125 can decrease the magnitude of the reactance adjustment value δ. After the variable transmitter reactance X_{tx} is adjusted in step 320, loop 303 returns to step 306, where the input power is again compared to the target power level.

[0123] Referring to the receiver-side loop, loop 305, if the input power of the transmitter is equal to the target power, at step 308, the receiver controller 129 measures the efficiency of the system 100. For example, when P_{in} is equal to P_{target}, the transmitter can send data indicating the measured value of P_{in} to the receiver 104. (It should be noted that measured transmitter power can be represented by a floating point number and, thus, may not exactly equal the target power, but may be equivalent within a predetermined tolerance.) Receiver controller 129 measures the output power of the receiver, and calculates the system efficiency $\eta(n)$ at time n based on the received transmitter power data and the measured receiver output power value.

[0124] At step 310, receiver controller 129 compares the system efficiency calculated at time n, to the system efficiency calculated at a previous time n-1. If the efficiency at time n is greater than the efficiency at time n-1, then, at step 312, the variable receiver reactance X_{rx} is adjusted by the receiver reactance step size ΔX_{rx}. For example, the change in receiver reactance ΔX_{rx} is added to the variable receiver

reactance X_{rx}. If the efficiency at time n is not greater than the efficiency at time n-1, then, at step 314, receiver controller 129 changes the sign of the receiver reactance step size ΔX_{rx} before adjusting the variable receiver reactance X_{rx} at step 312. For example, the value of the change in receiver reactance ε can be negated. For example, the direction of adjustments for the variable receiver reactance X_{rx} is swapped when the efficiency is no longer increasing between subsequent iterations of loop 305. As illustrated in by loop 305, direction of adjustments for the variable receiver reactance X_{rx} will then be retained in subsequent iterations of loop 305 until efficiency decreases again, thereby, maintaining a near-maximum system efficiency.

[0125] In some implementations, the magnitude of the reactance adjustment value ε can be varied. For example, if the efficiency at time n is less than a coarse adjustment threshold value (e.g., soon after system startup), then the receiver controller 129 can increase the magnitude of the reactance adjustment value ε. Correspondingly, if the the efficiency at time n is near an estimated maximum value for example, within a fine adjustment threshold of the estimated maximum value, then the receiver controller 129 can decrease the magnitude of the reactance adjustment value ε.

[0126] FIG. 4 depicts a flowchart of an exemplary control process 400 for operating a wireless power transmission system. In some examples, the example process 400 can be provided as computer-executable instructions executed using one or more processing devices (e.g., processors or microcontrollers) or computing devices. In some examples, the process 400 may be executed by hardwired electrical circuitry, for example, as an ASIC or an FPGA controller.

[0127] Process 400 is similar to process 300, but includes control of inverter bus voltage V_{bus} to adjust transmitter power P_{in}, and measurements of and the use of inverter power factor (e.g., inverter AC voltage V_{AC} and inverter AC current I_{AC} phase difference φ) to tune the transmitter IMN 124.

[0128] Portions of process 400 are be performed by a wireless power transmitter 102 (e.g., transmitter controller 125) and portions of process 400 are performed by a wireless power receiver 104 (e.g., receiver controller 129). Process 400 includes three control loops 401, 403, and 405. Loops 401 and 403 are performed by a transmitter 102 to tune a transmitter IMN 124 and to control the transmitter power. Loop 401 is a phase loop that tunes the transmitter IMN 124 by adjusting reactance X3 to achieve a target phase φ relationship between the inverter AC output voltage and inverter AC

output current (e.g., inverter power factor), hereinafter referred to as "inverter output phase φ_{inv}" and "target inverter output phase φ_{target}." Loop 403 is a power control loop that controls and maintains the transmitter power magnitude P_{in} at or near the target power P_{target} by adjusting the inverter bus voltage V_{bus}. In some implementations, loops 401 and 403 are local loops that do not require communication with other devices (e.g., receiver 104) to be performed. In some implementations, loops 401 and 403 are executed by a transmitter at between 1 – 10 kHz. Loops 401 and 403 can be characterized by:

$$P_{in} = \frac{\frac{8}{\pi^2} V_{bus}^2}{R_{inv}^2 + X_{inv}^2} R_{inv}$$

where P_{in} is the power of the inverter, V_{bus} is the DC bus voltage of the inverter 122, R_{inv} is the effective resistance as seen by the inverter, and X_{inv} is the effective reactance as seen by the inverter.

[0129] Loop 405 is performed by a receiver 104 to tune a receiver IMN 126 based on system efficiency. Loop 405 is similar to loop 305 of process 300. For example, loop 405 can employ a "perturb-and-observe" strategy to improve efficiency by adjusting reactance X3 of a receiver IMN 126 to continually improve efficiency over consecutive iterations. Loop 405 depends on input power data from transmitter 102 to calculate system efficiency at each iteration. In some implementations, loop 405 operates at the rate of communication between transmitter 102 and receiver 104, for example, 40 Hz.

[0130] Block 402 lists the inputs and initial conditions for process 400 which include a variable transmitter reactance X_{tx} (e.g., X3 of transmitter IMN 124), set to a maximum reactance value $X_{tx,max}$; a variable receiver reactance X_{rx} (e.g., X3 of receiver IMN 126), set to a minimum reactance value $X_{rx,min}$; a system efficiency η, initially set to zero; a transmitter reactance step size ΔX_{tx}, set to an adjustment value greater than zero; a receiver reactance step size ΔX_{rx}, set to an adjustment value greater than zero; and a bus voltage step size ΔV_{bus} set to an adjustment value greater than zero. In some implementations, the reactance step sizes ΔX_{tx} and ΔX_{rx} and bus voltage step size ΔV_{bus} are constant values. In some implementations, the reactance step sizes ΔX_{tx} and ΔX_{rx} and bus voltage step size ΔV_{bus} can be variable. For example, controller 125 or controller 129 can increase or decrease the magnitude of the respective step sizes dynamically during process 400.

[0131] Process 400 starts at step 404. At step 406, transmitter controller 125 measures the inverter output phase φ_{inv}, and compares the measured inverter output phase φ_{inv} to a target inverter output phase φ_{target}. If φ_{inv} equals φ_{target} the process 400 proceeds to step 408 of loop 403. If φ_{inv} does not equal φ_{target} the process 400 proceeds to step 424 of loop 401. In some implementations, φ_{target} is slightly greater than 0 so the inverter still sees a slightly inductive load.

[0132] Referring first to phase loop, loop 401, if the inverter output phase is not equal to the target inverter output phase, at step 406 transmitter controller 125 compares the inverter output phase to the target inverter output phase, at step 424, to determine whether the inverter output phase is greater than the target inverter output phase. If φ_{inv} is greater than φ_{target}, then, at step 426, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a minimum value $X_{tx,min}$. If the variable transmitter reactance X_{tx} is already at a minimum value $X_{tx,min}$, then loop 401 proceeds to step 408 with no adjustment to the variable transmitter reactance X_{tx}. If the variable transmitter reactance X_{tx} is not at a minimum value $X_{tx,min}$, then, at step 332, transmitter controller 125 decrements the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 401 reverts back to step 406 to reevaluate the inverter output phase.

[0133] If, at step 424, φ_{inv} is not greater than φ_{target}, then, at step 430, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$. If the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$, then loop 401 proceeds to step 408 with no adjustment to the variable transmitter reactance X_{tx}. If the variable transmitter reactance X_{tx} is not at a maximum value $X_{tx,max}$, then, at step 420, transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 401 reverts back to step 406 to reevaluate the inverter output phase.

[0134] Referring to the power loop, loop 403, at step 408 transmitter controller 125 measures the input power P_{in}, and compares the measured input power P_{in} to a target power level P_{target}. If P_{in} equals P_{target} the process 400 reverts to step 406 of loop 401. In addition, transmitter controller 125 can send data indicating the measured value of P_{in} to the receiver 104. If P_{in} does not equal P_{target}, process 400 proceeds to step 418. In some implementations or some operation modes, the target power level is set by the transmitter 102. In some implementations or some operation modes, the target power

level is set by the receiver 104. For example, when in steady-state operations (e.g., normal operations apart from startup or shutdown sequences), system 100 can operate as a demand based system. For example, receiver 104 can request power levels from the transmitter 102. Transmitter controller 125 can calculate a target input power level based on the demanded power level from the receiver 104. For example, transmitter controller 125 can convert the demanded power to a target input power level that would be required to transmit the demanded power level by accounting for expected losses in the transmitter (e.g., IMN losses and inverter losses).

[0135] If the power of the transmitter is not equal to the target power, at step 418 transmitter controller 125 compares the input power to the target power level to determine whether the input power is less than the target power level. If P_{in} is less than P_{target}, then, at step 420, transmitter controller 125 increments the inverter bus voltage V_{bus} by the bus voltage step size ΔV_{bus}, and loop 403 reverts back to step 408 to reevaluate the power of the transmitter. If P_{in} is not less than P_{target}, then, at step 422, transmitter controller 125 decrements the inverter bus voltage V_{bus} by the bus voltage step size ΔV_{bus}, and loop 403 reverts back to step 408 to reevaluate the power of the transmitter.

[0136] In some implementations, the magnitude of the transmitter reactance step size ΔX_{tx} can be varied. For example, if the difference between φ_{inv} and φ_{target} is large, for example, greater than a coarse adjustment threshold value, then the transmitter controller 125 can increase the transmitter reactance step size ΔX_{tx}. Correspondingly, if the difference between φ_{inv} and φ_{target} is small, for example, less than a fine adjustment threshold value, then the transmitter controller 125 can decrease the magnitude of the transmitter reactance step size ΔX_{tx}.

[0137] In some implementations, the magnitude of the bus voltage step size ΔV_{bus} can be varied. For example, if the difference between P_{in} and P_{target} is large, for example, greater than a coarse adjustment threshold value, then the transmitter controller 125 can increase the bus voltage step size ΔV_{bus}. Correspondingly, if the difference between P_{in} and P_{target} is small, for example, less than a fine adjustment threshold value, then the transmitter controller 125 can decrease the magnitude of the bus voltage step size ΔV_{bus}.

[0138] Referring to the receiver-side loop, loop 405, at step 409 receiver 104 receives transmitter power data. For example, when P_{in} is equal to P_{target} at step 408,

the transmitter 102 can send data indicating the measured value of P_{in} to the receiver 104. At step 410, the receiver controller 129 measures the efficiency of the system 100. Receiver controller 129 measures the output power of the receiver 104, and calculates the system efficiency $\eta(n)$ at time n based on the received transmitter power data and the measured receiver output power value.

[0139] At step 412, receiver controller 129 compares the system efficiency calculated at time n, to the system efficiency calculated at a previous time n-1. If the efficiency at time n is greater than the efficiency at time n-1, then, at step 414, the variable receiver reactance X_{rx} is adjusted by the receiver reactance step size ΔX_{rx}. For example, the change in receiver reactance ΔX_{rx} is added to the variable receiver reactance X_{rx}. If the efficiency at time n is not greater than the efficiency at time n-1, then, at step 416, receiver controller 129 changes the sign of the receiver reactance step size ΔX_{rx} before adjusting the variable receiver reactance X_{rx} at step 414. For example, the value of the receiver reactance step size ΔX_{rx} can be negated. For example, the direction of adjustments for the variable receiver reactance X_{rx} is swapped when the efficiency is no longer increasing between subsequent iterations of loop 405. As illustrated in by loop 405, direction of adjustments for the variable receiver reactance X_{rx} will then be retained in subsequent iterations of loop 405 until efficiency decreases again, thereby, maintaining a near-maximum system efficiency.

[0140] In some implementations, the magnitude of the receiver reactance step size ΔX_{rx} can be varied. For example, if the efficiency at time n is less than a coarse adjustment threshold value (e.g., soon after system startup), then the receiver controller 129 can increase the magnitude of the receiver reactance step size ΔX_{rx}. Correspondingly, if the efficiency at time n is near an estimated maximum value for example, within a fine adjustment threshold of the estimated maximum value, then the receiver controller 129 can decrease the magnitude of the receiver reactance step size ΔX_{rx}.

[0141] FIGS. 5A – 5C depicts a flowchart of an exemplary control processes 500a, 500b, and 500c for operating a wireless power transmission system. In some examples, the processes 500a, 500b, and 500c can be provided as computer-executable instructions executed using one or more processing devices (e.g., processors or microcontrollers) or computing devices. In some examples, the processes 500a, 500b, and 500c may be executed by hardwired electrical circuitry, for example, as an ASIC or

an FPGA controller. Processes 500a, 500b, and 500c are related to processes 300 and 400, but include additional steps that evaluate and control additional system parameters to operate a wireless power transmission system.

[0142] Referring to FIG. 5A, process 500a includes portions that are be performed by a wireless power transmitter 102 (e.g., transmitter controller 125) and portions that are performed by a wireless power receiver 104 (e.g., receiver controller 129). Process 500a includes three control loops 501a, 503a, and 505. Loops 501a and 503a are performed by a transmitter 102 to tune a transmitter IMN 124 and to control the transmitter power. Loop 501a is a phase loop that tunes the transmitter IMN 124 by adjusting reactance X3 to achieve a target inverter output phase φ_{target}. Loop 501a also includes safety checks to ensure that current, voltage, or other device limitations are not exceeded. Loop 503a is a power control loop that controls and maintains the transmitter power magnitude P_{in} at or near the target power P_{target} by adjusting the inverter bus voltage V_{bus}. Loop 503a also incorporates adjustments to inverter frequency f_{inv} to control transmitter power. In some implementations, loops 501a and 503a are local loops that do not require communication with other devices (e.g., receiver 104) to be performed. In some implementations, loops 501a and 503a are executed by a transmitter at between 1 – 10 kHz.

[0143] Loop 505 is performed by a receiver 104 to tune a receiver IMN 126 based on system efficiency. Loop 505 is the same as loop 405 of process 400 the operation of which is described above.

[0144] Block 502 lists the inputs and initial conditions for process 500a which include a variable transmitter reactance X_{tx} (e.g., X3 of transmitter IMN 124), set to a maximum reactance value $X_{tx,max}$; a variable receiver reactance X_{rx} (e.g., X3 of receiver IMN 126), set to a minimum reactance value $X_{rx,min}$; an inverter frequency f_{inv}, set to a maximum frequency $f_{inv,max}$; a system efficiency η, initially set to zero; a transmitter reactance step size ΔX_{tx}, set to an adjustment value greater than zero; a receiver reactance step size ΔX_{rx}, set to an adjustment value greater than zero; an inverter frequency step size Δf_{inv} set to an adjustment value greater than zero; and a bus voltage step size ΔV_{bus} set to an adjustment value greater than zero. In some implementations, the reactance step sizes ΔX_{tx} and ΔX_{rx}, bus voltage step size ΔV_{bus}, and inverter frequency step size Δf_{inv} are constant values. In some implementations, the reactance step sizes ΔX_{tx} and ΔX_{rx}, bus voltage step size ΔV_{bus}, and inverter frequency step size

Δf_{inv} can be variable. For example, controller 125 or controller 129 can increase or decrease the magnitude of the respective step sizes dynamically during process 500a.

