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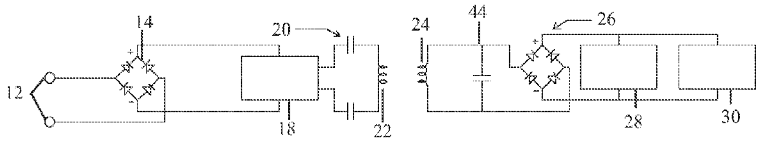

Figure 3

(57) Abstract: A resonant induction wireless power transmission apparatus having intrinsic line power factor correction provides a method of wireless transmission with a near unity power factor, low harmonic distortion load at the line connection point without employing specific power factor correction circuitry. The apparatus provides a transmission frequency inverter operated with a rectified sinusoidal supply voltage instead of a conventional direct current voltage. The resonant induction transfer coil pair is transformed into an impedance inverter by addition of two series connected resonating capacitors of specific value. The impedance inverter raises the secondary side voltage under conditions of light loading and in this way forces line frequency source current and secondary side load current to be proportional, thereby maintaining near unity line load power factor and low harmonic current distortion.

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METHOD AND APPARATUS FOR INTRINSIC POWER FACTOR CORRECTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to U.S. Provisional Patent Application No. 62/065,889, filed October 20, 2014. The contents of that application are hereby incorporated by reference.

TECHNICAL FIELD

[0002] The invention relates to the transmission of electrical energy by means of resonant induction. More specifically, the invention relates to a method of wireless transmission that provides a near unity power factor, low harmonic distortion load at the line connection point without employing specific power factor correction circuitry. Instead, the apparatus described herein provides a low harmonic distortion, near unity power factor without the need for a specific power factor correction stage thereby reducing component cost, apparatus size, and power conversion losses.

BACKGROUND

[0003] Inductive power transmission has many important applications spanning many industries and markets. Although the disclosure contained here contemplates the use of this invention to applications requiring relatively high power (in excess of 100 watts), the potential list of power applications is not limited and this invention can be applied to a wide range of power requirements.

[0004] Figure 1 shows a conceptual representation of a prior art resonant inductive power transmission system 10. As illustrated, a source of alternating, line frequency electrical energy is provided on AC line 12 and converted into direct current with a line frequency rectifier 14 and shunt capacitor ripple filter 16. A DC-AC inverter 18 converts the direct current energy into high frequency alternating current which is applied by means of a resonating network 20 to the primary side induction coil 22. Typical operating frequencies are in the range of 15-50 kHz.

[0005] Magnetic coupling between the primary side induction coil 22 and the secondary side induction coil 24 transfers primary side energy to the secondary side where it is rectified by high frequency rectifier 26, ripple filtered by ripple filter 28 and used to charge a remotely located battery 30. A resonating network 32 resonates the secondary side induction coil 24 thereby enabling maximum current flow and maximum energy transfer.

[0006] The nature of the load presented to the AC line connection in the circuit of Figure 1 is determined by the line rectifier - shunt ripple filter capacitor combination. In operation, the line rectifier current is zero unless the instantaneous rectified line voltage exceeds the shunt capacitor voltage. This means that the rectifier current is not sinusoidal but is instead a narrow pulse that occurs just before the line voltage sinusoid reaches its maximum value. Because the rectifier current is a narrow pulse instead of a sinusoid, it contains considerable harmonic content. The associated line frequency harmonic currents are harmful to electric power distribution components and also to other loads connected to the distribution system and are for that reason restricted to low amplitude by utility or government regulation.

[0007] Another difficulty is the fact that the line frequency rectifier current peak occurs before the line frequency voltage maximum. This means that the fundamental harmonic component of the line frequency rectifier current pulse leads the line frequency voltage sinusoid creating an undesirable leading current factor which is also subject to regulatory restrictions. Increasing the capacitance of the shunt line frequency ripple filter capacitor 16 reduces the magnitude of the direct current line frequency ripple but also undesirably increases the magnitude and decreases the width of the rectifier current pulse, thereby increasing undesirable line frequency harmonic distortion and unacceptable line power factor.

[0008] The problem then is how to convert line frequency alternating current into direct current while drawing an in-phase, sinusoidal current from the line voltage source. Figure 2 shows the conventional solution to this problem, namely, the addition of a power factor correction stage 34. Note that power factor correction in this usage implies both the elimination of rectifier created line frequency harmonic distortion as well as alignment of line frequency voltage and current sinusoids.

[0009] The power factor correction stage 34 shown in Figure 2 consists of a DC-to-DC boost converter although buck and boost-buck converters topologies can be employed as well. A shunt switching device depicted in Figure 2 as a shunt field effect transistor 36 controls inductor current and therefore AC line current by means of pulse duration. When the shunt transistor 36 is on, inductor current ramps up at a rate proportional to the instantaneous rectified line voltage. Energy stored in the inductor 38 is dumped into the shunt filter capacitor 16 through the series diode 40 when the shunt transistor 36 turns off. A control circuit 42 monitors the rectified line current and continuously adjusts the transistor conduction intervals such that the rectified line current remains proportional to the line voltage. In this way, the line frequency rectifier current is made to be half-cycle sinusoidal and proportional to the line voltage amplitude, harmonic distortion is forced to zero, the power factor is forced to unity, and the DC-AC inverter supply voltage is held essentially constant.

[0010] However, there are at least two distinct disadvantages to the conventional method of power factor correction depicted in Figure 2. Namely, the added power conversion stage increases the cost and the volume of the apparatus and also introduces unwanted energy conversion losses. It is desired to provide a near unity power factor, low harmonic distortion load at the line connection point in a resonant inductive power transmission system without employing such specific power factor correction circuitry. The invention addresses this need in the art.

SUMMARY

[0011] The invention addresses the above mentioned limitations of the prior art by changing the operating parameters of the resonant induction wireless power apparatus so that it intrinsically provides a low harmonic distortion, near unity power factor line load without the need of an additional energy conversion power factor correction. The post-rectifier, line frequency ripple filter, and shunt capacitor of conventional circuits are eliminated and the DC-to-AC inverter is powered not by smoothed, constant value DC voltage but by a half-sinusoidal voltage derived from the full wave rectification of the line sinusoid.

[0012] In an exemplary embodiment, the envelope of the high frequency rectangle wave developed by the DC-AC inverter is no longer constant but varies continuously in a half-sinusoidal fashion. The conventional transmission coil pair is combined with resonating capacitors with values specifically selected such that the resonant transmission coil pair becomes a resonant impedance inverter having 90 degrees of transmission phase shift that forces the system load current magnitude, and therefore the AC line current, to be proportional and in phase with the AC line voltage, thus ensuring near unity AC load power factor and low AC line harmonic current content.

[0013] On the secondary side of the wireless power transmission coil pair, a rectifier rectifies the transmission frequency sinusoid. A post-rectifier filter removes the inverter frequency ripple and delivers line frequency, half-sinusoid current to the constant DC voltage load. In a three phase AC line source embodiment, the current delivered to the load is the sum of three rectified sinusoids offset from each other by 120 degrees and therefore has reduced line frequency ripple.

[0014] In the exemplary embodiment, the invention provides an apparatus that maintains near unity AC line power factor and low AC line harmonic current content. The system includes, on the transmission side, a line frequency rectifier not followed by a line frequency ripple filter, a DC-to-AC inverter that inverts the rectified AC line frequency to an envelope modulated high frequency rectangular waveform with an amplitude that varies continuously in a half-sinusoidal fashion, a transmission coil pair that is combined with resonating capacitors with values specifically selected such that the resonant transmission coil pair becomes a resonant impedance inverter having 90 degrees of transmission phase shift, and a primary side induction coil. On the receiving side, the system includes a transmission frequency rectifier and associated transmission frequency ripple filter that provides half-sinusoidal, non-alternating DC current to the receiving side load.

[0015] In another exemplary embodiment, the invention is used in applications where the power flows from a DC power source to an AC load. In such an embodiment, the intrinsic power factor correction apparatus includes a DC power source, a shunt ripple filter capacitor that provides line frequency ripple filtering of an output of the DC power source, a DC-to-AC inverter that converts a line frequency ripple filtered DC voltage from an output of the shunt ripple filter capacitor to an output square wave voltage, an impedance inverter that converts the output square wave voltage to a sinusoidal wave at a frequency of the DC-to-AC inverter that is envelope modulated by a line frequency sinusoid to form a bipolar sinusoidal envelope, a secondary side rectifier that converts the bipolar sinusoidal envelope into a unipolar half-sinusoidal envelope, a de-rectification network that inverts a polarity of every other cycle of the unipolar half-sinusoidal envelope to generate a sinusoidal waveform, and an AC load that receives the sinusoidal waveform. As in the case of the AC source and DC load, the impedance inverter raises a secondary side voltage under conditions of light loading so as to force line frequency source current from the DC power source and a current at the AC load to be proportional so as to maintain near unity line load power factor and low harmonic current distortion. In an exemplary embodiment, this is accomplished by using a Terman impedance inverting network as the impedance network so as to provide a voltage transformation that varies with an instantaneous load voltage at the secondary side of the Terman impedance inverting network. A ripple filter network also may be provided to remove high frequency ripple from the unipolar half-sinusoidal envelope before it is applied to the de-rectification network. The de-rectification network itself may include power semiconductor switches in a half wave or full wave bridge configuration.

[0016] In yet another embodiment, a three phase AC grid load is accommodated using three independent DC-to-AC inverter strings where each string drives one of the three AC constant voltage loads that together constitute an AC three phase constant voltage load. An isolation transformer may be used in each string to provide galvanic isolation between the DC power source and the AC load. Also, the DC power source may include three equal voltage independent DC power sources or three DC source nodes may be tied together and fed by a single DC power source.

DETAILED DESCRIPTION OF DRAWINGS

[0015] The foregoing and other beneficial features and advantages of the invention will become apparent from the following detailed description in connection with the attached figures, of which:

[0016] Figure 1 is a conceptual representation of a prior art resonant induction wireless power transfer system without power factor correction.

[0017] Figure 2 is a conceptual representation of a prior art resonant induction wireless power transfer system with added power factor correction circuitry.