[0145] Process 500a starts at step 504. At step 506, transmitter controller 125 performs several checks while tuning the inverter frequency in step 508. Transmitter controller 125 compares the measured input power P_{in} to a target power level P_{target}, the measured inverter output phase φ_{inv} to an inverter output phase limit φ_{limit} (e.g., 45 degrees), and the inverter frequency f_{inv} to the minimum inverter frequency $f_{inv,min}$. When all of the comparisons in step 506 are true, then transmitter controller 125 decrements the inverter frequency f_{inv} by inverter frequency step size Δf_{inv} at step 508. If any of the comparisons are false, the process 500a proceeds to step 510 of loop 501a.

[0146] Referring to phase loop, loop 501a, if the inverter output phase is not equal to the target inverter output phase, at step 510 transmitter controller 125 compares the inverter output phase to the target inverter output phase, at step 536, to determine whether the inverter output phase is greater than the target inverter output phase. If φ_{inv} is greater than φ_{target}, then, at step 538, transmitter controller 125 performs several additional checks. At step 538, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a minimum value $X_{tx,min}$; whether P_{in} is greater than P_{target}, or whether a safety check has failed. The safety check can be, for example, an over voltage or over current check. If any of the checks are true, then loop 501a proceeds to an additional safety check at step 540. The safety check at step 540 can be the same safety check as performed at step 538, for example, to determine whether the safety check at step 538 was the check that caused the transmitter controller 125 to proceed to step 540. If so, then transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501a reverts back to step 506. If not, then loop 501a proceeds to step 512 of loop 503a to adjust the transmitter power. If all of the checks at step 538 are false, then transmitter controller 125 decrements the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501a reverts back to step 506.

[0147] Referring back to step 536, if φ_{inv} is not greater than φ_{target}, then, at step 546, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$. If the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$, then loop 501a issue a fault condition 548. If the variable transmitter reactance X_{tx} is not at a maximum value $X_{tx,max}$, then, at step 550,

transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501a reverts back to step 506.

[0148] Referring to the power loop, loop 503a, at step 512 transmitter controller 125 measures the input power P_{in}, and compares the measured input power P_{in} to a target power level P_{target}. If P_{in} equals P_{target} the process 500a reverts to step 506. In addition, transmitter controller 125 can send data indicating the measured value of P_{in} to the receiver 104. If P_{in} does not equal P_{target} process 500a proceeds to step 522. At step 522, transmitter controller 125 compares the input power to the target power level to determine whether the input power is greater than the target power level. If P_{in} is not greater than P_{target}, then, at step 534, transmitter controller 125 increments the inverter bus voltage V_{bus} by the bus voltage step size ΔV_{bus}, and loop 503a reverts back to step 506. If P_{in} is greater than P_{target}, then, at step 524, transmitter controller 125 checks the bus voltage. If the bus voltage V_{bus} is greater than a minimum bus voltage $V_{bus,min}$, then, at step 532, transmitter controller 125 decrements the inverter bus voltage V_{bus} by the bus voltage step size ΔV_{bus}, and loop 503a reverts back to step 506.

[0149] If, at step 524, the bus voltage V_{bus} is at a minimum bus voltage $V_{bus,min}$, then the transmitter controller 125 reduces the transmitter power by adjusting either the variable transmitter reactance X_{tx} or the inverter frequency f_{inv}. At step 526, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$. If the variable transmitter reactance X_{tx} is not at a maximum value $X_{tx,max}$, then, at step 530, transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501 reverts back to step 506. If the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$, then the transmitter controller 125 checks whether the inverter frequency f_{inv} is less than a maximum inverter frequency $f_{inv,max}$ at step 527. If the inverter frequency f_{inv} is already at a maximum value $f_{inv,max}$, then loop 503a reverts to step 506 with no adjustments to the bus voltage V_{bus}, the variable transmitter reactance X_{tx}, or the inverter frequency f_{inv}. If the inverter frequency f_{inv} is not already at a maximum value $f_{inv,max}$, then, at step 528, transmitter controller 125 increments the inverter frequency f_{inv} by the frequency step size Δf_{inv}, and loop 503a reverts back to step 506.

[0150] Referring to FIG. 5B, process 500b differs from process 500a by monitoring and controlling inverter phase shift θ_{inv} instead of inverter frequency f_{inv}. For example,

in some implementations, inverter power can be controlled by adjusting the internal phase shift θ_{inv} between bridge circuits in the inverter. In such implementations, a phase shift θ_{inv} of zero degrees may produce a minimum (e.g., zero) inverter power, and a phase shift θ_{inv} of 180 degrees may produce a maximum inverter power for a given bus voltage V_{bus}. More specifically, in process 500b steps 560, 562, 564, 566, and 568 replace steps 502, 506, 508, 527, and 528 of process 500a, respectively.

[0151] Process 500b includes portions that are be performed by a wireless power transmitter 102 (e.g., transmitter controller 125) and portions that are performed by a wireless power receiver 104 (e.g., receiver controller 129). Process 500b includes three control loops 501b, 503b, and 505. Loops 501b and 503b are performed by a transmitter 102 to tune a transmitter IMN 124 and to control the transmitter power. Loop 501b is a phase loop that tunes the transmitter IMN 124 by adjusting reactance X3 to achieve a target inverter output phase φ_{target}. Loop 501b also includes safety checks to ensure that current, voltage, or other device limitations are not exceeded. Loop 503b is a power control loop that controls and maintains the transmitter power magnitude P_{in} at or near the target power P_{target} by adjusting the inverter bus voltage V_{bus}. Loop 503b also incorporates adjustments to inverter phase shift θ_{inv} to control transmitter power. In some implementations, loops 501b and 503b are local loops that do not require communication with other devices (e.g., receiver 104) to be performed. In some implementations, loops 501b and 503b are executed by a transmitter at between 1 – 10 kHz.

[0152] Loop 505 is performed by a receiver 104 to tune a receiver IMN 126 based on system efficiency. Loop 505 is the same as loop 405 of process 400 the operation of which is described above.

[0153] Block 560 lists the inputs and initial conditions for process 500b which include a variable transmitter reactance X_{tx} (e.g., X3 of transmitter IMN 124), set to a maximum reactance value $X_{tx,max}$; a variable receiver reactance X_{rx} (e.g., X3 of receiver IMN 126), set to a minimum reactance value $X_{rx,min}$; an inverter phase shift θ_{inv}, set to a minimum phase shift $\theta_{inv,min}$; a system efficiency η, initially set to zero; a transmitter reactance step size ΔX_{tx}, set to an adjustment value greater than zero; a receiver reactance step size ΔX_{rx}, set to an adjustment value greater than zero; an inverter phase shift step size $\Delta\theta_{inv}$ set to an adjustment value greater than zero; and a bus voltage step size ΔV_{bus} set to an adjustment value greater than zero. In some implementations, the

reactance step sizes ΔX_{tx} and ΔX_{rx}, bus voltage step size ΔV_{bus}, and inverter phase shift step size $\Delta\theta_{inv}$ are constant values. In some implementations, the reactance step sizes ΔX_{tx} and ΔX_{rx}, bus voltage step size ΔV_{bus}, and inverter phase shift step size $\Delta\theta_{inv}$ can be variable. For example, controller 125 or controller 129 can increase or decrease the magnitude of the respective step sizes dynamically during process 500b.

[0154] Process 500b starts at step 504. At step 562, transmitter controller 125 performs several checks while tuning the inverter phase shift in step 564. Transmitter controller 125 compares the measured input power P_{in} to a target power level P_{target} and the inverter phase shift θ_{inv} to a phase shift limit θ_{limit} (e.g., 180 degrees). When all of the comparisons in step 564 are true, then transmitter controller 125 increments the inverter phase shift θ_{inv} by inverter phase shift step size $\Delta\theta_{inv}$ at step 564. If any of the comparisons are false, at step 582, transmitter controller 125 checks whether the inverter phase shift θ_{inv} is less than the phase shift limit θ_{limit}. If so, process 500b proceeds to step 566. If not, process 500b proceeds to step 510 of loop 501b.

[0155] Referring to phase loop, loop 501b, if the inverter output phase is not equal to the target inverter output phase, at step 510 transmitter controller 125 compares the inverter output phase to the target inverter output phase, at step 536, to determine whether the inverter output phase is greater than the target inverter output phase. If φ_{inv} is greater than φ_{target}, then, at step 538, transmitter controller 125 performs several additional checks. At step 538, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a minimum value $X_{tx,min}$; whether P_{in} is greater than P_{target}, or whether a safety check has failed. The safety check can be, for example, an over voltage or over current check. If any of the checks are true, then loop 501b proceeds to an additional safety check at step 540. The safety check at step 540 can be the same safety check as performed at step 538, for example, to determine whether the safety check at step 538 was the check that caused the transmitter controller 125 to proceed to step 540. If so, then transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501b reverts back to step 562. If not, then loop 501b proceeds to step 512 of loop 503b to adjust the transmitter power. If all of the checks at step 538 are false, then transmitter controller 125 decrements the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501b reverts back to step 562.

[0156] Referring back to step 536, if φ_{inv} is not greater than φ_{target}, then, at step 546, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$. If the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$, then loop 501b issue a fault condition 548. If the variable transmitter reactance X_{tx} is not at a maximum value $X_{tx,max}$, then, at step 550, transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501b reverts back to step 562.

[0157] Referring to the power loop, loop 503b, at step 512 transmitter controller 125 measures the input power P_{in}, and compares the measured input power P_{in} to a target power level P_{target}. If P_{in} equals P_{target} the process 500b reverts to step 562. In addition, transmitter controller 125 can send data indicating the measured value of P_{in} to the receiver 104. If P_{in} does not equal P_{target}, process 500b proceeds to step 522. At step 522, transmitter controller 125 compares the input power to the target power level to determine whether the input power is greater than the target power level. If P_{in} is not greater than P_{target}, then, at step 534, transmitter controller 125 increments the inverter bus voltage V_{bus} by the bus voltage step size ΔV_{bus}, and loop 503b reverts back to step 562. If P_{in} is greater than P_{target}, then, at step 524, transmitter controller 125 checks the bus voltage. If the bus voltage V_{bus} is greater than a minimum bus voltage $V_{bus,min}$, then, at step 532, transmitter controller 125 decrements the inverter bus voltage V_{bus} by the bus voltage step size ΔV_{bus}, and loop 503b reverts back to step 562.

[0158] If, at step 524, the bus voltage V_{bus} is at a minimum bus voltage $V_{bus,min}$, then the transmitter controller 125 reduces the transmitter power by adjusting either the variable transmitter reactance X_{tx} or the inverter phase shift θ_{inv}. At step 526, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$. If the variable transmitter reactance X_{tx} is not at a maximum value $X_{tx,max}$, then, at step 530, transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501b reverts back to step 562. If the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$, then the transmitter controller 125 checks whether the inverter phase shift θ_{inv} is greater than a minimum inverter phase shift $\theta_{inv,min}$ at step 566. If the inverter phase shift θ_{inv} is already at a minimum value $\theta_{inv,min}$, then loop 503b reverts to step 562 with no adjustments to the bus voltage V_{bus}, the variable transmitter reactance X_{tx}, or the inverter phase shift θ_{inv}. If the inverter phase shift θ_{inv} is not already at a

minimum value $\theta_{inv,min}$, then, at step 568, transmitter controller 125 decrements the inverter phase shift θ_{inv} by the phase shift step size $\Delta\theta_{inv}$, and loop 503b reverts back to step 562.

[0159] Referring to FIG. 5C, process 500c combines aspects of processes 500a and 500b. Process 500c includes portions that are be performed by a wireless power transmitter 102 (e.g., transmitter controller 125) and portions that are performed by a wireless power receiver 104 (e.g., receiver controller 129). Process 500c includes three control loops 501c, 503c, and 505. Loops 501c and 503c are performed by a transmitter 102 to tune a transmitter IMN 124 and to control the transmitter power. Loop 501c is a phase loop that tunes the transmitter IMN 124 by adjusting reactance X3 to achieve a target inverter output phase φ_{target}. Loop 501b also includes safety checks to ensure that current, voltage, or other device limitations are not exceeded. Loop 503c is a power control loop that controls and maintains the transmitter power magnitude P_{in} at or near the target power P_{target} by adjusting the inverter bus voltage V_{bus}. Loop 503c also incorporates adjustments to both inverter frequency f_{inv} and inverter phase shift θ_{inv} to control transmitter power. In some implementations, loops 501c and 503c are local loops that do not require communication with other devices (e.g., receiver 104) to be performed. In some implementations, loops 501c and 503c are executed by a transmitter at between 1 – 10 kHz.

[0160] Loop 505 is performed by a receiver 104 to tune a receiver IMN 126 based on system efficiency. Loop 505 is the same as loop 405 of process 400 the operation of which is described above.

[0161] Block 580 represents the inputs and initial conditions for process 500c which include a variable transmitter reactance X_{tx} (e.g., X3 of transmitter IMN 124), set to a maximum reactance value $X_{tx,max}$; a variable receiver reactance X_{rx} (e.g., X3 of receiver IMN 126), set to a minimum reactance value $X_{rx,min}$; an inverter frequency f_{inv}, set to a maximum frequency $f_{inv,max}$; an inverter phase shift θ_{inv}, set to a minimum phase shift $\theta_{inv,min}$; a system efficiency η, initially set to zero; a transmitter reactance step size ΔX_{tx}, set to an adjustment value greater than zero; a receiver reactance step size ΔX_{rx}, set to an adjustment value greater than zero; an inverter frequency step size Δf_{inv} set to an adjustment value greater than zero; an inverter phase shift step size $\Delta\theta_{inv}$ set to an adjustment value greater than zero; and a bus voltage step size ΔV_{bus} set to an adjustment value greater than zero. In some implementations, the reactance step sizes

ΔX_{tx} and ΔX_{rx}, bus voltage step size ΔV_{bus}, inverter frequency step size Δf_{inv}, and inverter phase shift step size $\Delta\theta_{inv}$ are constant values. In some implementations, the reactance step sizes ΔX_{tx} and ΔX_{rx}, bus voltage step size ΔV_{bus}, inverter frequency step size Δf_{inv}, and inverter phase shift step size $\Delta\theta_{inv}$ can be variable. For example, controller 125 or controller 129 can increase or decrease the magnitude of the respective step sizes dynamically during process 500c.

[0162] Process 500c starts at step 504. At step 562, transmitter controller 125 performs several checks while tuning the inverter phase shift in step 564. Transmitter controller 125 compares the measured input power P_{in} to a target power level P_{target} and the inverter phase shift θ_{inv} to a phase shift limit θ_{limit} (e.g., 180 degrees). When all of the comparisons in step 564 are true, then transmitter controller 125 increments the inverter phase shift θ_{inv} by inverter phase shift step size $\Delta\theta_{inv}$ at step 564. If any of the comparisons are false, at step 582, transmitter controller 125 checks whether the inverter phase shift θ_{inv} is less than the phase shift limit θ_{limit}. If so, process 500c proceeds to step 566. If not, process 500c proceeds to step 506.