[0018] Figure 3 is a conceptual representation of an embodiment of the invention.

[0019] Figure 4 is a representation of a Terman Tee configuration impedance matching network.

[0020] Figure 5 shows the conversion of a coupled inductor Tee wireless power coil pair equivalent circuit into a resonant impedance inverter.

[0021] Figure 6 is schematic diagram of a circuit used for computer circuit analysis of the embodiment of Figure 3.

[0022] Figure 7 is a graph showing linear results of spice stimulation generated by computer modeling of the load current versus inverter source voltage, at resonance and off resonance.

[0023] Figure 8 is a conceptual representation of the application of the invention to three phase line frequency sources using three isolated inverters and inverter output voltage summation.

[0024] Figure 9 illustrates an alternative embodiment with the summation transformer of Figure 8 replaced by a primary side induction coil implemented as three independent, co-located, induction coils sharing a common magnetic core.

[0025] Figure 10 illustrates a conceptual block diagram and associated voltage waveforms for a DC-to-AC inverter based useful for applications in which power flows instead in the opposite direction from DC-source to ac-load with the apparatus providing a near unity power factor AC source.

[0026] Figure 11 illustrates an embodiment for accommodating a three phase AC grid load using three independent DC-to-AC inverter strings as in Figure 9, where each string drives one of the three AC constant voltage loads that together constitute an AC three phase constant voltage load.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0027] The present invention may be understood more readily by reference to the following detailed description taken in connection with the accompanying figures and examples, which form a part of this disclosure. It is to be understood that this invention is not limited to the specific products, methods, conditions or parameters described and/or shown herein, and that the terminology used herein is for the purpose of describing particular embodiments by way of example only and is not intended to be limiting of any claimed invention. Similarly, any description as to a possible mechanism or mode of action or reason for improvement is meant to be illustrative only, and the invention herein is not to be constrained by the correctness or incorrectness of any such suggested mechanism or mode of action or reason for improvement.

[0028] A detailed description of illustrative embodiments of the present invention will now be described with reference to Figures 3-11. Although this description provides a detailed example of possible implementations of the present invention, it should be noted that these details are intended to be exemplary and in no way delimit the scope of the invention.

[0029] As will now be explained, the system described herein and shown in Figure 3 is explained in the context of a resonant induction wireless battery charging apparatus, although it will become apparent to those skilled in the art that the invention has numerous other applications. It will be appreciated by those skilled in the art that the embodiment of Figure 3 departs from conventional resonant induction wireless battery charging practice in a number of ways. For example, battery charging current is not constant; it varies in a half-sinusoidal or rectified sinusoidal fashion. In this way, battery charging current is proportional to and in phase with a single phase AC line voltage sinusoid source. The secondary side rectifier load impedance is understood to be non-linear, behaving as a constant voltage load with a small Thevenin resistance. No current flows through the secondary side rectifier unless the applied alternating voltage exceeds the battery terminal voltage. The primary side, secondary side induction coil pair 22, 24 and associated resonating capacitors 20, 44 can be configured to function as a voltage step up network under conditions of light loading. Such resonant LC networks are intrinsically high Q under light load conditions and large voltage step up ratios are possible at the resonant frequency.

[0030] During the period of no rectifier current flow, the resistive losses in the secondary side resonant circuit are zero, the instantaneous loaded Q is very high, and significant voltage transformation occurs. Under such instantaneous no-load conditions, the resonant circuit output voltage applied to the secondary side rectifier 26 increases until it exceeds the battery terminal voltage and battery current begins to flow. With proper design, the secondary side battery charging current can be made to flow throughout the duration of the line frequency half-cycle and be proportional to the absolute value of the AC line voltage, thereby presenting a low distortion, unity power factor load to the AC line frequency source without using a specific power factor correction stage.

[0031] The invention described herein makes use of an impedance inverter that provides a voltage transformation that varies continuously as a function of the instantaneous battery terminal impedance as required to maintain proportionality between the line current and the line voltage over each line half-cycle. As known to those skilled in the art, an impedance inverter is a bi-directional two-port network in which a low impedance applied to one port creates a high impedance at the other port.

[0032] A λ/4 transmission line transformer is an example of an impedance inverter implementation. Impedance inverter realizations are not limited to transmission line implementations. For example, there are multiple, lumped circuit configurations including ladder circuit networks. The invention makes use of a three element Tee impedance matching network as described by Terman (Radio Engineers handbook, First Edition, McGraw Hill, 1943) and shown in Figure 4. Terman impedance matching network reactances are found as follows:

$$Z_1 = -j\frac{R_1\,Cos\,\beta - \sqrt{R_1\,R_2}}{Sin\,\beta} \qquad Z_2 = -j\frac{R_2\,Cos\,\beta - \sqrt{R_1\,R_2}}{Sin\,\beta} \qquad Z_3 = -j\frac{\sqrt{R_1\,R_2}}{Sin\,\beta}$$

where R_1 is the two port source impedance, R_2 is the two port load impedance, and β is the phase shift through the network in radians. The Tee impedance matching network functions as an impedance inverting network when designed to have a 90 degree, $|\beta| = \pi/2$ transmission phase shift. For $|\beta| = \pi/2$ the reactance design equations simplify to:

$$Z_1 = Z_2 = -Z_3 = -j\,\sqrt{R_1\,R_2}$$

[0033] In an exemplary embodiment, the values of R_1 and R_2 are not constant but vary continuously during each rectified half-cycle. The geometric product $\sqrt{R_1\,R_2}$ is constant and the three network reactances have equal magnitude. This observation is used in the subsequent design of the resonant induction coil matching networks.

[0034] Figure 5 shows how a resonant induction wireless power coil pair can be transformed into a resonant Terman impedance inverter. Figure 5A shows the wireless power coil pair equivalent circuit of a wireless power transmission coil pair having a coupling coefficient of .385 at 19 kHz. The primary and secondary side winding inductances of 130 μH and the mutual inductance of 50 μH have reactances of +j17.9 and +j5.97, respectively, at 19 kHz.

[0035] In Figure 5B, resonating capacitors 46, 48 are added to the network series arms of the equivalent circuit of Figure 5A. The reactance is selected to completely cancel the reactance of the series inductors Z1, Z2 at 19 kHz and to add an additional series capacitive reactance with the same magnitude as the reactance of the shunt, mutual inductance element Z3 also at 19 kHz. The resulting network in Figure 5C is an impedance inverting two-port equivalent circuit incorporating a wireless power transfer, coupled inductor pair.

[0036] The impedance inverting network of Figure 5C reduces or eliminates inductive wireless power transfer line current harmonic distortion as follows. Just after the line voltage zero-crossing, the magnitude of the rectified line voltage and the magnitude of the inverter voltage output is small. Rectified current provided to the vehicle battery 30 is zero or very small. The impedance on the secondary side of the Terman impedance inverter is very high; therefore, the impedance on the primary side of the impedance inverter is very low. The impedance inverter sees a low impedance load and supplies substantial primary side current. The secondary side voltage increases until it exceeds the battery voltage. Battery charge current starts to flow, the impedance seen by the inverter increases, and the system stabilizes with moderate line current, moderate inverter current, and moderate battery charging current.

[0037] Near the peak of the line voltage cycle, the magnitude of the rectified line voltage and the magnitude of the impedance inverter voltage output is large. Rectified current provided to the vehicle battery is large as well. The impedance on the secondary side of the Terman impedance inverter is low; therefore, the impedance on the primary side of the impedance inverter is relatively high. The compensational action of the impedance inverter makes the line current and the battery charging current proportional to the magnitude of the line voltage, exactly the condition required for unity power factor and zero harmonic distortion. A conventional line filter network may be used to suppress inverter switching frequency transients.

[0038] Figure 6 shows a schematic of an electronic circuit representing a resonant induction wireless power apparatus of the type illustrated in Figure 3 for which the transfer coil pair 22, 24 has been converted into a resonant impedance inverter following the method outlined in Figure 5 that was subjected to time domain computer circuit analysis. The mutually coupled, wireless power induction coils, represented by their equivalent Tee circuit having primary and secondary side winding inductances of 130 μH and a mutual inductance of 50 μH, is transformed into a resonant impedance inverting network 50 following the method described with respect to Figure 5. The AC voltage source 52 represents the output voltage of the primary side inverter 18. The secondary side high frequency rectifier 26 and associated high frequency ripple current filter 28 are shown. The secondary side battery charging load 30 is represented by a direct current voltage source having a small Thevenin resistance representing battery internal resistance.

[0039] The inverter output voltage amplitude varies in proportion to the rectified, but not filtered, line frequency voltage. In order to determine the load current as a function of the inverter voltage, a computer simulation was conducted. Time domain circuit simulation was conducted for multiple values of inverter output voltage ranging from zero volts to the peak value of the rectified line voltage. The corresponding load current is graphed in Figure 7 as a function of the inverter, rectified sine supply voltage.

[0040] As shown in Figure 7, with the AC voltage source frequency set to 19 kHz, the network resonant frequency, battery charging current is linear and proportional to the inverter source voltage. It is important to note battery charging current linearity is maintained even for line source voltages much less than the battery open circuit terminal voltage, a consequence of the voltage transformation properties of a resonant circuit when lightly loaded. The linear curve of Figure 7 shows the desirable condition of secondary side load current, and therefore inverter supply current and line current being proportional to line voltage, a condition that insures low levels of line frequency harmonic distortion and unity line frequency power factor. When operated above and below the impedance inverter resonant frequency, at 17, 18 and 20 kHz as indicated on Figure 7, the line voltage/line current relationship is no longer proportional at low line voltages resulting in line current harmonic distortion and degraded line power factor. When operated at the impedance inverter resonant frequency, current varies in a half-sinusoidal or rectified sinusoidal fashion.

[0041] Conventionally, battery charging is mediated by a battery management system that monitors and controls battery charging current and maximum battery voltage as well as other relevant parameters such as temperature, sometimes for the battery as a whole but also for individual cells. In current practice, battery/cell management systems require the use of DC charging current and will likely malfunction in the presence of half-sinusoidal charging current. This difficulty is eliminated by modifying the battery management system to respond to the RMS charging current instead of the average or peak measurement methodology employed conventionally.