[0163] At step 506, transmitter controller 125 performs several checks while tuning the inverter frequency in step 508. Transmitter controller 125 compares the measured input power P_{in} to a target power level P_{target}, the measured inverter output phase φ_{inv} to an inverter output phase limit φ_{limit} (e.g., 45 degrees), and the inverter frequency f_{inv} to the minimum inverter frequency $f_{inv,min}$. When all of the comparisons in step 506 are true, then transmitter controller 125 decrements the inverter frequency f_{inv} by inverter frequency step size Δf_{inv} at step 508. If any of the comparisons are false, the process 500a proceeds to step 510 of loop 501c.

[0164] Referring to phase loop, loop 501c, if the inverter output phase is not equal to the target inverter output phase, at step 510 transmitter controller 125 compares the inverter output phase to the target inverter output phase, at step 536, to determine whether the inverter output phase is greater than the target inverter output phase. If φ_{inv} is greater than φ_{target}, then, at step 538, transmitter controller 125 performs several additional checks. At step 538, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a minimum value $X_{tx,min}$; whether P_{in} is greater than P_{target}, or whether a safety check has failed. The safety check can be, for example, an over voltage or over current check. If any of the checks are true, then loop 501c proceeds to an additional safety check at step 540. The safety check at step 540 can be

the same safety check as performed at step 538, for example, to determine whether the safety check at step 538 was the check that caused the transmitter controller 125 to proceed to step 540. If so, then transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501c reverts back to step 562. If not, then loop 501c proceeds to step 512 of loop 503c to adjust the transmitter power. If all of the checks at step 538 are false, then transmitter controller 125 decrements the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501c reverts back to step 562.

[0165] Referring back to step 536, if φ_{inv} is not greater than φ_{target}, then, at step 546, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$. If the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$, then loop 501c issue a fault condition 548. If the variable transmitter reactance X_{tx} is not at a maximum value $X_{tx,max}$, then, at step 550, transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501c reverts back to step 562.

[0166] Referring to the power loop, loop 503b, at step 512 transmitter controller 125 measures the input power P_{in}, and compares the measured input power P_{in} to a target power level P_{target}. If P_{in} equals P_{target} the process 500c reverts to step 562. In addition, transmitter controller 125 can send data indicating the measured value of P_{in} to the receiver 104. If P_{in} does not equal P_{target} process 500c proceeds to step 522. At step 522, transmitter controller 125 compares the input power to the target power level to determine whether the input power is greater than the target power level. If P_{in} is not greater than P_{target}, then, at step 534, transmitter controller 125 increments the inverter bus voltage V_{bus} by the bus voltage step size ΔV_{bus}, and loop 503c reverts back to step 562. If P_{in} is greater than P_{target}, then, at step 524, transmitter controller 125 checks the bus voltage. If the bus voltage V_{bus} is greater than a minimum bus voltage $V_{bus,min}$, then, at step 532, transmitter controller 125 decrements the inverter bus voltage V_{bus} by the bus voltage step size ΔV_{bus}, and loop 503c reverts back to step 562.

[0167] If, at step 524, the bus voltage V_{bus} is at a minimum bus voltage $V_{bus,min}$, then the transmitter controller 125 reduces the transmitter power by adjusting either the variable transmitter reactance X_{tx}, the inverter frequency f_{inv}, or the inverter phase shift θ_{inv}. At step 526, transmitter controller 125 checks whether the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$. If the variable transmitter

reactance X_{tx} is not at a maximum value $X_{tx,max}$, then, at step 530, transmitter controller 125 increments the variable transmitter reactance X_{tx} by the transmitter reactance step size ΔX_{tx}, and loop 501c reverts back to step 562.

[0168] If the variable transmitter reactance X_{tx} is already at a maximum value $X_{tx,max}$, then the transmitter controller 125 checks whether the inverter frequency f_{inv} is less than a maximum inverter frequency $f_{inv,max}$ at step 527. If the inverter frequency f_{inv} is not already at a maximum value $f_{inv,max}$, then, at step 528, transmitter controller 125 increments the inverter frequency f_{inv} by the frequency step size Δf_{inv}, and loop 503c reverts back to step 562. If the inverter frequency f_{inv} is already at a maximum value $f_{inv,max}$, then the transmitter controller 125 checks whether the inverter phase shift θ_{inv} is greater than a minimum inverter phase shift $\theta_{inv,min}$ at step 566. If the inverter phase shift θ_{inv} is already at a minimum value $\theta_{inv,min}$, then loop 503c reverts to step 562 with no adjustments to the bus voltage V_{bus}, the variable transmitter reactance X_{tx}, or the inverter phase shift θ_{inv}. If the inverter phase shift θ_{inv} is not already at a minimum value $\theta_{inv,min}$, then, at step 568, transmitter controller 125 decrements the inverter phase shift θ_{inv} by the phase shift step size $\Delta\theta_{inv}$, and loop 503c reverts back to step 562.

[0169] In some implementations, the magnitude of the transmitter reactance step size ΔX_{tx} can be varied. For example, if the difference between φ_{inv} and φ_{target} is large, for example, greater than a coarse adjustment threshold value, then the transmitter controller 125 can increase the transmitter reactance step size ΔX_{tx}. Correspondingly, if the difference between φ_{inv} and φ_{target} is small, for example, less than a fine adjustment threshold value, then the transmitter controller 125 can decrease the magnitude of the transmitter reactance step size ΔX_{tx}.

[0170] In some implementations, the magnitude of the bus voltage step size ΔV_{bus} can be varied. For example, if the difference between P_{in} and P_{target} is large, for example, greater than a coarse adjustment threshold value, then the transmitter controller 125 can increase the bus voltage step size ΔV_{bus}. Correspondingly, if the difference between P_{in} and P_{target} is small, for example, less than a fine adjustment threshold value, then the transmitter controller 125 can decrease the magnitude of the bus voltage step size ΔV_{bus}.

[0171] In some implementations, the magnitude of the inverter frequency step size Δf_{inv} can be varied. For example, if the difference between P_{in} and P_{target}, in step 506, is large, for example, greater than a coarse adjustment threshold value, then the

transmitter controller 125 can increase the inverter frequency step size Δf_{inv}. Correspondingly, if the difference between P_{in} and P_{target} is small, for example, less than a fine adjustment threshold value, then the transmitter controller 125 can decrease the magnitude of inverter frequency step size Δf_{inv}.

[0172] In some implementations, the magnitude of the inverter phase shift step size $\Delta\theta_{inv}$ can be varied. For example, if the difference between P_{in} and P_{target}, in step 562, is large, for example, greater than a coarse adjustment threshold value, then the transmitter controller 125 can increase the inverter phase shift step size $\Delta\theta_{inv}$. Correspondingly, if the difference between P_{in} and P_{target} is small, for example, less than a fine adjustment threshold value, then the transmitter controller 125 can decrease the magnitude of inverter phase shift step size $\Delta\theta_{inv}$.

[0173] The following table (Table 1) shows experimental measurements of output voltage and efficiency (Eff.) for variations between relative positions of a wireless power transmitter and receiver for charging an electric vehicle operating according to processes described herein. Position X is the position of the receiver resonator coil relative to the transmitter resonator coil along the X-axis, where the X-axis runs along a width of the vehicle (e.g., driver door to passenger door), and where X = 0 is the center of transmitter resonator coil. Position Y is the position of the receiver resonator coil relative to the transmitter resonator coil along the Y-axis, where the Y-axis runs along a length of the vehicle (e.g., front of the vehicle to the rear of the vehicle), and where Y= 0 is the center of the transmitter resonator coil. Position Z is the separation distance between the receiver resonator coil and the transmitter resonator coil along the vertical Z-axis.

Table 1

Z (mm)	X (mm)	Y (mm)	Vout (V)	Eff (%)
160	0	0	280	94.01
160	0	0	350	94.46
160	0	0	420	94.42
160	100	75	280	94.03
160	100	75	350	94.32
160	100	75	420	93.84

160	150	75	280	93.74
160	150	75	350	94.08
160	150	75	420	93.56
190	0	0	280	94.14
190	0	0	350	94.50
190	0	0	420	94.19
190	100	75	280	93.81
190	100	75	350	93.75
190	100	75	420	93.11
190	150	75	280	93.10
190	150	75	350	93.10
190	150	75	420	91.86
220	0	0	280	93.97
220	0	0	350	94.03
220	0	0	420	93.27
220	100	75	280	92.82
220	100	75	350	92.52

[0174] FIG. 6A depicts a flowchart of an exemplary startup process 600 for a wireless power transmission control system. In some examples, the process 600 can be provided as computer-executable instructions executed using one or more processing devices (e.g., processors or microcontrollers) or computing devices. In some examples, the process 600 may be executed by hardwired electrical circuitry, for example, as an ASIC or an FPGA controller. Some portions of process 600 can be be performed by a wireless power transmitter 102 (e.g., transmitter controller 125) and some portions of process 600 can be performed by a wireless power receiver 104 (e.g., receiver controller 129).

[0175] Block 602 lists the inputs and initial conditions for the system startup process 600 which include a power factor correction (PFC) stage of a transmitter set to OFF; an inverter pulse width modulation (PWM) set to OFF; an inverter frequency f_{inv} set to a maximum frequency $f_{inv,max}$; a variable transmitter reactance X_{tx} (e.g., X3 of transmitter IMN 124) set to a maximum reactance value $X_{tx,max}$; and a variable receiver

reactance Xrx (e.g., X3 of receiver IMN 126) set to a maximum reactance value $X_{rx,max}$. The startup process 600 begins at step 604, the PFC is turned ON and bus voltage V_{bus} is brought to minimum bus voltage $V_{bus,min}$. At step 606, the inverter PWMs are turned ON. At step 608, variable receiver reactance X_{rx} is adjusted to minimum receiver reactance $X_{rx,min}$. At step 610, inverter frequency f_{inv} is adjusted to target inverter frequency $f_{inv,target}$. At step 612, the system begins steady state operations, e.g., according to one of processes 300, 400, 500a, 500b, or 500c.

[0176] FIG. 6A depicts a flowchart of an exemplary shutdown process 601 for a wireless power transmission control system m. In some examples, the process 601 can be provided as computer-executable instructions executed using one or more processing devices (e.g., processors or microcontrollers) or computing devices. In some examples, the process 601 may be executed by hardwired electrical circuitry, for example, as an ASIC or an FPGA controller. Some portions of process 601 can be performed by a wireless power transmitter 102 (e.g., transmitter controller 125) and some portions of process 601 can be performed by a wireless power receiver 104 (e.g., receiver controller 129).

[0177] Shutdown process 601 begins, at step 612, with the system in steady state operation, e.g., according to one of processes 300, 400, 500a, 500b, or 500c. At step 614, variable receiver reactance X_{rx} is brought to minimum receiver reactance $X_{rx,min}$. At step 616, variable transmitter reactance X_{tx} is brought to maximum transmitter reactance $X_{tx,max}$, and at step 618, bus voltage V_{bus} is brought to minimum bus voltage $V_{bus,min}$. In some implementations, steps 616 and 618 can be performed directly by a transmitter. In some implementations, steps 616 and 618 can be performed indirectly. For example, steps 616 and 618 will be performed automatically as part of the steady state operations of processes 500a, 500b, and 500c (steps 524, 532, 526, and 530) simply be adjusting the target power P_{target} to a shutdown value $P_{shutdown}$ at step 615. For example, $P_{shutdown}$ can be zero or near zero. As P_{target} is decreased, the variable transmitter reactance X_{tx} is brought to maximum transmitter reactance $X_{tx,max}$ and bus voltage V_{bus} is brought to minimum bus voltage $V_{bus,min}$ by the steady state transmitter operations process. At step 620, the PFC is turned OFF and V_{bus} is brought to 0 V. At step 622, the inverter PWMs are turned off. In some implementations, the wireless communication between the receiver and transmitter may be remain on or be turned off after power transmission is secured.

[0178] While the disclosed techniques have been described in connection with certain preferred embodiments, other embodiments will be understood by one of ordinary skill in the art and are intended to fall within the scope of this disclosure. For example, designs, methods, configurations of components, etc. related to transmitting wireless power have been described above along with various specific applications and examples thereof. Those skilled in the art will appreciate where the designs, components, configurations or components described herein can be used in combination, or interchangeably, and that the above description does not limit such interchangeability or combination of components to only that which is described herein.

[0179] For illustrative purposes, the foregoing description focuses on the use of devices, components, and methods in high power wireless power transfer applications, e.g., power transfer for charging electric vehicles.

[0180] More generally, however, it should be understood that devices that can receive power using the devices, components, and methods disclosed herein can include a wide range of electrical devices, and are not limited to those devices described for illustrative purposes herein. In general, any portable electronic device, such as a cell phone, keyboard, mouse, radio, camera, mobile handset, headset, watch, headphones, dongles, multifunction cards, food and drink accessories, and the like, and any workspace electronic devices such as printers, clocks, lamps, headphones, external drives, projectors, digital photo frames, additional displays, and the like, can receive power wirelessly using the devices, components, and methods disclosed herein. Furthermore, any electrical device, such as electric or hybrid vehicles, motorized wheel chairs, scooters, power tools, and the like, can receive power wirelessly using the devices, components, and methods disclosed herein. In addition, the devices, components, and methods disclosed herein may be used for applications outside of wireless power transfer.

[0181] In this disclosure, certain circuit or system components such as capacitors, inductors, resistors, are referred to as circuit "components" or "elements." The disclosure also refers to series and parallel combinations of these components or elements as elements, networks, topologies, circuits, and the like. More generally, however, where a single component or a specific network of components is described herein, it should be understood that alternative embodiments may include networks for elements, alternative networks, and/or the like.

[0182] As used herein, the equalities and inequalities when referring to comparisons between transmitter or receiver operating parameters is not intended to require exact equivalence of values, but instead refers to an equivalence of values that are within a threshold or a tolerance of one another. For example, measured values such as powers, voltages, currents, and phases can be represented and stored as floating point numbers. As such, exact equivalence may be unlikely deepening on the precision of the measurements. Therefore, equivalence between such numbers and target values refers to equivalence within a threshold range, for example, equivalence within a tolerance of ±1%, ±2%, ±5%, or ±10% of the target value. Similarly, inequalities may require a measured value to be greater or less than a target value by an additional ±1%, ±2%, ±5%, or ±10% of the target value.

[0183] As used herein, the term "coupled" when referring to circuit or system components is used to describe an appropriate, wired or wireless, direct or indirect, connection between one or more components through which information or signals can be passed from one component to another.

[0184] As used herein, the term "direct connection" or "directly connected," refers to a direct connection between two elements where the elements are connected with no intervening active elements between them. The term "electrically connected" or "electrical connection," refers to an electrical connection between two elements where the elements are connected such that the elements have a common potential. In addition, a connection between a first component and a terminal of a second component means that there is a path between the first component and the terminal that does not pass through the second component.

[0185] Implementations of the subject matter and the operations described in this specification can be realized in digital electronic circuitry, or in computer software, firmware, or hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of one or more of them. Implementations of the subject matter described in this specification can be realized using one or more computer programs, i.e., one or more modules of computer program instructions, encoded on computer storage medium for execution by, or to control the operation of, data processing apparatus. Alternatively or in addition, the program instructions can be encoded on an artificially generated propagated signal, e.g., a machine-generated electrical, optical, or electromagnetic signal that is generated to encode information for

transmission to suitable receiver apparatus for execution by a data processing apparatus. A computer storage medium can be, or be included in, a computer-readable storage device, a computer-readable storage substrate, a random or serial access memory array or device, or a combination of one or more of them. Moreover, while a computer storage medium is not a propagated signal; a computer storage medium can be a source or destination of computer program instructions encoded in an artificially generated propagated signal. The computer storage medium can also be, or be included in, one or more separate physical components or media (e.g., multiple CDs, disks, or other storage devices).