[0042] Effective battery charging requires charging current magnitude be altered according to the battery state of charge as controlled by the battery charging algorithm. In an exemplary embodiment of the invention, maximum battery charging current magnitude is set by the design of the impedance inversion network and by the magnitude of the rectified, half-sinusoidal line voltage that supplies the inverter 18. Further control (reduction) of battery charging current is obtained by pulse width modulation of the inverter 18, by inverter pulse phasing, by inverter pulse dropping and by active control of the secondary side rectifier 26. These control methods employed individually or in combination enable effective control of charging current magnitude while maintaining low harmonic distortion, near unity power factor.

[0043] While low to medium power wireless power systems operate from single phase power connections, high power systems generally require a three phase connection. Even though a rectified single phase sinusoid source has a large ripple component, the sum of three rectified sinusoidal sources, with each sinusoid displaced by 120 degrees, is much smaller. Reduced charging ripple current is sometimes desirable for compatibility with battery management system circuitry and for reduction of the peak to average charging current ratio in order to limit battery resistive losses during fast charging.

[0044] Figure 8 shows an embodiment of the invention implemented with a three phase line voltage source 54. Each phase has a separate rectifier 14 and inverter 18. The three inverters switch synchronously and the inverter outputs are combined by a summing transformer 56 that can be three physically independent transformers or a single transformer with six windings on a common core with three phase partial flux cancellation allowing more efficient use of the core material. The summation transformer 56 also provides galvanic isolation from the AC line. Filters on the three phase lines (not shown in Figure 8) reject inverter switching frequency components resulting in a new unity, low harmonic distortion three phase load. As in prior art Figure 1, resonating network 20 connects the inverters 18 to the primary side induction coil 22. Magnetic coupling between the primary side induction coil 22 and the secondary side induction coil 24 transfers primary side energy to the secondary side where it is rectified by high frequency rectifier 26, ripple filtered by ripple filter 28 and used to charge a remotely located battery 30. A resonating network 44 resonates the secondary side induction coil 24 thereby enabling maximum current flow and maximum energy transfer.

[0045] Figure 9 shows an alternative embodiment of Figure 8 where the summation transformer 56 is replaced with the primary side induction coil 22 implemented as three independent, co-located, induction coils 23, sharing a common magnetic core with a secondary side induction coil that is connected to the secondary side rectifier. A separate DC-AC inverter 18 and associated line frequency rectifier 14 drives each of the three primary coils through resonating networks 20. Power summation then occurs as the summation of primary coil flux fields such that dedicated combining transformers 56 are not required. Those skilled in the art will appreciate that the embodiment of Figure 9 eliminates the size, weight and cost of the combining transformers at the cost of adding two primary coils and two sets of resonating capacitors.

[0046] The power factor correction action of a Terman impedance inverter network as described herein can be advantageously employed in apparatus other than resonant induction wireless power transfer systems. Such applications include:

Wired –as opposed to wireless- battery charging;

Metal plating;

Electro-chemical processing such as electrolysis;

Induction heating;

Alternating current welding;

Gaseous discharge processes including fluorescent and arc lighting; and

Any other application providing direct current derived from an alternating current source to loads that can tolerate full wave rectified sinusoidal direct current.

[0047] In power factor control of wireless induction power transfer, the Terman impedance inversion network is absorbed into the Tee equivalent circuit of the wireless transfer, mutually coupled, air core coil pair, where one element of the Tee equivalent circuit is the mutual inductance. Those skilled in the art will appreciate that in non-wireless power transfer applications, the impedance inversion network can implemented at three discrete, non-mutually coupled components giving a significant increase in design flexibility.

[0048] In the applications discussed above, power flows from AC-source to DC-load with the apparatus providing a near unity power factor load to the AC source. The teachings of the invention apply equally to applications in which power flows instead in the opposite direction from DC-source to AC-load with the apparatus providing a near unity power factor AC source. A reversed power flow apparatus finds application as inverters feeding DC power from alternative energy sources such as photovoltaic panels and wind generators into the 50 or 60 Hz utility grid.

[0049] Figure 10 illustrates a conceptual block diagram and associated voltage waveforms for a DC-to-AC inverter system useful for applications in which power flows instead in the opposite direction from DC-source to AC-load with the apparatus providing a near unity power factor AC source. As illustrated, the circuit of Figure 10 includes DC power source 60 followed by a shunt ripple filter capacitor 62 that provides line frequency ripple filtering. The line frequency ripple filtered DC voltage is applied to a high frequency DC-to-AC inverter 64. High frequency in this context means high with respect to the line frequency. The output square wave voltage, 66, is applied to the input of a Terman impedance inverting network 68 that provides a voltage transformation that varies with the instantaneous load voltage at the far side of the impedance inversion network.

[0050] The waveform 70 at the output of the impedance inversion network 68 is a sinusoidal wave at the DC-to-AC inverter frequency, envelope modulated by a line frequency sinusoid. A high frequency rectifier 72 converts the bipolar sinusoidal envelope into a unipolar, half-sinusoidal envelope 74. A high frequency ripple filter network 76 removes the high frequency ripple giving a ripple free, line frequency half-sinusoidal waveform 78. A derectification network 80 including power semiconductor switches in a half wave or full wave bridge configuration inverts the polarity of every other cycle of waveform 78 to generate waveform 82, thereby allowing power flow into the constant AC voltage load 84, which represents an infinite grid.

[0051] A three phase AC grid load is accommodated as shown in Figure 11 with three independent DC-to-AC inverter strings, each string being the same as a single phase inverter string with isolation transformers 90 added. Each string drives one of the three AC constant voltage loads that together constitute an AC three phase constant voltage load 92. Isolation transformers 90 provide galvanic isolation from the AC load 92. The DC source 94 can be three equal voltage independent DC sources as shown in Figure 10 or the three DC source nodes can be tied together and fed by a single DC source. The filter capacitor 96 filters the 120 Hz half-sinusoidal current variation that would otherwise be present at the DC source node. The elements and operation are otherwise the same as in the circuit configuration of Figure 10.

[0052] Those skilled in the art will appreciate that the invention is not limited to wireless power device applications. In addition to wireless inductive charging applications, the invention may also be applied to uses outside of the transportation industry such as AC induction motors, motor controllers, resonant power supplies, industrial inductive heating, melting, soldering, and case hardening equipment, welding equipment, power transformers, electronic article surveillance equipment, induction cooking appliances and stoves, other industrial equipment, and other applications incorporating plug-in charging by a plug-in charger, as well as to other non-battery charging applications such as electrochemistry, electroplating and all other loads that can be operated with a half-sinusoidal current waveform from a single phase line source, or reduced ripple waveform that results from the summation of a multiphase line source. These and other such embodiments are considered to be included within the scope of the invention as defined by the following claims.

WHAT IS CLAIMED

1. An intrinsic power factor correction apparatus, comprising:

an AC line source;

a line frequency rectifier connected to said AC line source to provide a half-sinusoidal rectified supply voltage;

an impedance inverter responsive to said half-sinusoidal rectified supply voltage to provide an impedance inverted secondary side voltage at an output;

a secondary side rectifier that rectifies said secondary side voltage;

a secondary side ripple filter that filters a rectified output from said secondary side rectifier to remove inverter frequency ripple and deliver a line frequency half-sinusoid current at an output; and

a load that receives said line frequency half-sinusoid current,

wherein said impedance inverter raises said secondary side voltage under conditions of light loading so as to force line frequency source current from said AC line source and said line frequency half-sinusoid current at said load to be proportional so as to maintain near unity line load power factor and low harmonic current distortion.

2. The apparatus of claim 1, wherein said impedance inverter includes a Terman Tee configuration impedance matching network and two series connected resonating capacitors having values selected such that the impedance inverter has 90 degrees of transmission phase shift that forces a load current magnitude applied to said load to be proportional and in phase with the AC line source.

3. The apparatus of claim 1, wherein said AC line source comprises a three phase AC line source, a line frequency rectifier is connected to each phase of the three phase AC line source to provide a half-sinusoidal rectified supply voltage, and a summing transformer provides galvanic isolation from the AC line source, an output of said summing transformer being provided to said impedance inverter.

4. The apparatus of claim 3, wherein said summing transformer comprises three physically independent transformers.

5. The apparatus of claim 3, wherein said summing transformer comprises a single transformer with six windings on a common core with three phase partial flux cancellation.

6. The apparatus of claim 3, further comprising filters on the three phase AC lines that reject switching frequency components of said transmission frequency inverter.

7. The apparatus of claim 3, wherein said line frequency half-sinusoid current delivered to the load is a sum of three rectified sinusoids from each AC line phase offset from each other by 120 degrees.

8. The apparatus of claim 1, wherein said AC line source comprises a three phase AC line source, a line frequency rectifier is connected to each phase of the three phase AC line source to provide a half-sinusoidal rectified supply voltage, and a primary side induction coil is implemented as three independent, co-located, induction coils sharing a common magnetic core with a secondary side induction coil that is connected to said secondary side rectifier.

9. The apparatus of claim 1, wherein the AC line source is a plug-in charger.

10. The apparatus of claim 1, wherein the load is a battery charging load.

11. The apparatus of claim 1, wherein the load is an electrochemical or electroplated load that can be operated with a half-sinusoidal current waveform from a single phase line source or a summation of a multi-phase line source.

12. An intrinsic power factor correction apparatus, comprising:

a DC power source;

a shunt ripple filter capacitor that provides line frequency ripple filtering of an output of said DC power source;

a DC-to-AC inverter that converts a line frequency ripple filtered DC voltage from an output of said shunt ripple filter capacitor to an output square wave voltage;

an impedance inverter that converts said output square wave voltage to a sinusoidal wave at a frequency of the DC-to-AC converter that is envelope modulated by a line frequency sinusoid to form a bipolar sinusoidal envelope;

a secondary side rectifier that converts the rectifies said bipolar sinusoidal envelope into a unipolar half-sinusoidal envelope;

a de-rectification network that inverts a polarity of every other cycle of the unipolar half-sinusoidal envelope to generate a sinusoidal waveform; and

an AC load that receives said sinusoidal waveform,

wherein said impedance inverter raises a secondary side voltage under conditions of light loading so as to force line frequency source current from said DC power source and a current at said AC load to be proportional so as to maintain near unity line load power factor and low harmonic current distortion.

13. The apparatus of claim 12, wherein said impedance inverter comprises a Terman impedance inverting network that provides a voltage transformation that varies with an instantaneous load voltage at the secondary side of the Terman impedance inverting network.

14. The apparatus of claim 12, further comprising a ripple filter network that removes high frequency ripple from said unipolar half-sinusoidal envelope before said unipolar half-sinusoidal envelope is applied to said de-rectification network.

15. The apparatus of claim 12, wherein said de-rectification network includes power semiconductor switches in a half wave or full wave bridge configuration.

16. The apparatus of claim 12, further comprising an isolation transformer that provides galvanic isolation between said DC power source and said AC load.

17. An apparatus comprising an intrinsic power factor correction apparatus as in claim 16 for each phase of a three phase constant voltage applied to said AC load.

18. The apparatus of claim 17, wherein said DC power source comprises three equal voltage independent DC power sources.

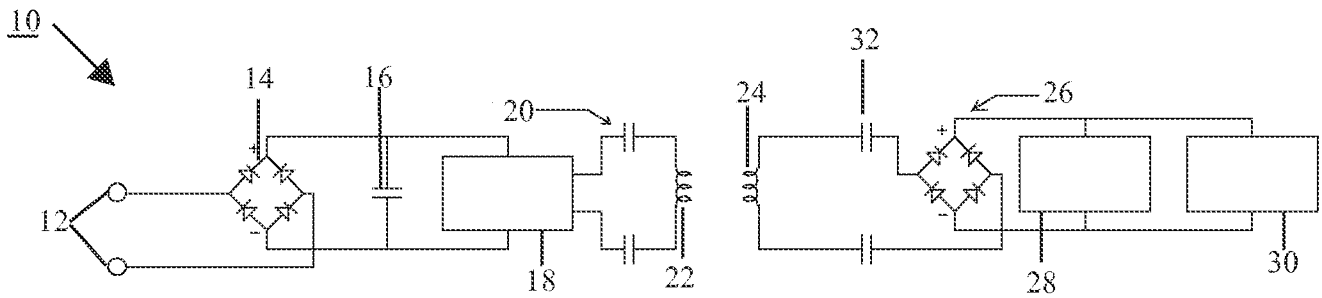


Figure 1

Prior Art

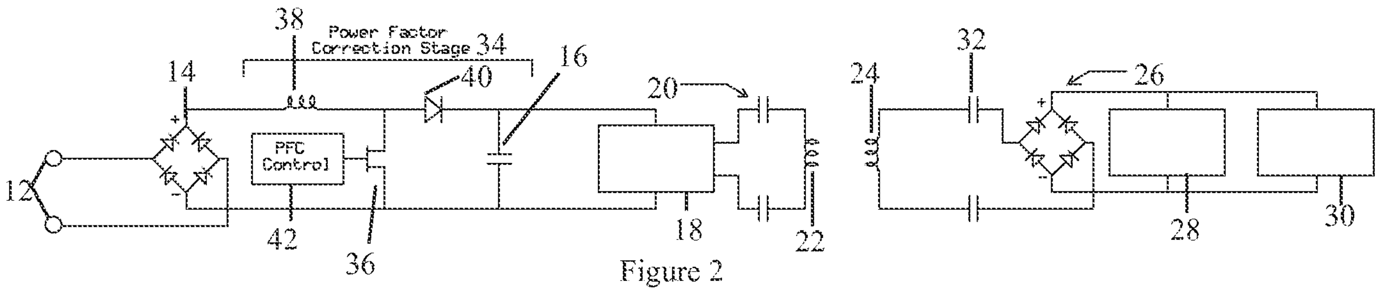


Figure 2

Prior Art

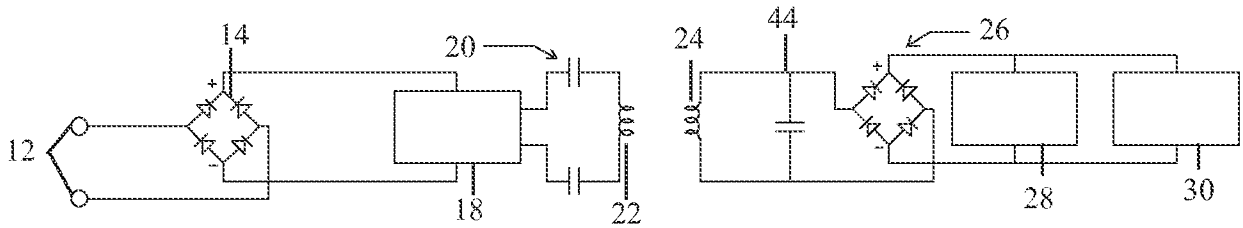


Figure 3

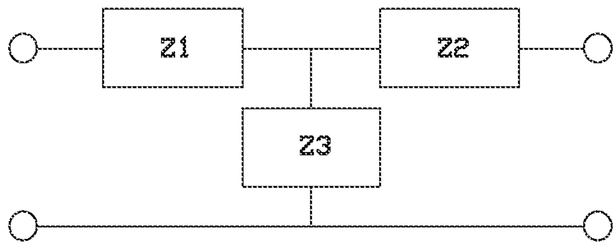


Figure 4

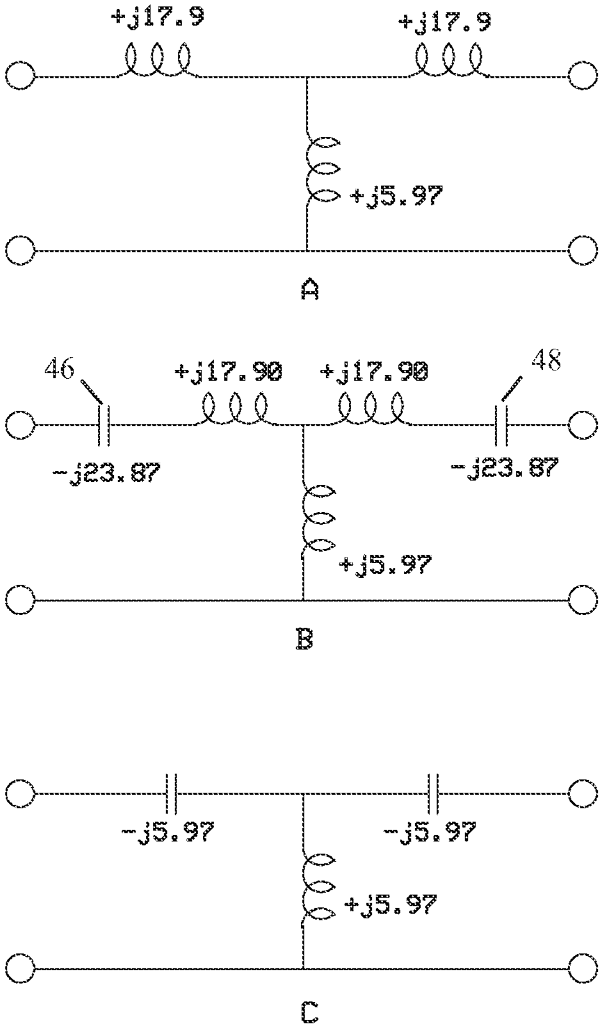


Figure 5

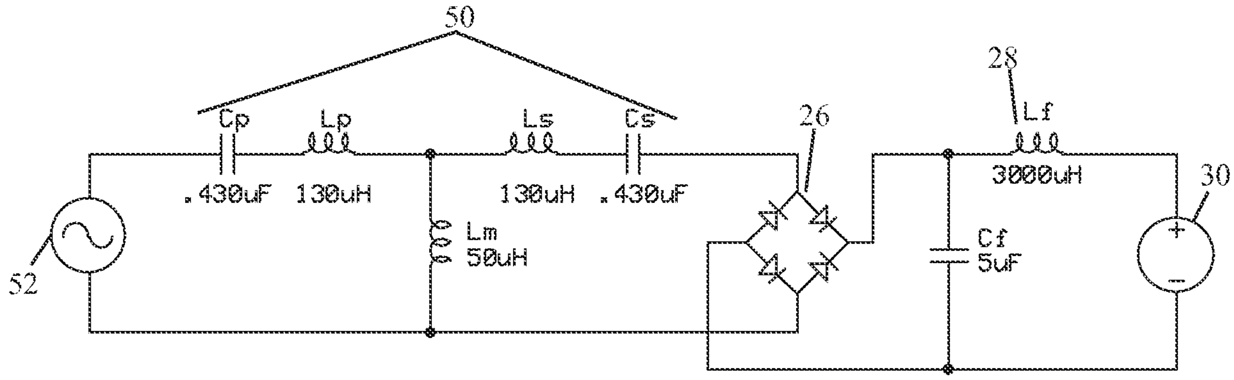


Figure 6

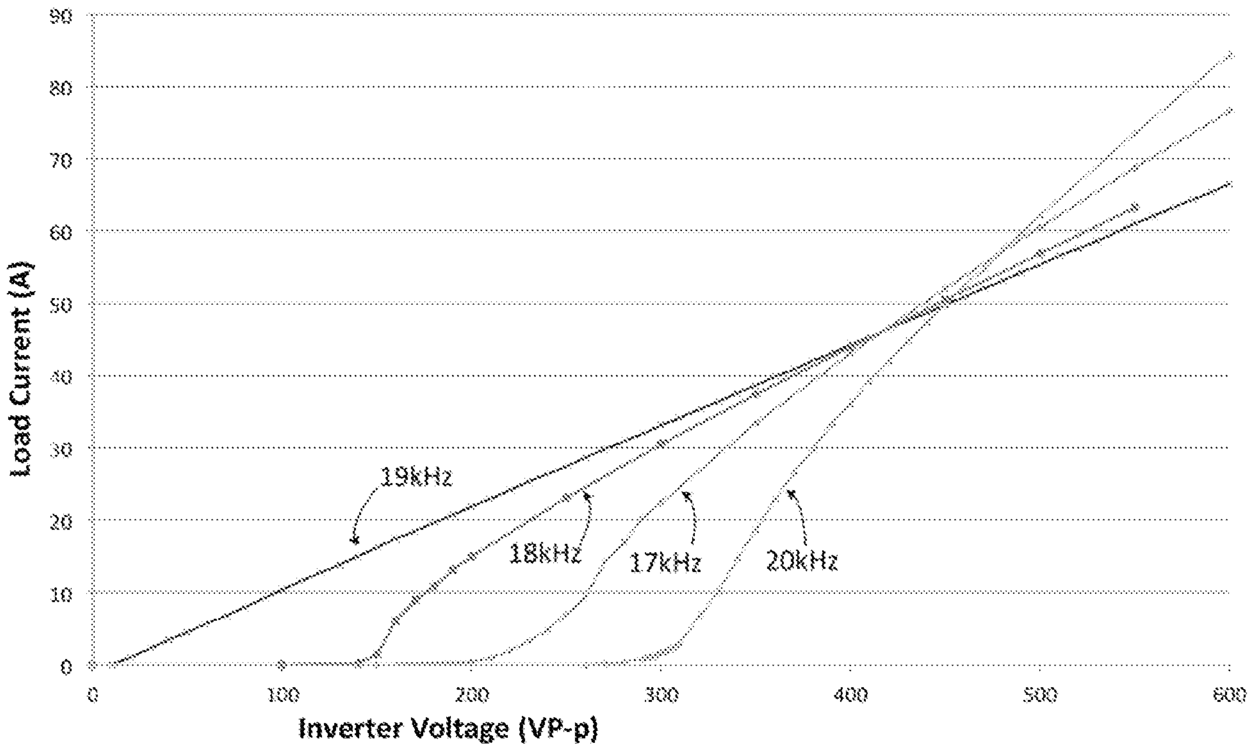
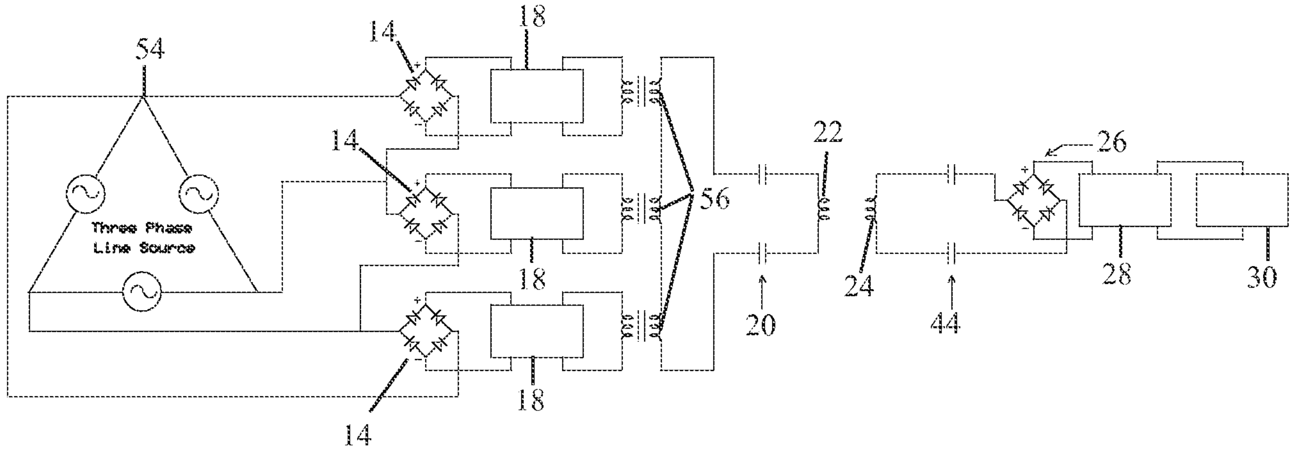


Figure 7


54
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Three Phase
Line Source
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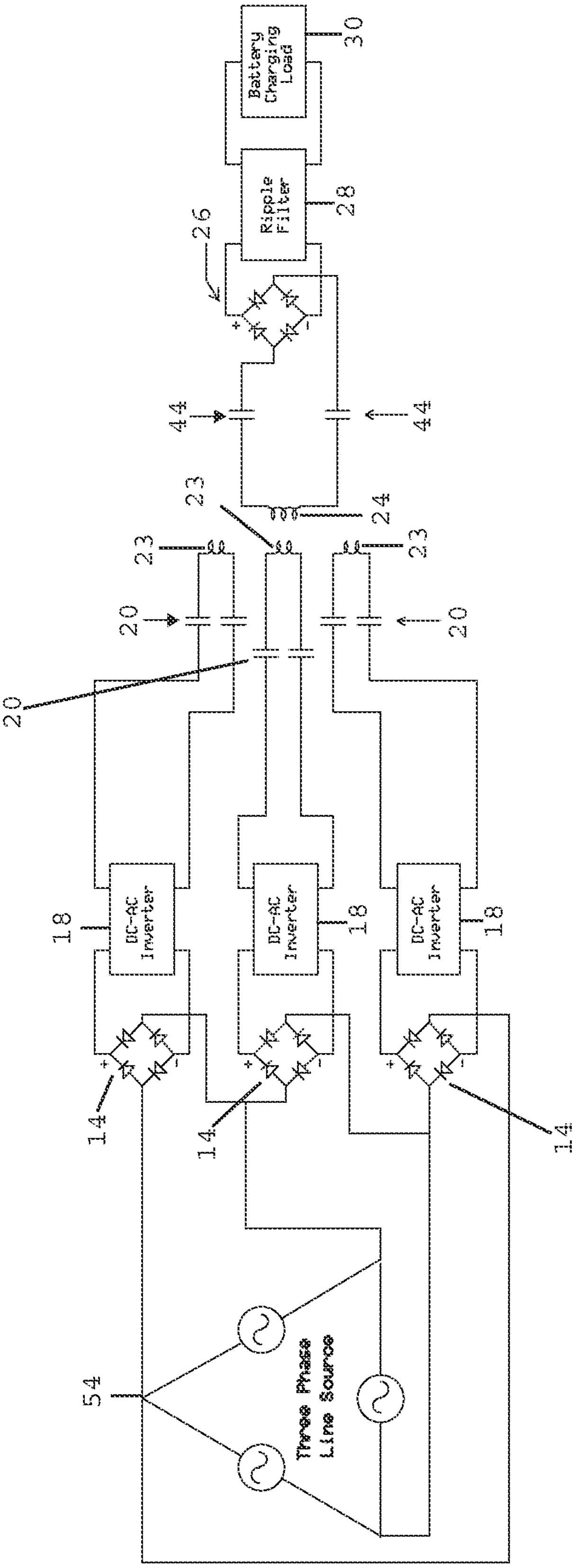
Figure 8


Battery Charging Load
30
Ripple Filter
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DC-AC Inverter
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DC-AC Inverter
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DC-AC Inverter
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Three Phase Line Source