[0186] The operations described in this specification can be implemented as operations performed by a data processing apparatus on data stored on one or more computer-readable storage devices or received from other sources.

[0187] The term "data processing apparatus" encompasses all kinds of apparatus, devices, and machines for processing data, including by way of example a programmable processor, a computer, a system on a chip, or multiple ones, or combinations, of the foregoing. The apparatus can include special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application-specific integrated circuit). The apparatus can also include, in addition to hardware, code that creates an execution environment for the computer program in question, e.g., code that constitutes processor firmware, a protocol stack, a database management system, an operating system, a cross-platform runtime environment, a virtual machine, or a combination of one or more of them. The apparatus and execution environment can realize various different computing model infrastructures, such as web services, distributed computing and grid computing infrastructures.

[0188] A computer program (also known as a program, software, software application, script, or code) can be written in any form of programming language, including compiled or interpreted languages, declarative or procedural languages, and it can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, object, or other unit suitable for use in a computing environment. A computer program may, but need not, correspond to a file in a file system. A program can be stored in a portion of a file that holds other programs or data (e.g., one or more scripts stored in a markup language document), in a single file dedicated to the program in question, or in multiple coordinated files (e.g., files that

store one or more modules, sub-programs, or portions of code). A computer program can be deployed to be executed on one computer or on multiple computers that are located at one site or distributed across multiple sites and interconnected by a communication network.

[0189] The processes and logic flows described in this specification can be performed by one or more programmable processors executing one or more computer programs to perform actions by operating on input data and generating output. The processes and logic flows can also be performed by, and apparatus can also be implemented as, special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application-specific integrated circuit).

[0190] Processors suitable for the execution of a computer program include, by way of example, both general and special purpose microprocessors, and any one or more processors of any kind of digital computer. Generally, a processor will receive instructions and data from a read-only memory or a random access memory or both. Elements of a computer can include a processor for performing actions in accordance with instructions and one or more memory devices for storing instructions and data. Generally, a computer will also include, or be operatively coupled to receive data from or transfer data to, or both, one or more mass storage devices for storing data, e.g., magnetic, magneto-optical disks, or optical disks. However, a computer need not have such devices. Moreover, a computer can be embedded in another device, e.g., a wireless power transmitter or receiver or a wirelessly charged or powered device such as a vehicle, a mobile telephone, a personal digital assistant (PDA), a mobile audio or video player, a game console, or a Global Positioning System (GPS) receiver, to name just a few. Devices suitable for storing computer program instructions and data include all forms of non-volatile memory, media and memory devices, including by way of example semiconductor memory devices, e.g., EPROM, EEPROM, and flash memory devices; magnetic disks, e.g., internal hard disks or removable disks; magneto-optical disks; and CD-ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

[0191] While this specification contains many specific implementation details, these should not be construed as limitations on the scope of any implementation of the present disclosure or of what may be claimed, but rather as descriptions of features specific to example implementations. Certain features that are described in this

specification in the context of separate implementations can also be implemented in combination in a single implementation. Conversely, various features that are described in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable sub-combination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a sub-combination or variation of a sub-combination.

[0192] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products.

What is claimed is:

1. A wireless energy transfer system comprising:

an energy transmitter comprising a transmitter-impedance matching network (IMN), the transmitter configured to perform operations comprising:

performing a first comparison between a characteristic of a power of the transmitter and a target power; and

adjusting, based on the first comparison, a reactance of the transmitter-IMN to adjust the power of the transmitter; and

an energy receiver comprising a receiver-IMN, the receiver configured to perform operations comprising;

determining an efficiency of the wireless energy transfer system at a second time based on power data from the transmitter;

performing a second comparison between the efficiency at the second time and an efficiency of the wireless energy transfer system at a first time, the first time being prior to the second time; and

adjusting, based on the second comparison, a reactance of the receiver-IMN.

2. The system of claim 1, wherein adjusting the reactance of the receiver-IMN comprises adjusting the reactance of the receiver-IMN by a variable reactance adjustment value.

3. The system of any preceding claim, wherein the first comparison and adjustment to the reactance of the transmitter-IMN occur iteratively until the characteristic of the power is within a threshold value of the target power.

4. The system of any preceding claim, wherein adjusting the reactance of the receiver-IMN comprises in response to the efficiency at the second time being less than the efficiency at the first time, negating a reactance adjustment value, and wherein adjusting the reactance of the receiver-IMN comprises adjusting the reactance of the receiver-IMN by the negated reactance adjustment value.

5. The system of any one of claims 1 to 3, wherein adjusting the reactance of the transmitter-IMN comprises in response to the power being less than the target power, adjusting the reactance of the transmitter-IMN by a first reactance adjustment value and in response to the power being greater than the target power, adjusting the reactance of the transmitter-IMN by a second, different reactance adjustment value.

6. The system of claim 5, wherein the first reactance adjustment value is equal in magnitude and opposite in sign to the second reactance adjustment value

7. The system of any preceding claim, wherein the first comparison is between a power factor of the power of the transmitter and a target power factor, and wherein the operations of the transmitter further comprise:

a third comparison between a magnitude of the power and a target power magnitude, wherein the third comparison follows the first comparison; and

adjusting, based on the third comparison, a bus voltage of the transmitter to adjust the power of the transmitter.

8. The system of claim 7, wherein the power factor is represented by a phase relationship between a transmitter voltage and a transmitter current.

9. The system of any one of claims 7 and 8, wherein the first comparison and adjustment of the reactance of the transmitter-IMN based on the first comparison occur iteratively until the power factor of the power is within a threshold value of the target power factor.

10. The system of any one of claims 7 to 9, wherein the steps of performing the first comparison and adjusting the reactance of the transmitter-IMN are iterated at a faster rate than the steps of performing the third comparison and adjusting the bus voltage.

11. The system of any preceding claim, wherein the transmitter is an electric vehicle charger and wherein the receiver is a coupled to a power system of an electric vehicle.

12. The system of any preceding claim, wherein the operations of the transmitter further comprise shutting down the wireless energy transfer system by reducing the target power to zero.

13. The system of any preceding claim, wherein the operations of the transmitter further comprise shutting down a power inverter in the transmitter.

14. The system of any preceding claim, wherein the operations of the transmitter further comprise starting up the transmitter by adjusting the reactance of the transmitter-IMN to a maximum value.

15. The system of any preceding claim, wherein the operations of the transmitter further comprise starting up the transmitter by adjusting a frequency of an inverter to a target frequency.

16. The system of any preceding claim, wherein the operations of the receiver further comprise starting up the receiver by adjusting the reactance of the receiver-IMN to a minimum value.

17. The system of any preceding claim, wherein the operations of the receiver further comprise starting up the receiver by adjusting the reactance of the receiver-IMN from a maximum value to a minimum value.

18. The system of any preceding claim, wherein the transmitter-IMN comprises a tunable reactive element electrically connected between an inverter and at least one fixed reactive element, and wherein adjusting the reactance of the transmitter-IMN comprises adjusting the tunable reactive element.

19. The system of any preceding claim, wherein the receiver-IMN comprises a tunable reactive element electrically connected between a rectifier and at least one fixed reactive element, and wherein adjusting the reactance of the receiver-IMN comprises adjusting the tunable reactive element.

20. The system of any preceding claim, wherein the steps of performing the first comparison and adjusting the reactance of the transmitter-IMN are iterated at a faster rate than the steps of performing the second comparison and adjusting the reactance of the receiver-IMN.

21. The system of any preceding claim, wherein determining the efficiency of the wireless energy transfer system comprises:

receiving power data from the transmitter;

determining an output power of the receiver; and

calculating the efficiency of the wireless energy transfer system based on the power data from the transmitter and the output power of the receiver.

22. The system of any preceding claim, wherein the operations of the transmitter further comprise:

performing a plurality of checks comprising a check of a magnitude of the power, a check of a power factor of the power, and a check of a frequency of an inverter in the transmitter; and

in response to the plurality checks, selectively adjusting the frequency of the inverter to adjust the power of the transmitter.

23. The system of any preceding claim, wherein the operations of the transmitter further comprise:

performing a plurality of checks comprising a check of a magnitude of the power and a check of a phase shift of an inverter of the transmitter; and

in response to the plurality checks, selectively adjusting the phase shift of the inverter to adjust the power of the transmitter.

24. The system of any one of claims 7 to 10, wherein the operations of the transmitter further comprise, before adjusting the bus voltage, verifying that the bus voltage is greater than a minimum bus voltage.

25. The system of any preceding claim, wherein the first comparison is between a power factor of the power of the transmitter and a target power factor, and wherein the operations of the transmitter further comprise:

performing a third comparison between a magnitude of the power and a target power magnitude; and

adjusting, based on the third comparison, the reactance of the transmitter-IMN to reduce the power of the transmitter.

26. The system of any one of claims 1 to 24, wherein the first comparison is between a power factor of the power of the transmitter and a target power factor, and wherein the operations of the transmitter further comprise:

performing a third comparison between a magnitude of the power and a target power magnitude; and

adjusting, based on the third comparison, a frequency of an inverter of the transmitter to reduce the power of the transmitter.

27. The system of any one of claims 1 to 24, wherein the first comparison is between a power factor of the power of the transmitter and a target power factor, and wherein the operations of the transmitter further comprise:

performing a third comparison between a magnitude of the power and a target power magnitude; and

adjusting, based on the third comparison, a phase shift of an inverter of the transmitter to reduce the power of the transmitter.

28. A wireless energy transmitter comprising a transmitter-impedance matching network (IMN), the transmitter configured to perform operations comprising:

performing a first comparison between a characteristic of a power of the transmitter and a target power;

adjusting, based on the first comparison, a reactance of the transmitter-IMN to adjust the power of the transmitter; and

transmitting power data that indicates the power of the transmitter to a wireless energy receiver.

29. The transmitter of claim 28, wherein the first comparison and adjustment to the reactance of the transmitter-IMN occur iteratively until the characteristic of the power is within a threshold value of the target power.

30. The transmitter of any one of claims 28 and 29, wherein adjusting the reactance of the transmitter-IMN comprises, in response to the power being less than the target power, adjusting the reactance of the transmitter-IMN by a first reactance adjustment value and in response to the power being greater than the target power, adjusting the reactance of the transmitter-IMN by a second, different reactance adjustment value.

31. The transmitter of claim 30, wherein the first reactance adjustment value is equal in magnitude and opposite in sign to the second reactance adjustment value

32. The transmitter of any one of claims 28-31, wherein the first comparison is between a power factor of the power of the transmitter and a target power factor, and wherein the operations of the transmitter further comprise:

a third comparison between a magnitude of the power and a target power magnitude, wherein the third comparison follows the first comparison; and

adjusting, based on the third comparison, a bus voltage of the transmitter to adjust the power of the transmitter.

33. The transmitter of claim 32, wherein the power factor is represented by a phase relationship between a transmitter voltage and a transmitter current.

34. The transmitter of any one of claims 32 and 33, wherein the first comparison and adjustment of the reactance of the transmitter-IMN based on the first comparison occur iteratively until the power factor of the power is within a threshold value of the target power factor.

35. The transmitter of any one of claims 32 to 34, wherein the steps of performing the first comparison and adjusting the reactance of the transmitter-IMN are iterated at a

faster rate than the steps of performing the third comparison and adjusting the bus voltage.

36. The transmitter of any one of claims 28 to 35, wherein the transmitter is an electric vehicle charger.

37. The transmitter of any one of claims 28 to 36, wherein the operations of the transmitter further comprise shutting down the wireless energy transfer system by reducing the target power to zero.

38. The transmitter of any one of claims 28 to 37, wherein the operations of the transmitter further comprise shutting down a power inverter in the transmitter.

39. The transmitter of any one of claims 28 to 38, wherein the operations of the transmitter further comprise starting up the transmitter by adjusting the reactance of the transmitter-IMN to a maximum value.

40. The transmitter of any one of claims 28 to 39, wherein the operations of the transmitter further comprise starting up the transmitter by adjusting a frequency of an inverter to a target frequency.

41. The transmitter of any one of claims 28 to 40, wherein the transmitter-IMN comprises a tunable reactive element electrically connected between an inverter and at least one fixed reactive element, and wherein adjusting the reactance of the transmitter-IMN comprises adjusting the tunable reactive element.

42. The transmitter of any one of claims 28 to 41, wherein the transmitter further comprises an inductive coil coupled to at least portion of the transmitter-IMN to form a transmitter resonator.

43. The transmitter of any one of claims 28 to 42, wherein the operations of the transmitter further comprise:

performing a plurality of checks comprising a check of a magnitude of the power, a check of a power factor of the power, and a check of a frequency of an

inverter in the transmitter; and

in response to the plurality checks, selectively adjusting the frequency of the inverter to adjust the power of the transmitter.

44. The transmitter of any one of claims 28 to 43, wherein the operations of the transmitter further comprise:

performing a plurality of checks comprising a check of a magnitude of the power and a check of a phase shift of an inverter of the transmitter; and

in response to the plurality checks, selectively adjusting the phase shift of the inverter to adjust the power of the transmitter.

45. The transmitter of any one of claims 32 to 35, wherein the operations of the transmitter further comprise, before adjusting the bus voltage, verifying that the bus voltage is greater than a minimum bus voltage.

46. The transmitter of any one of claims 28 to 45, wherein the first comparison is between a power factor of the power of the transmitter and a target power factor, and wherein the operations of the transmitter further comprise:

a third comparison between a magnitude of the power and a target power magnitude;

adjusting, based on the third comparison, the reactance of the transmitter-IMN to reduce the power of the transmitter.

47. The transmitter of any one of claims 28 to 45, wherein the first comparison is between a power factor of the power of the transmitter and a target power factor, and wherein the operations of the transmitter further comprise:

a third comparison between a magnitude of the power and a target power magnitude;

adjusting, based on the third comparison, a frequency of an inverter of the transmitter to reduce the power of the transmitter.

48. The transmitter of any one of claims 28 to 45, wherein the first comparison is between a power factor of the power of the transmitter and a target power factor, and wherein the operations of the transmitter further comprise:

a third comparison between a magnitude of the power and a target power magnitude;

adjusting, based on the third comparison, a phase shift of an inverter of the transmitter to reduce the power of the transmitter.

49. A wireless energy receiver comprising a receiver-impedance matching network (IMN), the receiver configured to perform operations comprising:

determining an efficiency of a wireless energy transfer system at a second time based on power data from a wireless energy transmitter;

performing a second comparison between the efficiency at the second time and an efficiency of the wireless energy transfer system at a first time, the first time being prior to the second time; and

adjusting, based on the second comparison, a reactance of the receiver-IMN.

50. The receiver of claim 49, wherein adjusting the reactance of the receiver-IMN comprises adjusting the reactance of the receiver-IMN by a variable reactance adjustment value.

51. The receiver of any one of claims 49 and 50, wherein adjusting the reactance of the receiver-IMN comprises, in response to the efficiency at the second time being less than the efficiency at the first time, negating a reactance adjustment value, and wherein adjusting the reactance of the receiver-IMN comprises adjusting the reactance of the receiver-IMN by the negated reactance adjustment value.