Figure 9

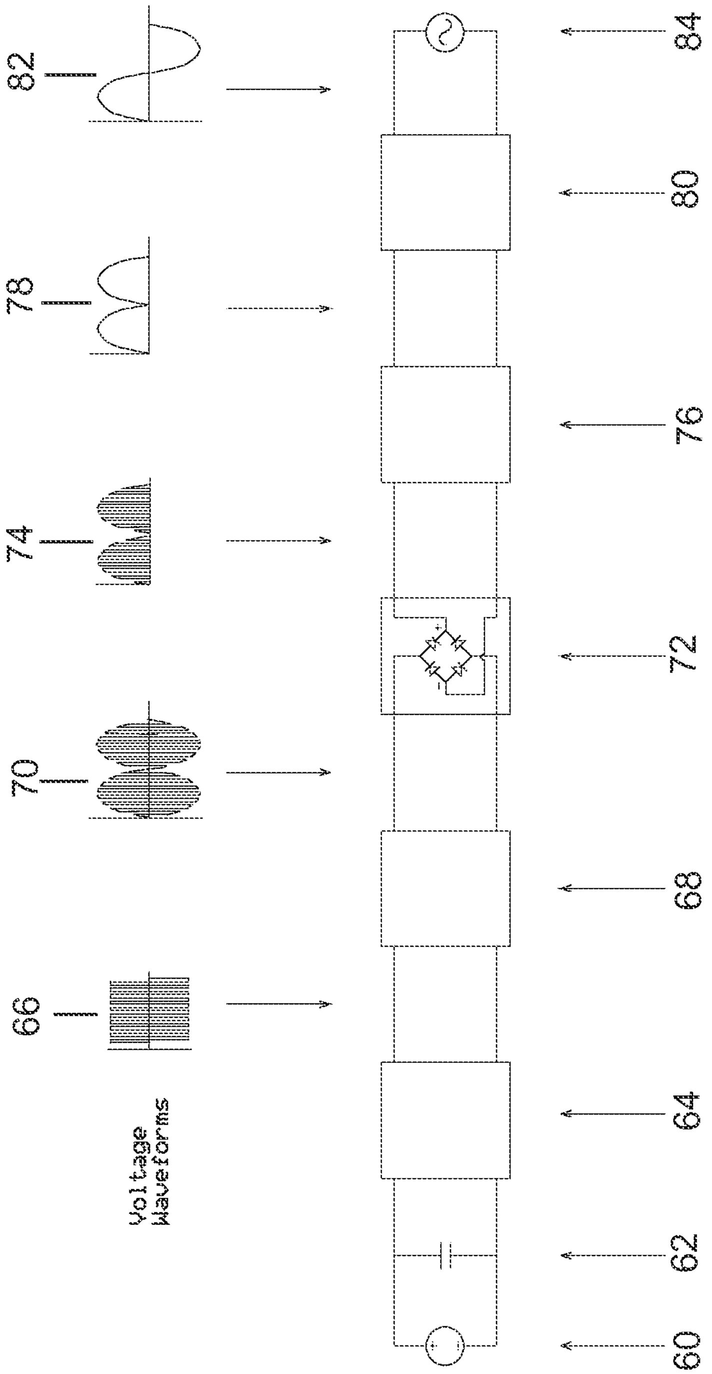

Figure 10

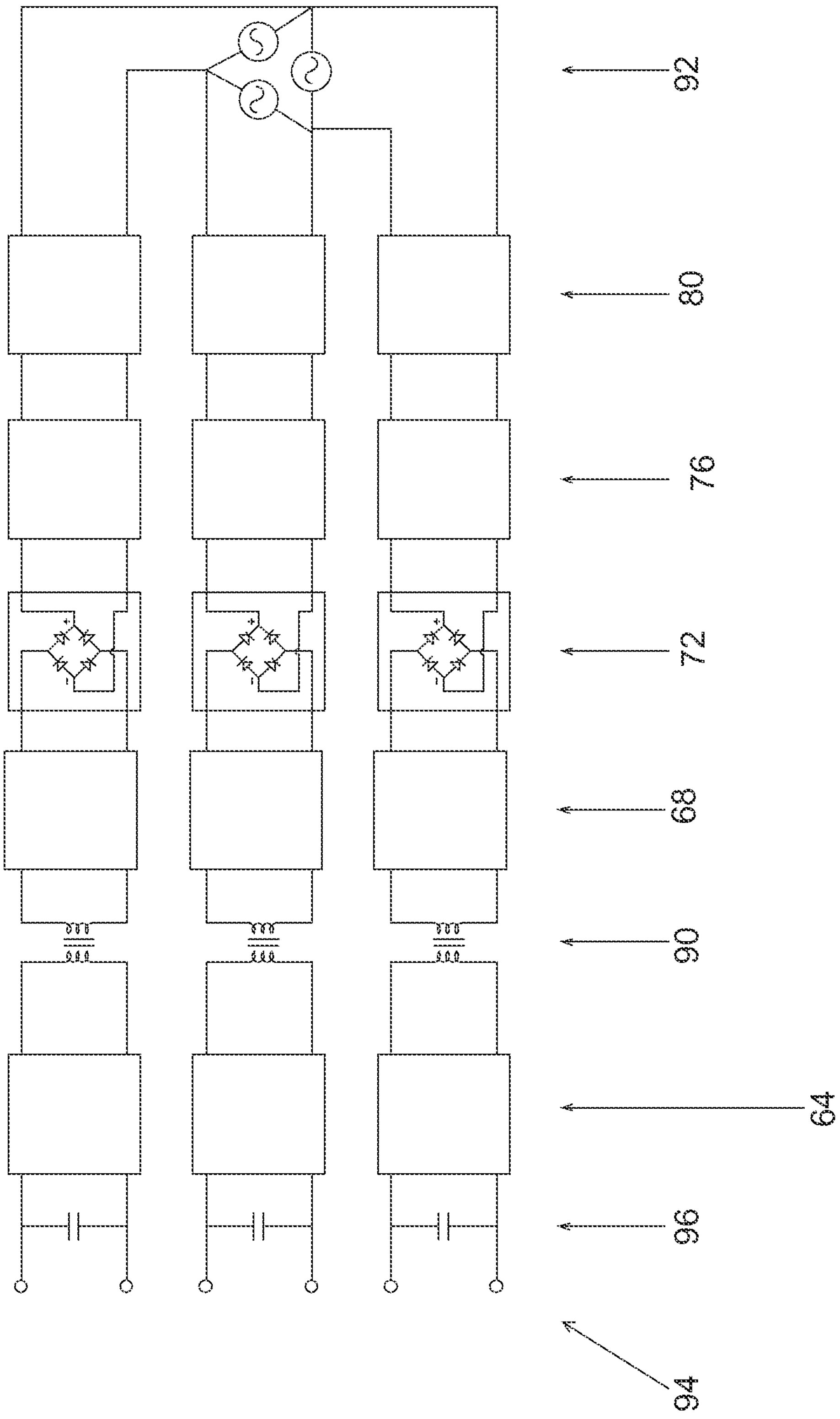

Figure 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/056204

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H02M 7/00 (2015.01)
CPC - H02M 7/00 (2015.10)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - H02M 1/00, 1/12, 1/14, 3/00, 3/335, 7/00 (2015.01)
CPC - H02M 1/00, 1/12, 1/14, 3/00, 3/335, 7/00 (2015.10)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 363/34, 84, 88, 89, 90 (Keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Orbit, Google Patents, Google, ProQuest
Search terms used: rectifier, impedance inverter, ripple filter, power factor correction

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2011/0254379 A1 (MADAWALA) 20 October 2011 (20.10.2011) entire document	1-18
Y	US 4,916,380 A (BURROUGHS) 10 April 1990 (10.04.1990) entire document	1-18
Y	US 3,704,433 A (GARRISON et al) 28 November 1972 (28.11.1972) entire document	2, 13
Y	US 4,992,723 A (ZYLSTRA et al) 12 February 1991 (12.02.1991) entire document	3-8
Y	US 8,384,371 B2 (ROSE) 26 February 2013 (26.02.2013) entire document	4
Y	US 3,792,286 A (MEIER) 12 February 1974 (12.02.1974) entire document	5
Y	US 7,679,943 B2 (O'BRYANT et al) 16 March 2010 (16.03.2010) entire document	9
Y	US 2010/0124083 A1 (TINSLEY, III et al) 20 May 2010 (20.05.2010) entire document	17, 18

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 December 2015	12 JAN 2016

Name and mailing address of the ISA/	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

(19)中华人民共和国国家知识产权局

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代理人 李春晖 李德山

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H02M 7/00(2006.01)

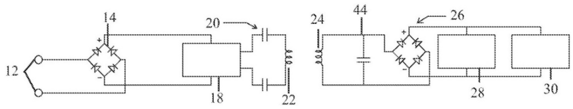
权利要求书2页 说明书7页 附图6页

(54)发明名称

用于内在功率因数校正的方法和设备

(57)摘要

一种具有内在线功率因数校正的谐振感应无线电力传输设备提供了一种在不采用特定功率因数校正电路的情况下在线连接点处提供接近一的功率因数的低谐波失真负载的无线传输方法。该设备提供以整流的正弦供应电压替代常规直流电压来操作的传输频率转换器。谐振感应传输线圈对通过添加具有特定值的两个串联的谐振电容器而转变成阻抗变换器。阻抗变换器在轻负载条件下提升次级侧电压并以此方式促使线频率源电流与次级侧负载电流成比例,从而保持接近一的线负载功率因数和低的谐波电流失真。



CN 107112912 A

1.一种内在功率因数校正设备,包括：

AC线源；

线频率整流器,所述线频率整流器连接至所述AC线源以提供半正弦整流供应电压；

阻抗变换器,所述阻抗变换器对所述半正弦整流供应电压进行响应以在输出处提供阻抗变换后的次级侧电压；

次级侧整流器,所述次级侧整流器对所述次级侧电压进行整流；

次级侧纹波滤波器,所述次级侧纹波滤波器对来自所述次级侧整流器的整流输出进行滤波以去除变换器频率纹波,并且在输出处提供线频率半正弦电流;以及

负载,所述负载接收所述线频率半正弦电流,

其中,所述阻抗变换器在轻负载条件下提升所述次级侧电压以促使来自所述AC线源的线频率源电流与所述负载处的所述线频率半正弦电流成比例,以保持接近一的线负载功率因数和低谐波电流失真。

2.根据权利要求1所述的设备,其中,所述阻抗变换器包括TermanT形配置阻抗匹配网络和具有以下值的两个串联的谐振电容器,所述值被选择使得所述阻抗变换器具有90度的传输相移,所述90度的传输相移促使施加至所述负载的负载电流量值与所述AC线源成比例并且同相。

3.根据权利要求1所述的设备,其中,所述AC线源包括三相AC线源,所述三相AC线源的每个相连接有线频率整流器以提供半正弦整流供应电压,求和变压器提供与所述AC线源的电隔离,所述求和变压器的输出被提供至所述阻抗变换器。

4.根据权利要求3所述的设备,其中,所述求和变压器包括三个物理上独立的变压器。

5.根据权利要求3所述的设备,其中,所述求和变压器包括在公共芯上具有六个绕组且三相的部分通量相消的单个变压器。

6.根据权利要求3所述的设备,还包括在三相AC线上的抑制所述传输频率转换器的开关频率分量的滤波器。

7.根据权利要求3所述的设备,其中,提供至所述负载的所述线频率半正弦电流是来自每个AC线相的彼此偏移120度的三个整流的正弦曲线之和。

8.根据权利要求1所述的设备,其中,所述AC线源包括三相AC线源,所述三相AC线源的每个相连接有线频率整流器以提供半正弦整流供应电压,初级侧感应线圈被实现为与连接至所述次级侧整流器的次级侧感应线圈共享公共磁芯的三个独立且共位的感应线圈。

9.根据权利要求1所述的设备,其中,所述AC线源是插入式充电器。

10.根据权利要求1所述的设备,其中,所述负载是电池充电负载。

11.根据权利要求1所述的设备,其中,所述负载是能够以来自单相线源的半正弦电流波形或多相线源之和进行操作的电化学负载或电镀负载。

12.一种内在功率因数校正设备,包括：

DC电源；

并联纹波滤波电容器,所述并联纹波滤波电容器提供对所述DC电源的输出的线频率纹波滤波；

DC至AC转换器,所述DC至AC转换器将来自所述并联纹波滤波电容器的输出的经线频率纹波滤波的DC电压转换成输出方波电压；

阻抗变换器,所述阻抗变换器将所述输出方波电压转换成处于所述DC至AC转换器的频率的正弦波,所述正弦波由线频率正弦曲线进行包络调制以形成双极性正弦包络;

次级侧整流器,所述次级侧整流器将所述双极性正弦包络整流成单极性半正弦包络;

去整流网络,所述去整流网络将所述单极性半正弦包络的每隔一个周期的极性反转以产生正弦波形;以及

AC负载,所述AC负载接收所述正弦波形,

其中,所述阻抗变换器在轻负载条件下提升次级侧电压以促使来自所述DC电源的线频率源电流与所述AC负载处的电流成比例,以保持接近一的线负载功率因数和低的谐波电流失真。