52. The receiver of any one of claims 49 and 551, wherein the receiver is a coupled to a power system of an electric vehicle.

53. The receiver of any one of claims 49 and 53, wherein the operations of the receiver further comprise starting up the receiver by adjusting the reactance of the receiver-IMN to a minimum value.

54. The receiver of any one of claims 49 and 53, wherein the operations of the receiver further comprise starting up the receiver by adjusting the reactance of the receiver-IMN from a maximum value to a minimum value.

55. The receiver of any one of claims 49 and 54, wherein the receiver-IMN comprises a tunable reactive element electrically connected between a rectifier and at least one fixed reactive element, and wherein adjusting the reactance of the receiver-IMN comprises adjusting the tunable reactive element.

56. The receiver of any one of claims 49 and 55, wherein determining the efficiency of the wireless energy transfer system comprises:

receiving power data from the transmitter;

determining an output power of the receiver; and

calculating the efficiency of the wireless energy transfer system based on the power data from the transmitter and the output power of the receiver.

57. The receiver of any one of claims 49 and 56, wherein the receiver further comprises an inductive coil coupled to at least portion of the receiver-IMN to form a receiver resonator.

58. A method of operating a wireless energy transfer system comprising:

tuning, by a wireless energy transmitter, a transmitter impedance matching network (IMN) of the wireless energy transmitter to achieve a target transmitter power characteristic;

sending, by the wireless energy transmitter, power data that indicates the power of the transmitter to a wireless energy receiver;

tuning, by the wireless energy receiver and based on the power data, the receiver-IMN to improve an efficiency of the wireless energy transfer system.

59. The method of claim 58, wherein the target transmitter power characteristic is a target power factor and the target transmitter power characteristic is a target power factor.

60. The method of claim 59, wherein the power factor is represented by a phase difference between a transmitter voltage and a transmitter current, and wherein the target power factor is a target phase difference.

61. The method of any one of claims 58 to 60, further comprising adjusting an inverter bus voltage to achieve a target power magnitude.

62. The method of any one of claims 58 to 61, further comprising adjusting an inverter bus voltage to achieve a target power magnitude.

63. The method of any one of claims 58 to 62, further comprising performing a safety check prior to adjusting the transmitter-IMN.

64. The method of claim 63, wherein the safety check is an over-voltage check or an over-current check.

65. The method of any one of claims 58 to 64, further comprising:

performing, by the transmitter, a plurality of checks comprising a check of a magnitude of a transmitter power, a check of a transmitter power factor, and a check of a frequency of an inverter in the transmitter; and

in response to the plurality checks, selectively adjusting the frequency of the inverter to adjust the power of the transmitter.

66. The method of any one of claims 58 to 65, further comprising:

performing a plurality of checks comprising a check of a magnitude of a transmitter power and a check of a phase shift of an inverter of the transmitter; and

in response to the plurality checks, selectively adjusting the phase shift of the inverter to adjust the power of the transmitter.

67. The method of any one of claims 58 to 66, wherein the transmitter is an electric vehicle charger and wherein the receiver is a coupled to a power system of an electric vehicle.

68. The method of any one of claims 58 to 67, further comprising adjusting, while starting up the transmitter, the reactance of the transmitter-IMN to a maximum value.

69. The method of any one of claims 58 to 68, further comprising adjusting, while starting up the receiver, the reactance of the receiver-IMN to a minimum value.

70. A wireless power transmission system without bus voltage control configured to implement a control loop for tuning power transmission, wherein the control loop includes:

a first sub-loop (305) to control output power of a transmitter of the wireless power transmission system; and

a second sub-loop (303) to tune a combined reactance of an inductor (L3d) and a capacitor (C3d) that couple a tank circuit to a rectifier in a receiver of the wireless power transmission system, wherein the second sub-loop (303) tunes the combined reactance by monitoring efficiency of wireless power transmission.

71. The wireless power transmission system of claim 70, wherein the second sub-loop (303) employs a perturb-and-observe strategy to improve efficiency based on a previous point by tuning the combined reactance of an inductor (L3d 150) and a capacitor (C3d 148) that couple a tank circuit to a rectifier in a receiver of the wireless power transmission system.

72. The wireless power transmission system of any one of claims 70 and 71, wherein the second sub-loop (303) is dependent on a power comparison (A06) where output power is compared to target power at a start of the control loop.

73. The wireless power transmission system of any one of claims 70 to 72, wherein the second sub-loop (303) operates at the rate of communication, for example, 40 Hz.

74. The wireless power transmission system of any one of claims 70 to 73, wherein the control loop is characterized by:

$$P_{inv} = \frac{\frac{8}{\pi^2} V_{bus}^2}{R_{inv}^2 + X_{inv}^2} R_{inv}$$

where P_{inv} is power out of an inverter of the transmitter of the wireless power transmission system,

V_{bus} is bus voltage,

R_{inv} is resistance seen by the inverter, and

X_{inv} is reactance seen by the inverter,

wherein the tuning occurs at X_{inv} = the combined reactance of the inductor (L3d 150) and the capacitor (C3d 148).

75. The wireless power transmission system of any one of claims 70 to 74, first sub-loop (305) is a local loop that does not communicate with another part of the wireless power transmission system.

76. The wireless power transmission system of any one of claims 70 to 75, wherein the first sub-loop (305) is faster than the second sub-loop (303), for example, wherein the first sub-loop (305) is on order of 1 to 10 kHz.

77. The wireless power transmission system of any one of claims 70 to 76, wherein the control loop includes preparing inputs (302), including:

setting transmitter reactance to a maximum value;

setting receiver reactance to a minimum value;

wherein the efficiency of wireless power transmission at time zero = 0 and receiver reactance is to be changed by a constant or variable value.

78. The wireless power transmission system of any one of claims 70 to 77, wherein the control loop starts by comparing (306) output power to target power.

79. The wireless power transmission system of claim 78, wherein if the output power equals the target power within a tolerance, then:

efficiency is measured (308) at a time n;

the efficiency at time n is compared (310) to efficiency at a previous time n-1;

if the efficiency at time n is greater than the efficiency at the previous time n-1,

then a change in receiver reactance is added (312) to the receiver reactance and the output power is compared to the target power;

if efficiency at time n is equal to or less than the efficiency at the previous time n-1, then a change in receiver reactance is negated (314), the negated change is added (312) to the receiver reactance, and the output power is compared (306) to the target power.

80. The wireless power transmission system of claim 78, wherein if the output power does not equal the target power within a tolerance, then:

it is determined (316) whether the output power is less than the target power;

if the output power is less than the target power, then a change in transmitter reactance is set (318) to –δ, the change in transmitter reactance is added (320) to the transmitter reactance, and the output power is compared (306) to the target power;

if the output power is greater than the target power, then the change in transmitter reactance is set (322) to δ, the change in transmitter reactance is added (320) to the transmitter reactance, and the output power is compared (306) to the target power.

81. A wireless power transmission system with bus voltage control configured to implement a control loop for tuning power transmission, wherein the control loop includes:

a first sub-loop (401) to control phase as defined: $\varphi = \arctan(X_{inverter}/R_{inverter})$.;

a second sub-loop (403) to control output power; and

a third sub-loop (405) to tune a combined reactance of an inductor (L3d 150) and a capacitor (C3d 148) that couple a tank circuit to a rectifier in a receiver of the wireless power transmission system by monitoring efficiency.

82. The wireless power transmission system of claim 81, wherein the third sub-loop (405) employs a perturb-and-observe strategy to improve efficiency based on a previous point by tuning the combined reactance of an inductor (L3d) and a capacitor (C3d).

83. The wireless power transmission system of any one of claims 81 and 82, wherein the third sub-loop (405) is dependent on a power comparison (408) and thus on the second sub-loop (403).

84. The wireless power transmission system of any one of claims 81 to 83, wherein the third sub-loop (405) operates at a rate of communication, for example, 40 Hz (speed of WiFi).

85. The wireless power transmission system of any one of claims 81 to 84, wherein the control loop (400) can be characterized by:

$$P_{inv} = \frac{\frac{8}{\pi^2} V_{bus}^2}{R_{inv}^2 + X_{inv}^2} R_{inv}$$

where

P_{inv} is power output from an inverter of the transmitter of the wireless power transmission system,

V_{bus} is bus voltage,

R_{inv} is resistance seen by the inverter, and

X_{inv} is the reactance seen by the inverter,

wherein tuning occurs at both V_{bus} and X3 = X_{inv}.

86. The wireless power transmission system of any one of claims 81 to 85, wherein the first sub-loop (401) is adjusted first, the second sub-loop (403) is then adjusted, and the third sub-loop (405) is then adjusted.

87. The wireless power transmission system of any one of claims 81 to 86, wherein the first sub-loop (401) runs on the order of 1 to 10 kHz.

88. The wireless power transmission system of any one of claims 81 to 87, wherein the first sub-loop (401) is a local loop and does not communicate with another part of the wireless power transmission system.

89. The wireless power transmission system of any one of claims 81 to 88, wherein the second sub-loop (403) is a local loop and does not communicate with another part of the wireless power transmission system.

90. The wireless power transmission system of any one of claims 81 to 89, wherein the second sub-loop (403) runs on the order of 1 to 10 kHz.

91. The wireless power transmission system of any one of claims 81 to 90, wherein the control loop includes preparing inputs (402), including:
setting transmitter reactance to a maximum value;
setting receiver reactance to a minimum value;
wherein the efficiency of wireless power transmission at time zero = 0, the receiver reactance is to be increased, the transmitter reactance is to be increased, the bus voltage is to be increased, and phase is to be increased.

92. The wireless power transmission system of any one of claims 81 to 91, wherein the control loop includes:
comparing a phase measured at the inverter to a target phase;
if the phase measured at the inverter equals the target phase, then output power is compared to target power.

93. The wireless power transmission system of any one of claims 81 to 92, wherein the third sub-loop (405) occurs if the output power equals the target power and includes: measuring (410) efficiency at a time n, comparing (412) efficiency at the time n to efficiency at a previous time n-1, if the efficiency at the time n is greater than the efficiency at the previous time n-1 then receiver reactance is incremented (414) whereas if the efficiency at the time n is less than or equal to the efficiency at the previous time n-1, then change in the receiver reactance is negated (416) and the negated value is added (414) to the receiver reactance.

94. The wireless power transmission system of any one of claims 81 to 93, wherein the second sub-loop (403) occurs if the output power does not equal the target power and includes: if the output power is less than the target power, increasing (420) the bus

voltage, and if the output power is greater than the target power, reducing (422) the bus voltage.

95. The wireless power transmission system of any one of claims 81 to 94, wherein the first sub-loop (401) occurs if a phase measured at inverter is not equal to a target phase and includes: if the phase measured at inverter is greater than a target phase, comparing (426) receiver reactance to a minimum receiver reactance and if the receiver reactance equals the minimum receiver reactance, then comparing (408) the output power to the target power whereas if the receiver reactance does not equal the minimum receiver reactance, decreasing (438) the transmitter reactance; and if the phase measured at the inverter is less than the target phase, then comparing(430) the receiver reactance to a maximum receiver reactance and if the receiver reactance equals maximum receiver reactance then comparing (408) the output power to the target power whereas if the receiver reactance does not equal the maximum receiver reactance then increasing (432) the transmitter reactance.

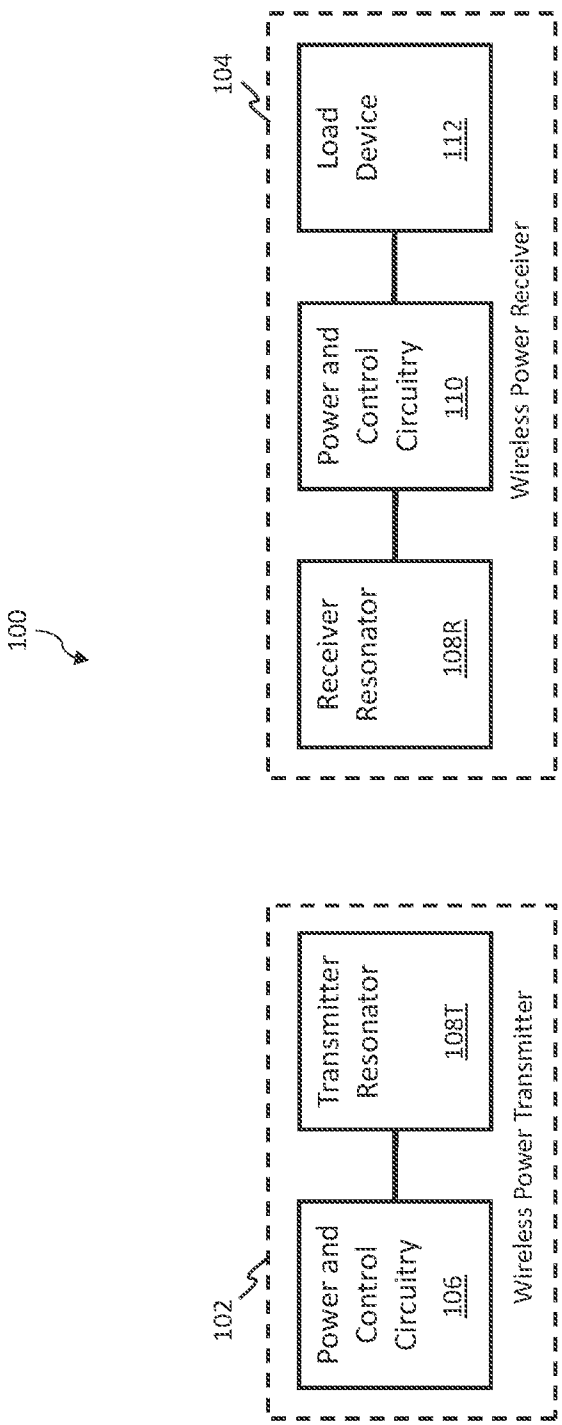
100
102
Power and Control Circuitry 106
Transmitter Resonator 108T
Wireless Power Transmitter
104
Receiver Resonator 108R
Power and Control Circuitry 110
Load Device 112
Wireless Power Receiver

FIG. 1A

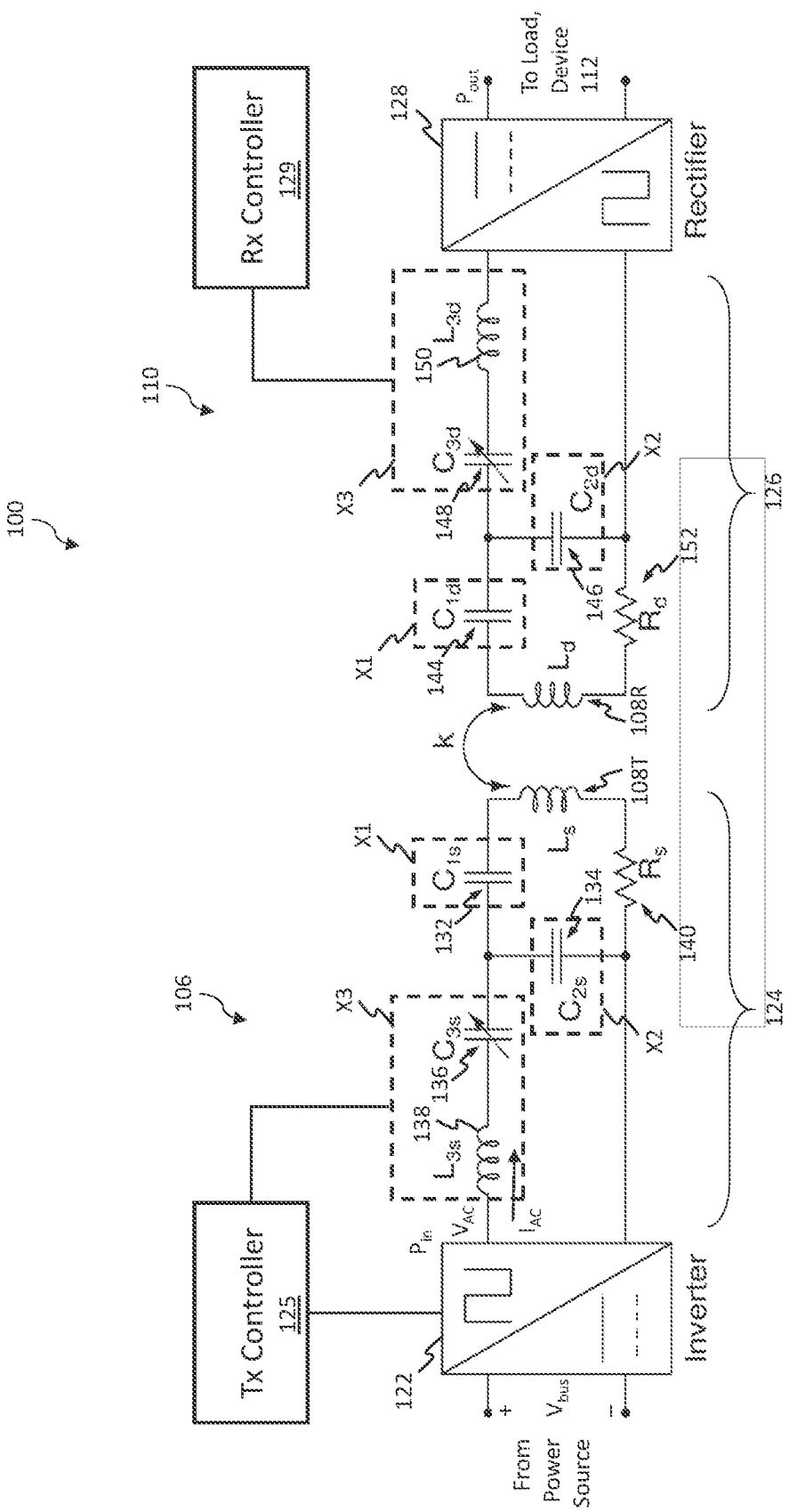
100
110
106
Rx Controller
129
Tx Controller
125
Rectifier
Inverter
To Load, Device 112
From Power Source
P_{out}
P_{in}
V_{bus}
V_{AC}
I_{AC}
L_{3d}
L_d
L_s
L_{3s}
C_{3d}
C_{2d}
C_{1d}
C_{1s}
C_{2s}
C_{3s}
R_d
R_s
k
X1
X2
X3
122
124
126
128
132
134
136
138
140
144
146
148
150
152
108R
108T

FIG. 1B

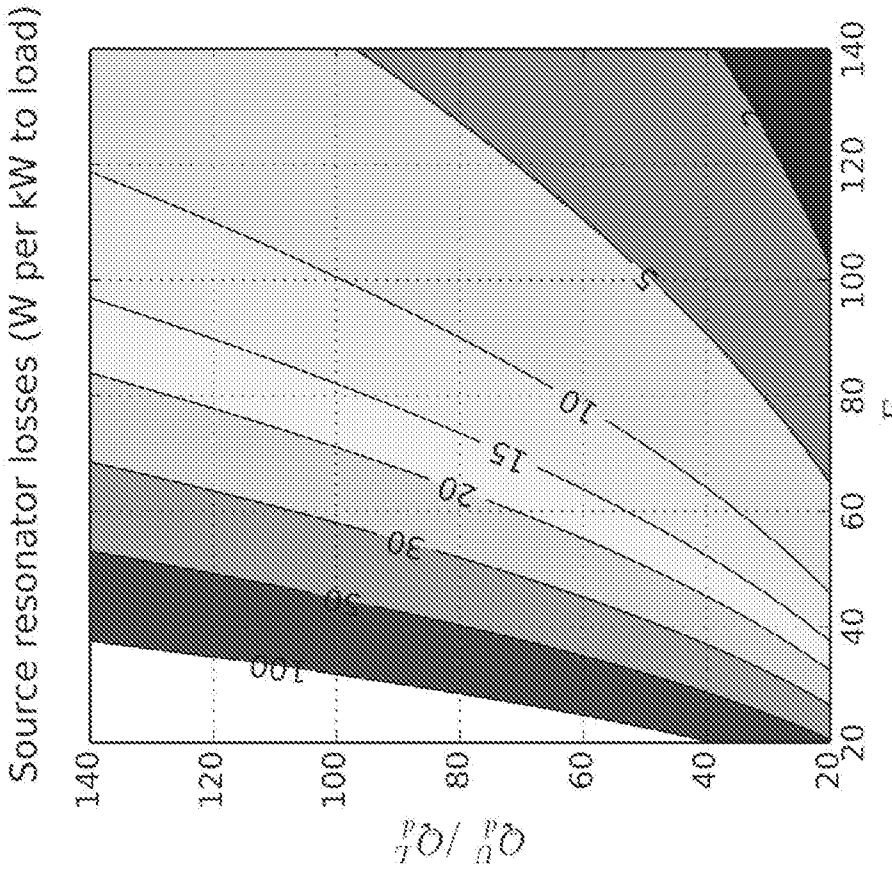
Source resonator losses (W per kW to load)
Q_d^U / Q_d^L
F_{oM}
20
40
60
80
100
120
140
100
50
30
20
15
10
5

FIG. 2A

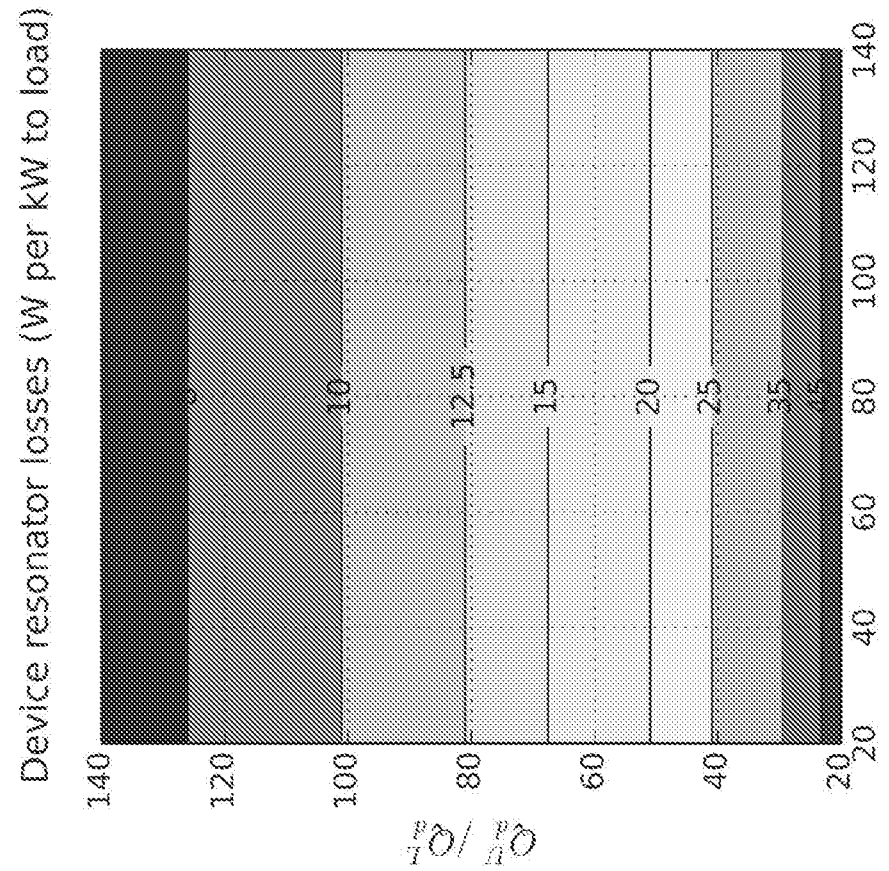
Device resonator losses (W per kW to load)
Q_d^U / Q_d^L
F_{oM}
20
40
60
80
100
120
140
10
12.5
15
20
25
35

FIG. 2B

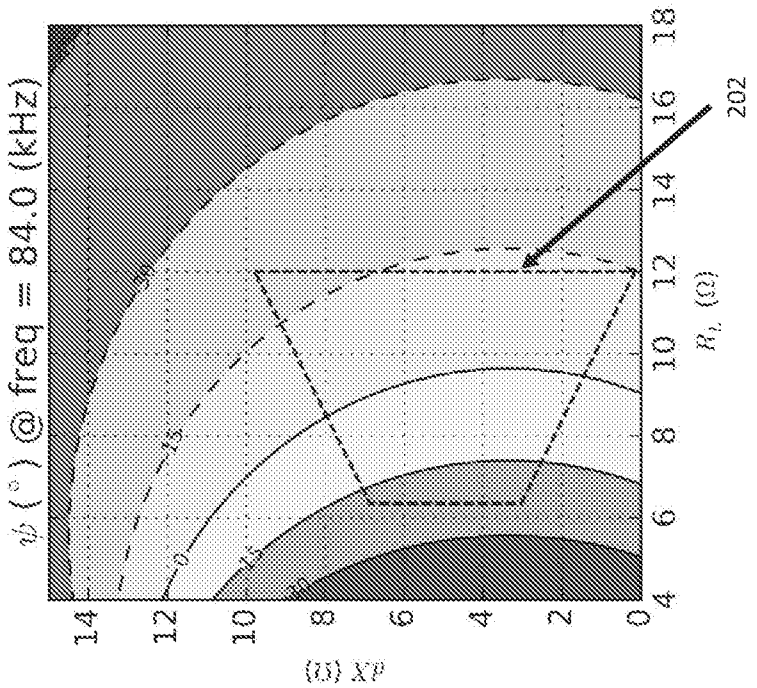
ψ (°) @ freq = 84.0 (kHz)
R_L (Ω)
X_P (Ω)
202

FIG. 2D

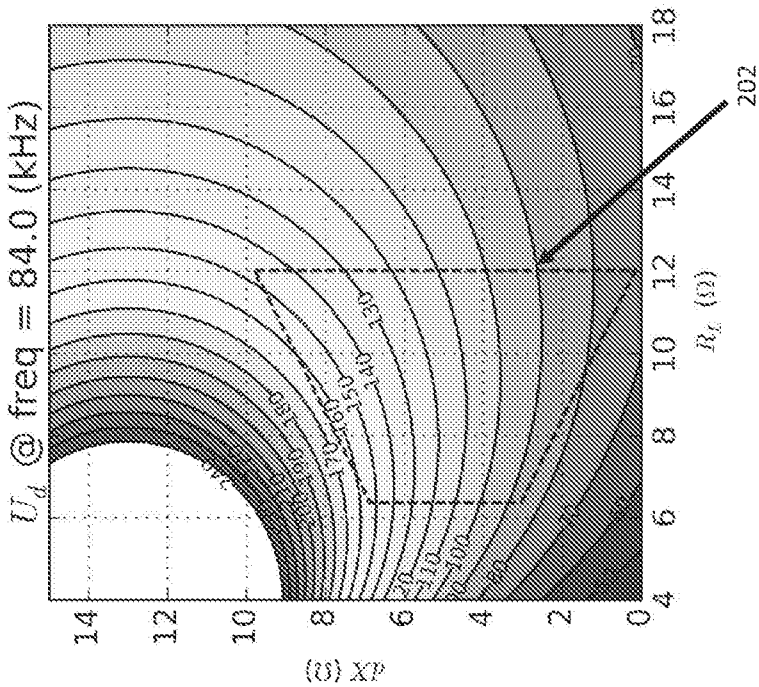
U_d @ freq = 84.0 (kHz)
R_L (Ω)
X_P (Ω)
202

FIG. 2C

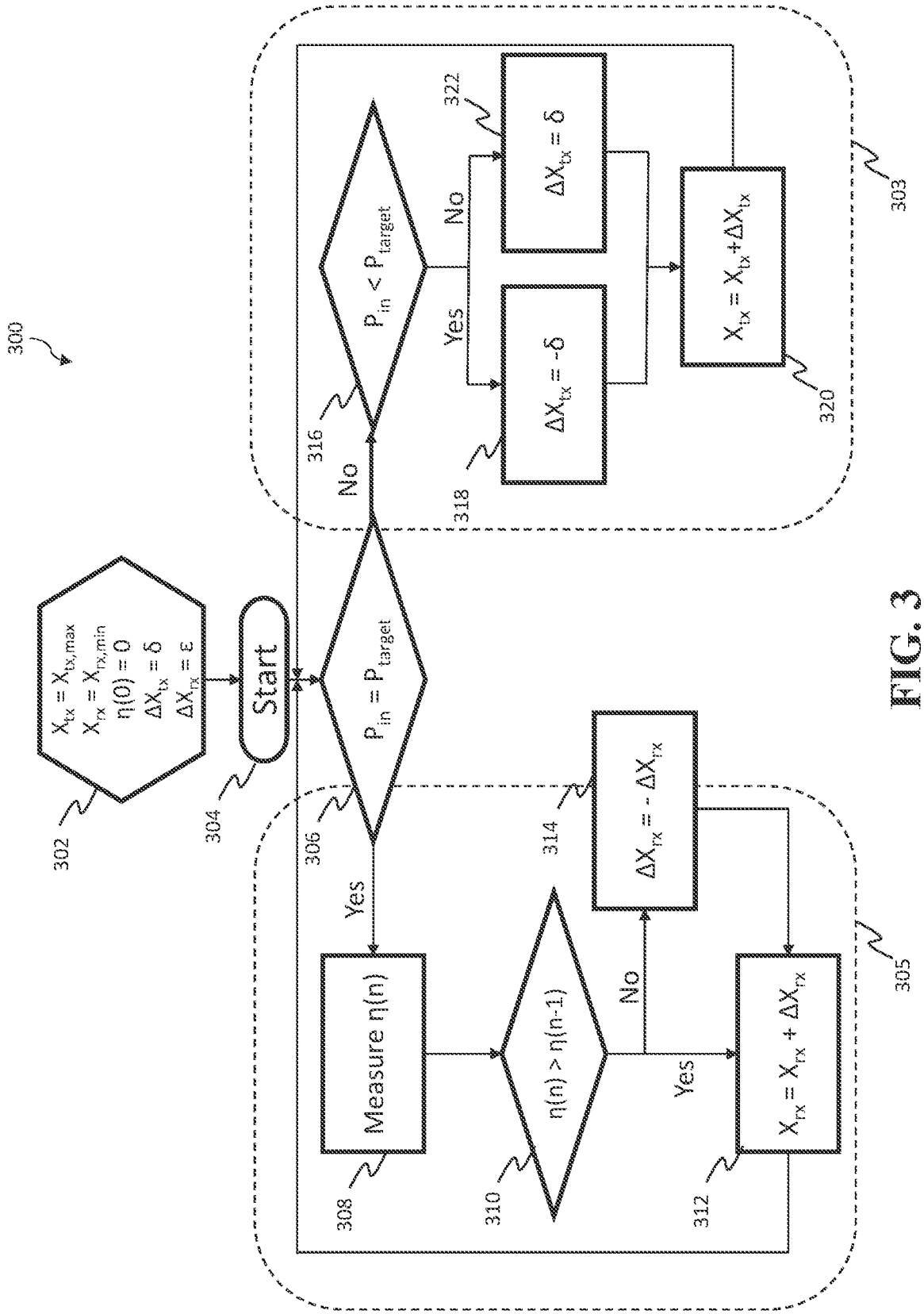
300
$X_{tx} = X_{tx,max}$
$X_{rx} = X_{rx,min}$
$\eta(0) = 0$
$\Delta X_{tx} = \delta$
$\Delta X_{rx} = \varepsilon$
302
Start
304
$P_{in} = P_{target}$
306
Yes
Measure $\eta(n)$
308
$\eta(n) > \eta(n-1)$
310
No
$\Delta X_{rx} = -\Delta X_{rx}$
314
Yes
$X_{rx} = X_{rx} + \Delta X_{rx}$
312
305
No
$P_{in} < P_{target}$
316
Yes
$\Delta X_{tx} = -\delta$
318
No
$\Delta X_{tx} = \delta$
322
$X_{tx} = X_{tx} + \Delta X_{tx}$
320
303