13.根据权利要求12所述的设备,其中,所述阻抗变换器包括Terman阻抗变换网络,所述Terman阻抗变换网络提供随着所述Terman阻抗变换网络的次级侧处的瞬时负载电压而变化的电压变换。

14.根据权利要求12所述的设备,还包括纹波滤波器网络,所述纹波滤波器网络用于在所述单极性半正弦包络被施加至所述去整流网络之前从所述单极性半正弦包络中去除高频纹波。

15.根据权利要求12所述的设备,其中,所述去整流网络包括处于半波或全波桥配置的功率半导体开关。

16.根据权利要求12所述的设备,还包括提供所述DC电源与所述AC负载之间的电隔离的隔离变压器。

17.一种针对施加至AC负载的三相恒定电压的每个相包括有如权利要求16所述的内在功率因数校正设备的设备。

18.根据权利要求17所述的设备,其中,所述DC电源包括三个等电压的独立DC电源。

用于内在功率因数校正的方法和设备

[0001] 相关申请的交叉引用

[0002] 本申请要求于2014年10月20日提交的美国临时专利申请62/065,889号的优先权。该申请的内容通过引用并入本文中。

技术领域

[0003] 本发明涉及借助于谐振感应的电能传输。更特别地，本发明涉及在不采用特定功率因数校正电路的情况下在线连接点处提供接近一的功率因数的低谐波失真负载的无线传输方法。作为替代，本文中描述的设备提供低谐波失真、接近一的功率因数，而无需特定功率因数校正级，从而降低了部件成本、设备尺寸和电力转换损耗。

背景技术

[0004] 感应式电力传输具有跨许多行业和市场的许多重要应用。虽然文中包含的公开内容考虑将本发明用于需要相对较高功率(超过100瓦)的应用，但是电力应用的潜在名单不受限制，并且本发明可以应用于广泛的电力需求。

[0005] 图1示出了现有技术谐振感应电力传输系统10的概念表示。如所示出的，在AC线12上提供交流源线频率电能，并且利用线频率整流器14和并联电容器纹波滤波器16将所述交流源线频率电能转换成直流电。DC-AC转换器18将直流能量转换成高频交流电，高频交流电借助于谐振网络20被施加至初级侧感应线圈22。典型的工作频率在15-50kHz的范围内。

[0006] 初级侧感应线圈22与次级侧感应线圈24之间的磁耦合将初级侧能量传输至次级侧，在次级侧，能量被高频整流器26整流、被纹波滤波器28进行纹波滤波并被用于对远端定位的电池30充电。谐振网络32使次级侧感应线圈24谐振，从而实现最大电流流动和最大能量传输。

[0007] 呈现给图1的电路中的AC线连接的负载的性质由线整流器-并联纹波滤波电容器组合来确定。在操作中，除非瞬时整流线电压超过并联电容器电压，否则线整流器电流为零。这意味着整流器电流不是正弦的，而作为替代是正好在线电压正弦曲线达到其最大值之前发生的窄脉冲。因为整流器电流是窄脉冲而不是正弦曲线，因此整流器电流包含相当多的谐波含量。关联的线频率谐波电流对电力配电部件有害并且也对连接至配电系统的其他负载有害，因此由于实用性或政府监管而被限制在低幅度。

[0008] 另一难点在于线频率整流器电流峰值发生在线频率电压最大之前的事实。这意味着线频率整流器电流脉冲的基本谐波分量超前于线频率电压正弦曲线，从而产生也受到监管限制的不期望的超前电流因数。增加并联线频率纹波滤波电容器16的电容降低了直流线频率纹波的幅度，但是也不利地增加了整流器电流脉冲的幅度并且减小了整流器电流脉冲的宽度，从而增加了不期望的线频率谐波失真和不能接受的线功率因数。

[0009] 问题则在于如何在将线频率交流电转换成直流电的同时从线电压源汲取同相正弦电流。图2示出了该问题的常规解决方案，即添加功率因数校正级34。注意，该使用中的功率因数校正意味着整流器产生的线频率谐波失真的消除以及线频率电压和电流正弦曲线

的对准。

[0010] 图2所示的功率因数校正级34包括DC至DC升压转换器，但是也可以采用降压转换器和升压-降压转换器拓扑。在图2中被描述为并联场效应晶体管36的并联开关器件借助于脉冲持续时间来控制电感器电流，并因此控制AC线电流。当并联晶体管36导通时，电感器电流以与瞬时整流线电压成比例的速率斜升。当并联晶体管36关断时，存储在电感器38中的能量通过串联二极管40被转储在并联滤波电容器16中。控制电路42监测整流的线电流并且不断地调节晶体管导通间隔，使得整流的线电流保持与线电压成比例。以这种方式，使得线频率整流器电流为半周期正弦并且与线电压幅值成比例、促使谐波失真为零、促使功率因数为一以及保持DC-AC转换器供应电压基本恒定。

[0011] 然而，图2描述的功率因数校正的常规方法存在至少两个明显的缺点。即添加的电力转换级增加了设备的成本和体积，并且还引入了不期望的能量转换损耗。期望在不采用这样的特定功率因数校正电路的情况下在谐振感应电力传输系统中的线连接点处提供接近一的功率因数的低谐波失真负载。本发明解决了本领域的该需求。

发明内容

[0012] 本发明通过改变谐振感应无线电力设备的操作参数来解决现有技术的上述限制，使得所述设备内在地提供低谐波失真的具有接近一的功率因数的线负载，而不需要另外的能量转换功率因数校正。去除了常规电路的后整流器、线频率纹波滤波器和并联电容器，并且DC至AC转换器不是由平滑的恒定值DC电压供电，而是由根据对线正弦曲线的全波整流得到的半正弦电压来供电。

[0013] 在示例性实施方式中，由DC-AC转换器产生的高频矩形波的包络不再是恒定的，而是以半正弦方式连续变化。常规传输线圈对与具有被特定选择的值的谐振电容器组合，使得谐振传输线圈对变成具有90度传输相移的谐振阻抗变换器，所述90度传输相移促使系统负载电流量值以及因而的AC线电流与AC线电压成比例并且同相，从而确保接近一的AC负载功率因数和低AC线谐波电流含量。

[0014] 在无线电力传输线圈对的次级侧，整流器对传输频率正弦曲线进行整流。后整流滤波器去除变换器频率纹波并且将线频率半正弦电流提供至恒定DC电压负载。在三相AC线源实施方式中，提供至负载的电流是彼此偏移120度的三个整流的正弦曲线之和，并且因此具有降低的线频率纹波。

[0015] 在示例性实施方式中，本发明提供一种保持接近一的AC线功率因数和低AC线谐波电流含量的设备。在传输侧，系统包括：线频率整流器，其后不跟有线频率纹波滤波器；DC至AC转换器，其将整流的AC线频率转换为幅值以半正弦方式连续变化的经包络调制的高频矩形波形；传输线圈对，其与具有被特定选择的值的谐振电容器组合，使得谐振传输线圈对变成具有90度传输相移的谐振阻抗变换器；以及初级侧感应线圈。在接收侧，系统包括传输频率整流器和关联的传输频率纹波滤波器，以向接收侧负载提供半正弦非交变DC电流。

[0016] 在另一示例性实施方式中，本发明用在电力从DC电源流向AC负载的应用中。在这样的实施方式中，内在功率因数校正设备包括：DC电源；并联纹波滤波电容器，其提供对DC电源的输出的线频率纹波滤波；DC至AC转换器，其将来自并联纹波滤波电容器的输出的经线频率纹波滤波的DC电压转换成输出方波电压；阻抗变换器，其将输出方波电压转换成处

于DC至AC转换器的频率的正弦波，该正弦波被线频率正弦曲线进行包络调制以形成双极性正弦包络；次级侧整流器，其将双极性正弦包络转换成单极性半正弦包络；去整流网络，其将单极性半正弦包络的每隔一个周期的极性反转以产生正弦波形；以及AC负载，其接收正弦波形。如在AC源和DC负载的情况下一样，阻抗变换器在轻负载条件下提升次级侧电压以促使来自DC电源的线频率源电流与AC负载处的电流成比例，以保持接近一的线负载功率因数和低谐波电流失真。在示例性实施方式中，这通过将Terman阻抗变换网络用作为阻抗网络来实现，以提供随Terman阻抗变换网络的次级侧处的瞬时负载电压而变化的电压变换。还可以提供纹波滤波器网络以在单极性半正弦包络被施加至去整流网络之前从单极性半正弦包络中去除高频纹波。去整流网络本身可以包括处于半波或全波桥配置的功率半导体开关。

[0017] 在又一实施方式中，使用三个独立的DC至AC转换器串来接纳三相AC电网负载，其中，每个串驱动一起构成AC三相恒压负载的三个AC恒压负载之一。每个串中可以使用隔离变压器以提供DC电源与AC负载之间的电隔离。另外，DC电源可以包括三个等电压的独立DC电源，或者三个DC源节点可以被连在一起并且由单个DC电源馈电。

附图说明

[0018] 根据以下结合附图的详细描述，本发明的前述有益特征和优点以及其他有益特征和优点将变得明显，在附图中：

[0019] 图1是不具有功率因数校正的现有技术谐振感应无线电力传输系统的概念表示。

[0020] 图2是添加有功率因数校正电路的现有技术谐振感应无线电力传输系统的概念表示。

[0021] 图3是本发明的实施方式的概念表示。

[0022] 图4是Terman T形配置阻抗匹配网络的表示。

[0023] 图5示出了将耦合的电感器T形无线电力线圈对等效电路转换成谐振阻抗变换器的转换。

[0024] 图6是用于图3的实施方式的计算机电路分析的电路的示意图。

[0025] 图7是示出在谐振和偏离谐振下通过对负载电流与变换器源电压的计算机建模而生成的spice仿真的线性结果的图。

[0026] 图8是使用三个隔离的转换器和转换器输出电压求和将本发明应用于三相线频率源的概念表示。

[0027] 图9示出了可替选实施方式，其中由被实现为共享公共磁芯的三个独立且共位的感应线圈来替代图8的求和变压器。

[0028] 图10示出了DC至AC转换器的概念框图和关联的电压波形，该DC至AC转换器用于其中电力以相反方向即从DC源流向ac负载并且设备提供接近一的功率因数的AC源的应用。