FIG. 3

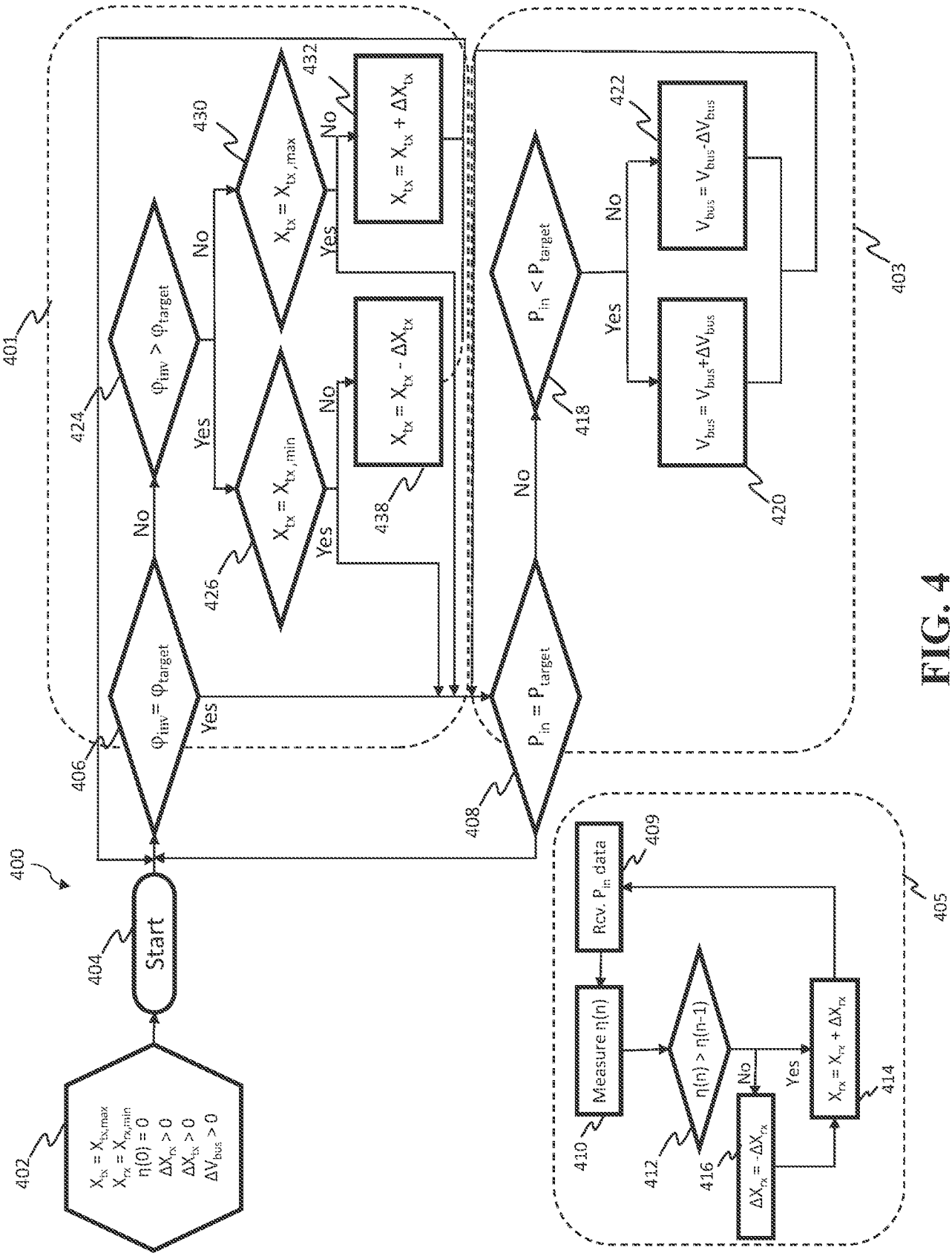
400
401
402
$X_{tx} = X_{tx,max}$
$X_{rx} = X_{rx,min}$
$\eta(0) = 0$
$\Delta X_{rx} > 0$
$\Delta X_{tx} > 0$
$\Delta V_{bus} > 0$
404
Start
405
409
Rcv. P_{in} data
410
Measure $\eta(n)$
412
$\eta(n) > \eta(n-1)$
414
$X_{rx} = X_{rx} + \Delta X_{rx}$
416
$\Delta X_{rx} = -\Delta X_{rx}$
No
Yes
403
406
$\varphi_{inv} = \varphi_{target}$
408
$P_{in} = P_{target}$
418
$P_{in} < P_{target}$
420
$V_{bus} = V_{bus} + \Delta V_{bus}$
422
$V_{bus} = V_{bus} - \Delta V_{bus}$
424
$\varphi_{inv} > \varphi_{target}$
426
$X_{tx} = X_{tx,min}$
430
$X_{tx} = X_{tx,max}$
432
$X_{tx} = X_{tx} + \Delta X_{tx}$
438
$X_{tx} = X_{tx} - \Delta X_{tx}$

FIG. 4

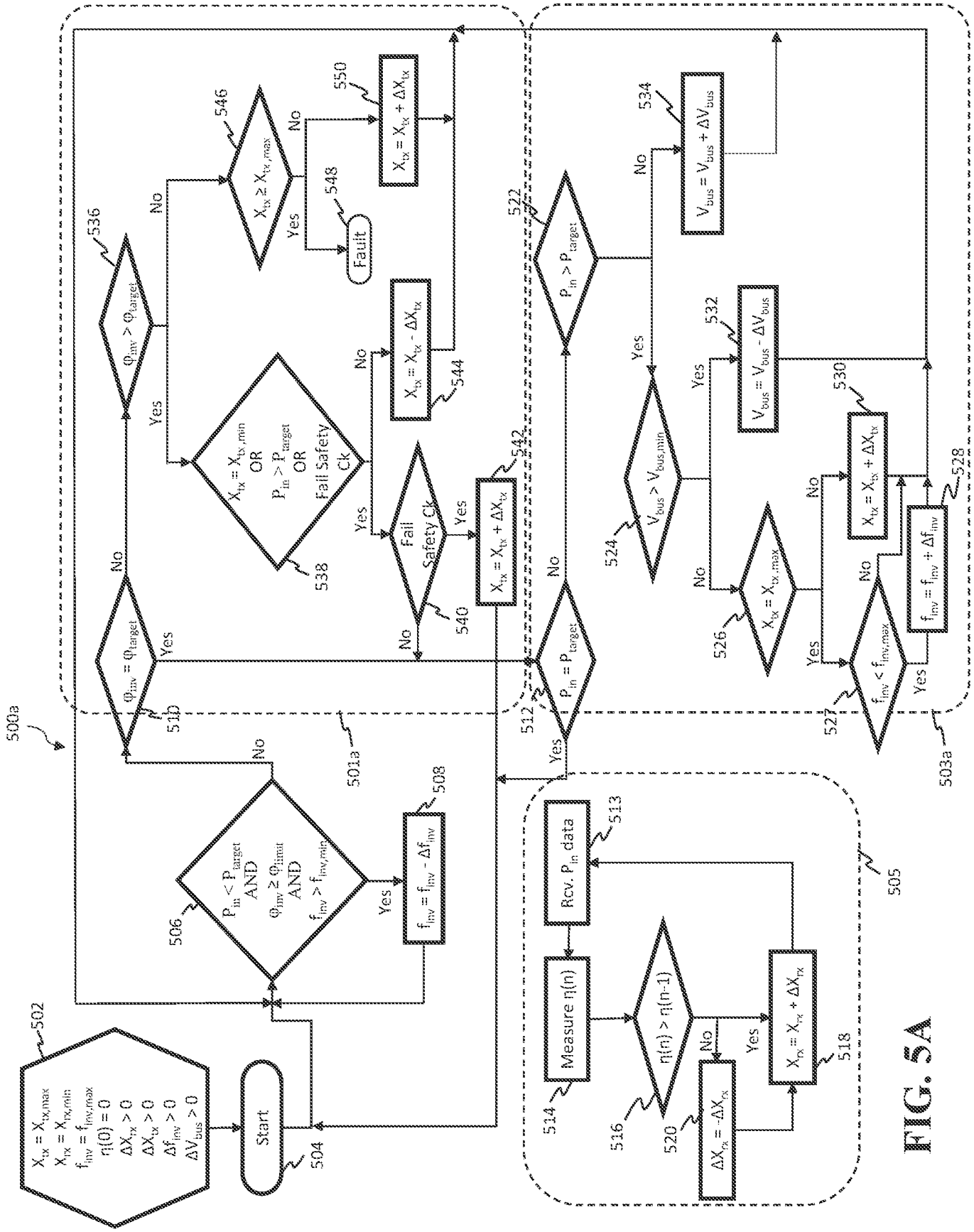
500a
501a
502
503a
504
505
506
508
510
512
513
514
516
518
520
522
524
526
527
528
530
532
534
536
538
540
542
544
546
548
550
Start
Fault
Rcv. P_{in} data
Measure η(n)
η(n) > η(n-1)
$P_{in} < P_{target}$ AND $\varphi_{inv} \geq \varphi_{limit}$ AND $f_{inv} > f_{inv,min}$
$f_{inv} = f_{inv} - \Delta f_{inv}$
$\varphi_{inv} = \varphi_{target}$
$P_{in} = P_{target}$
$X_{tx} = X_{tx} + \Delta X_{tx}$
$X_{tx} = X_{tx} - \Delta X_{tx}$
$X_{tx} = X_{tx,min}$ OR $P_{in} > P_{target}$ OR Fail Safety Ck
Fail Safety Ck
$X_{tx} \geq X_{tx,max}$
$\varphi_{inv} > \varphi_{target}$
$P_{in} > P_{target}$
$V_{bus} = V_{bus} + \Delta V_{bus}$
$V_{bus} > V_{bus,min}$
$V_{bus} = V_{bus} - \Delta V_{bus}$
$X_{tx} = X_{tx,max}$
$X_{tx} = X_{tx} + \Delta X_{tx}$
$f_{inv} < f_{inv,max}$
$f_{inv} = f_{inv} + \Delta f_{inv}$
$\Delta X_{rx} = -\Delta X_{rx}$
$X_{rx} = X_{rx} + \Delta X_{rx}$
$X_{tx} = X_{tx,max}$
$X_{rx} = X_{rx,min}$
$f_{inv} = f_{inv,max}$
$\eta(0) = 0$
$\Delta X_{rx} > 0$
$\Delta X_{tx} > 0$
$\Delta f_{inv} > 0$
$\Delta V_{bus} > 0$
Yes
No

FIG. 5A

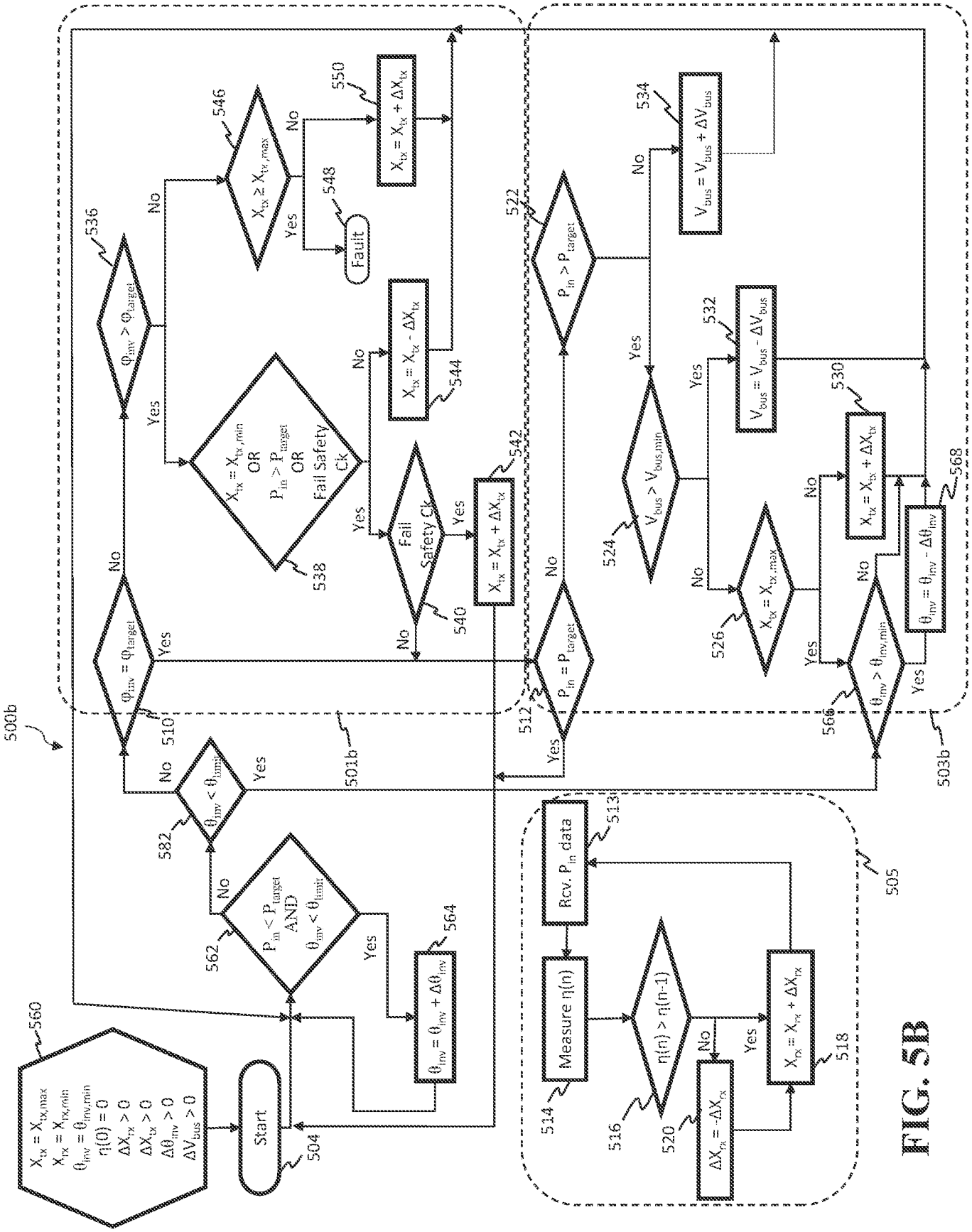
500b
501b
503b
505
Start
Fault
Fail Safety Ck
Rcv. P_{in} data
Measure η(n)
η(n) > η(n-1)
$P_{in} = P_{target}$
$P_{in} > P_{target}$
$\varphi_{inv} = \varphi_{target}$
$\varphi_{inv} > \varphi_{target}$
$\theta_{inv} < \theta_{limit}$
$\theta_{inv} > \theta_{inv,min}$
$V_{bus} > V_{bus,min}$
$X_{tx} \geq X_{tx,max}$
$X_{tx} = X_{tx,min}$ OR $P_{in} > P_{target}$ OR Fail Safety Ck
$P_{in} < P_{target}$ AND $\theta_{inv} < \theta_{limit}$
$X_{tx} = X_{tx,max}$
$X_{rx} = X_{rx,min}$
$\theta_{inv} = \theta_{inv,min}$
η(0) = 0
$\Delta X_{tx} > 0$
$\Delta X_{rx} > 0$
$\Delta\theta_{inv} > 0$
$\Delta V_{bus} > 0$
$X_{tx} = X_{tx} + \Delta X_{tx}$
$X_{tx} = X_{tx} - \Delta X_{tx}$
$X_{rx} = X_{rx} + \Delta X_{rx}$
$\Delta X_{rx} = -\Delta X_{rx}$
$\theta_{inv} = \theta_{inv} + \Delta\theta_{inv}$
$\theta_{inv} = \theta_{inv} - \Delta\theta_{inv}$
$V_{bus} = V_{bus} + \Delta V_{bus}$
$V_{bus} = V_{bus} - \Delta V_{bus}$
Yes
No
504
510
512
513
514
516
518
520
522
524
526
530
532
534
536
538
540
542
544
546
548
550
560
562
564
566
568

FIG. 5B

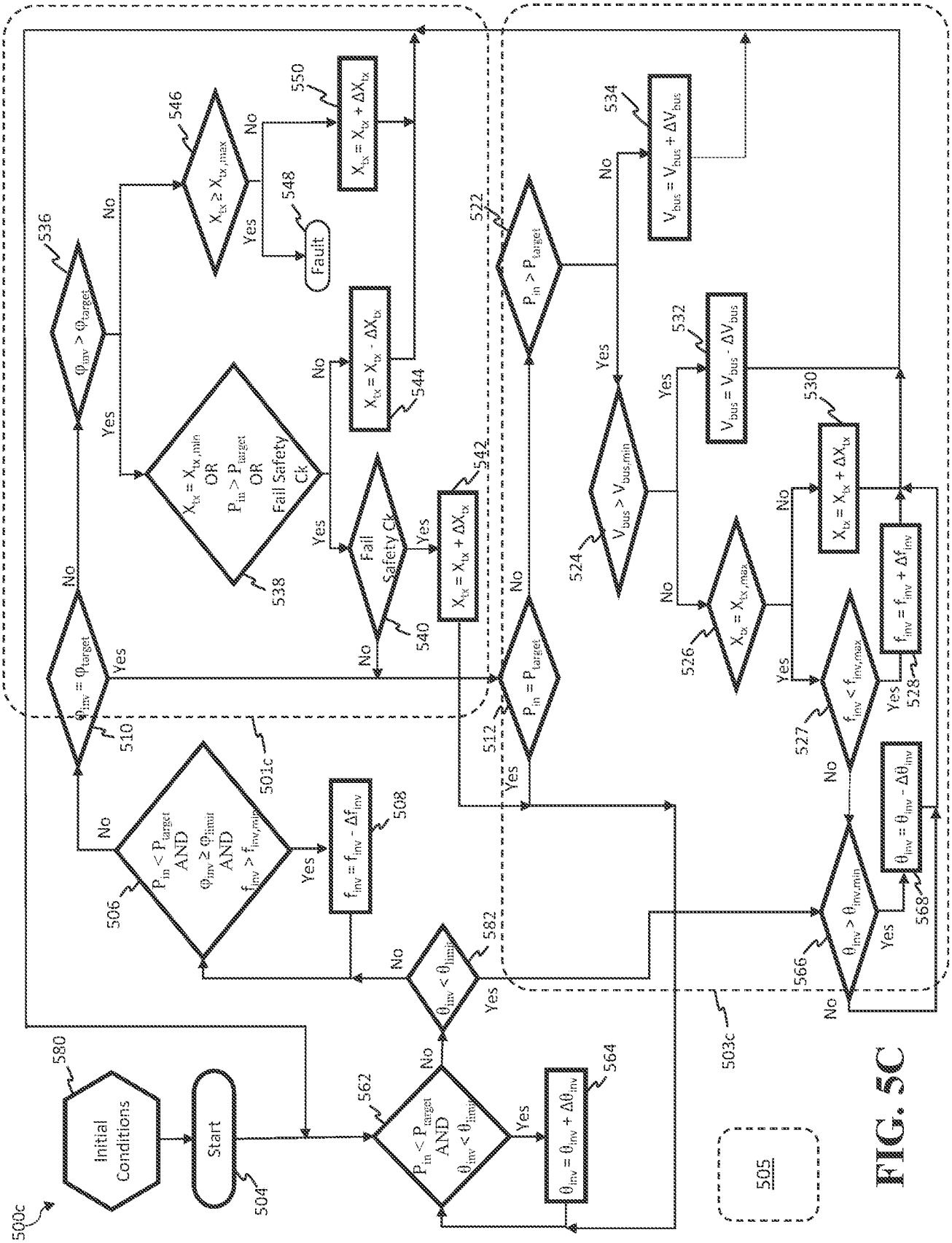
500c
Initial Conditions
580
Start
504
505
501c
503c
$\varphi_{inv} = \varphi_{target}$
510
$P_{in} < P_{target}$ AND $\varphi_{inv} \geq \varphi_{limit}$ AND $f_{inv} > f_{inv,min}$
506
$f_{inv} = f_{inv} - \Delta f_{inv}$
508
$P_{in} < P_{target}$ AND $\theta_{inv} < \theta_{limit}$
562
$\theta_{inv} = \theta_{inv} + \Delta\theta_{inv}$
564
$\theta_{inv} < \theta_{limit}$
582
$P_{in} = P_{target}$
512
$X_{tx} = X_{tx,min}$ OR $P_{in} > P_{target}$ OR Fail Safety Ck
538
Fail Safety Ck
540
$X_{tx} = X_{tx} + \Delta X_{tx}$
542
$X_{tx} = X_{tx} - \Delta X_{tx}$
544
$\varphi_{inv} > \varphi_{target}$
536
$X_{tx} \geq X_{tx,max}$
546
Fault
548
$X_{tx} = X_{tx} + \Delta X_{tx}$
550
$P_{in} > P_{target}$
522
$V_{bus} > V_{bus,min}$
524
$X_{tx} = X_{tx,max}$
526
$V_{bus} = V_{bus} - \Delta V_{bus}$
532
$V_{bus} = V_{bus} + \Delta V_{bus}$
534
$f_{inv} < f_{inv,max}$
527
$f_{inv} = f_{inv} + \Delta f_{inv}$
528
$X_{tx} = X_{tx} + \Delta X_{tx}$
530
$\theta_{inv} > \theta_{inv,min}$
566
$\theta_{inv} = \theta_{inv} - \Delta\theta_{inv}$
568
Yes
No

FIG. 5C

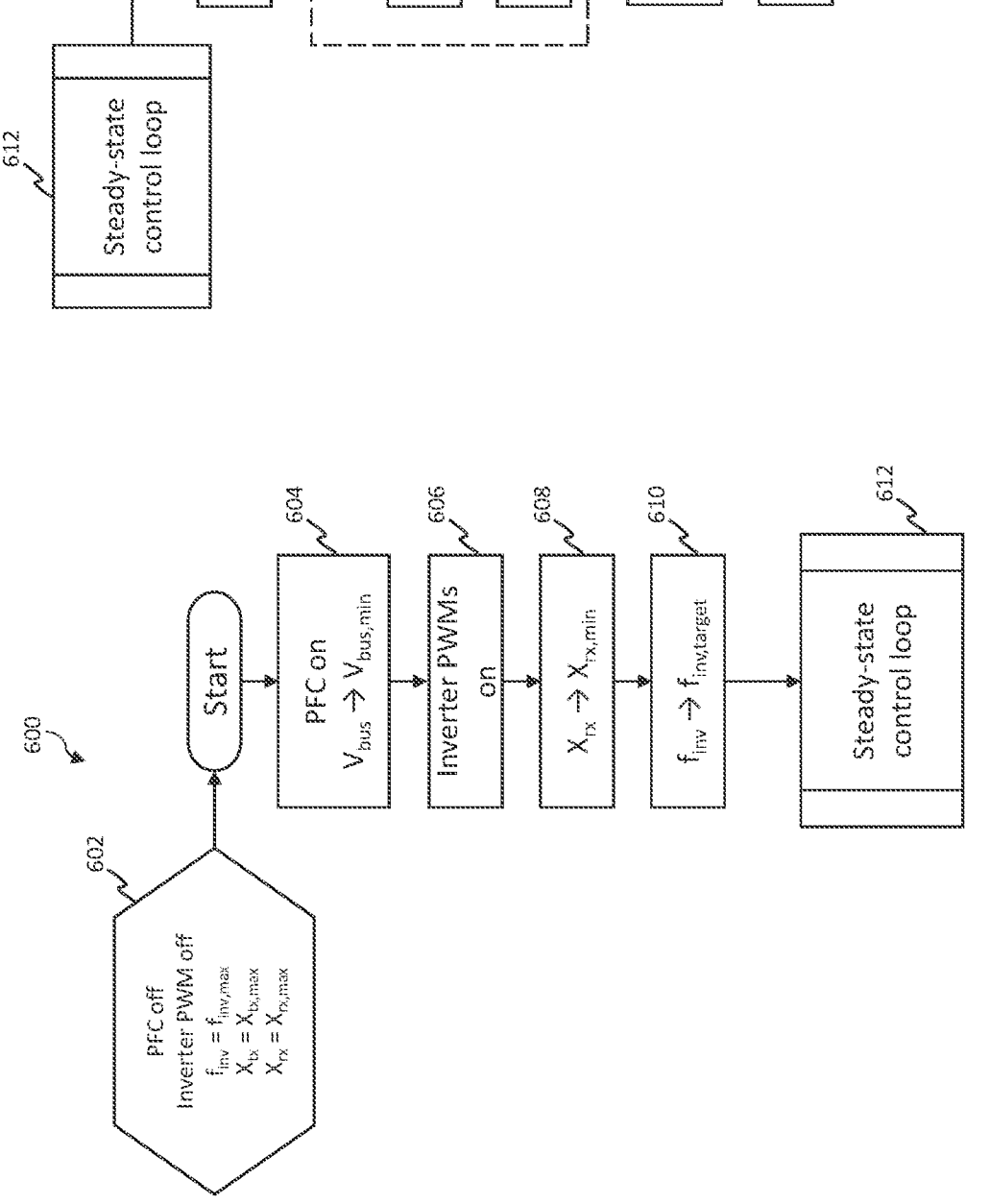
600
PFC off
Inverter PWM off
$f_{inv} = f_{inv,max}$
$X_{tx} = X_{tx,max}$
$X_{rx} = X_{rx,max}$
602
Start
PFC on
$V_{bus} \rightarrow V_{bus,min}$
604
Inverter PWMs on
606
$X_{rx} \rightarrow X_{rx,min}$
608
$f_{inv} \rightarrow f_{inv,target}$
610
Steady-state control loop
612

FIG. 6A

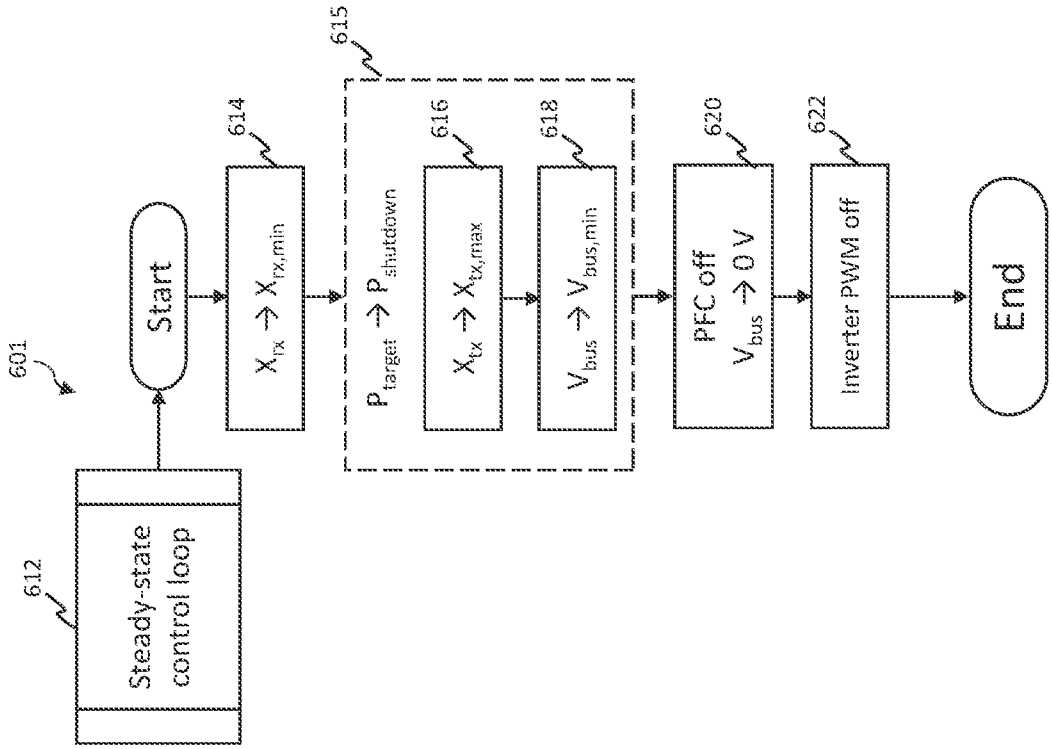
601
Start
$X_{rx} \rightarrow X_{rx,min}$
614
615
$P_{target} \rightarrow P_{shutdown}$
$X_{tx} \rightarrow X_{tx,max}$
616
$V_{bus} \rightarrow V_{bus,min}$
618
PFC off
$V_{bus} \rightarrow 0$ V
620
Inverter PWM off
622
End
Steady-state control loop
612

FIG. 6B