[0029] 图11示出了用于使用如图9中的三个独立的DC至AC转换器串来接纳三相AC电网负载的实施方式，其中，每个串驱动一起构成AC三相恒压负载的三个AC恒压负载之一。

具体实施方式

[0030] 通过参考结合形成本公开内容的一部分的附图和示例的以下详细描述可以更容

易地理解本发明。要理解，本发明不限于本文中描述的和/或示出的特定产品、方法、条件或参数，本文中使用的术语仅用于通过示例的方式描述特定实施方式的目的，而不意在限制任何所要求保护的发明。类似地，关于可能的机制或作用模式或改进理由的任何描述仅意味着是说明性的，并且本文的发明不受任何这样的建议机制或作用模式或改进理由的正确性或不正确性的限制。

[0031] 现在将参考图3至图11来描述本发明的说明性实施方式的详细描述。虽然本说明书提供了本发明的可能实现方式的详细示例，但是应当注意，这些细节意在是示例性的并且不以任何方式界定本发明的范围。

[0032] 如现在将要说明的，在谐振感应无线电池充电设备的背景下说明本文中描述的和在图3中示出的系统，但是对本领域技术人员而言明显的是本发明还具有许多其他应用。本领域技术人员将理解，图3的实施方式在多个方面背离常规的谐振感应无线电池充电实践。例如，电池充电电流不是恒定的；电池充电电流以半正弦或整流的正弦方式变化。以这种方式，电池充电电流与单相AC线电压正弦曲线源成比例并且同相。次级侧整流器负载阻抗被理解为非线性、表现为具有小的戴维南电阻的恒定电压负载。除非施加的交流电压超过电池端子电压，否则没有电流流过次级侧整流器。初级侧、次级侧感应线圈对22、24和关联的谐振电容器20、44可以被配置成在轻负载条件下用作电压升压网络。这样的谐振LC网络在轻负载条件下本质上是高Q，并且在谐振频率下大电压升压比是可能的。

[0033] 在没有整流器电流流动的时段期间，次级侧谐振电路中的电阻损耗为零，瞬时加载的Q非常高，并且发生显著的电压变换。在这样的瞬时空载条件下，施加至次级侧整流器26的谐振电路输出电压增加，直到其超过电池端子电压并且电池电流开始流动。在适当设计的情况下，可以使次级侧电池充电电流在整个线频率半周期的持续时间内流动，并且与AC线电压的绝对值成比例，从而在不使用特定功率因数校正级的情况下向AC线频率源提供低失真的功率因数为一的负载。

[0034] 本文中描述的本发明使用阻抗变换器(impedance inverter)，所述阻抗变换器提供根据需要随瞬时电池端子阻抗而不断地变化以在每个线半周期内保持线电流与线电压之间的比例性的电压变换。如本领域技术人员已知的，阻抗变换器是双向双端口网络，其中施加至一个端口的低阻抗在另一端口处产生高阻抗。

[0035] λ/4传输线变压器是阻抗变换器实现方式的示例。阻抗变换器实现形式不限于传输线实现方式。例如，存在包括梯形电路网络的多个集总电路配置。本发明使用由Terman(Radio Engineers handbook(无线电工程师手册)，第一版，McGraw Hill，1943)描述的在图4示出的三元件T形阻抗匹配网络。发现Terman阻抗匹配网络电抗如下：

[0036] $$Z_1 = -j\frac{R_1\,Cos\,\beta - \sqrt{R_1\,R_2}}{Sin\,\beta} \qquad Z_2 = -j\frac{R_2\,Cos\,\beta - \sqrt{R_1\,R_2}}{Sin\,\beta} \qquad Z_3 = -j\frac{\sqrt{R_1\,R_2}}{Sin\,\beta}$$

[0037] 其中，R_1是双端口源阻抗，R_2是双端口负载阻抗，并且β是以弧度为单位的通过网络的相移。T形阻抗匹配网络在被设计为具有90度|β|＝π/2的传输相移时用作为阻抗变换网络。对于|β|＝π/2，电抗设计等式被简化为：

[0038] $$Z_1 = Z_2 = -Z_3 = -j\sqrt{R_1\,R_2}$$

[0039] 在示例性实施方式中，R_1和R_2的值不是恒定的，而是在每个整流的半周期期间不断

地变化。几何乘积$\sqrt{R_1 R_2}$是恒定的，并且三个网络电抗具有相等的量值。该观察结果用于谐振感应线圈匹配网络的后续设计。

[0040] 图5示出了可以如何将谐振感应无线电力线圈对变换成谐振Terman阻抗变换器。图5A示出了在19kHz下具有.385的耦合系数的无线电力传输线圈对的无线电力线圈对等效电路。初级侧绕组和次级侧绕组的电感为130μH、互感为50μH，在19kHz下电抗分别为+j17.9和+j5.97。

[0041] 在图5B中，谐振电容器46、48被添加至图5A的等效电路的网络串联臂中。选择电抗以完全抵消串联电感器Z1、Z2在19kHz处的电抗，并且添加具有与并联互感元件Z3也在19kHz下的电抗相同量值的另外的串联容抗。图5C中得到的网络是包含无线电力传输耦合电感器对的阻抗变换双端口等效电路。

[0042] 图5C的阻抗变换网络如下所述地降低或消除感应无线电力传输线电流谐波失真。正好在线电压过零之后，整流的线电压的量值和变换器电压输出的量值比较小。提供至车辆电池30的整流电流为零或非常小。Terman阻抗变换器的次级侧的阻抗非常高；因此，阻抗变换器的初级侧的阻抗非常低。阻抗变换器看到低阻抗负载并且提供大的初级侧电流。次级侧电压增加直到其超过电池电压。电池充电电流开始流动，变换器所看到的阻抗增加，系统稳定于适中的线电流、适中的变换器电流、适中的电池充电电流。

[0043] 在线电压周期的峰值附近，整流的线电压的量值和阻抗变换器电压输出的量值较大。提供至车辆电池的整流电流也较大。Terman阻抗变换器的次级侧的阻抗较低；因此，阻抗变换器的初级侧的阻抗相对较高。阻抗变换器的补偿作用使得线电流和电池充电电流与线电压的量值成比例，这恰好是功率因数为一和零谐波失真所需的条件。可以使用常规的线滤波器网络来抑制转换器开关频率瞬变。

[0044] 图6示出了表示图3所示类型的谐振感应无线电力设备的电子电路的示意图，对于所述电子电路，传输线圈对22、24已经被转换成遵循图5概述的方法的谐振阻抗变换器，以进行时域计算机电路分析。由它们的等效T形电路表示的相互耦合的无线电力感应线圈被转换成遵循针对图5描述的方法的谐振阻抗变换网络50，其中所述等效T形电路具有电感为130μH并且互感为50μH的初级侧绕组和次级侧绕组。AC电压源52表示初级侧转换器18的输出电压。示出了次级侧高频整流器26和关联的高频纹波电流滤波器28。次级侧电池充电负载30由具有表示电池内阻的小的戴维南电阻的直流电压源表示。

[0045] 变换器输出电压幅值与整流的但未滤波的线频率电压成比例地变化。为了确定作为变换器电压的函数的负载电流，进行了计算机模拟。针对范围从零伏到整流的线电压的峰值的变换器输出电压的多个值进行时域电路模拟。图7绘制了作为变换器的整流正弦供应电压的函数的相应的负载电流。

[0046] 如图7所示，在AC电压源频率被设置为19kHz的情况下，网络谐振频率、电池充电电流是线性的并且与变换器源电压成比例。重要的是要注意，即使对于线源电压远小于电池开路端子电压也保持电池充电电流线性度，这是轻负载时谐振电路的电压变换特性的结果。图7的线性曲线示出了次级侧负载电流以及因而的变换器供应电流和线电流与线电压成比例的期望条件，该条件确保低水平的线频率谐波失真和为一的线频率功率因数。如图7所指示的，当在高于和低于阻抗变换器谐振频率在17kHz、18kHz和20kHz操作时，线电压/线电流关系在低线电压下不再成比例，从而引起线电流谐波失真和线功率因数降低。当在阻

抗变换器谐振频率下操作时，电流以半正弦或整流的正弦方式变化。

[0047] 常规地，有时对于作为整体的电池但还对于各个电池单元，电池充电由监测和控制电池充电电流和最大电池电压以及其他相关参数如温度的电池管理系统来调节。在当前实践中，电池/电池单元管理系统需要使用DC充电电流，并且在存在半正弦充电电流的情况下将可能会发生故障。通过响应于RMS充电电流而不是常规采用的平均或峰值测量方法来修改电池管理系统来消除这个困难。

[0048] 如由电池充电算法控制的，有效的电池充电需要根据电池充电状态来改变充电电流量值。在本发明的示例性实施方式中，通过阻抗变换网络的设计和向转换器18提供的整流的半正弦线电压的量值来设置最大电池充电电流量值。通过转换器18的脉宽调制、转换器脉冲定相、转换器脉冲下降以及次级侧整流器26的主动控制来获得对电池充电电流的进一步控制(降低)。这些单独或组合采用的控制方法使得能够有效地控制充电电流量值同时保持低谐波失真、接近一的功率因数。

[0049] 虽然低功率至中功率无线电力系统由单相电力连接而操作，但是大功率系统通常需要三相连接。即使整流的单相正弦曲线源具有大的纹波分量，但是三个整流的正弦源之和要小得多，其中各正弦曲线偏移120度。为了与电池管理系统电路的兼容性和降低峰值与平均充电电流比率，有时期望降低的充电纹波电流，以在快速充电期间限制电池电阻损耗。

[0050] 图8示出了利用三相线电压源54实现的本发明的实施方式。每个相具有单独的整流器14和转换器18。三个转换器同步地开关，并且转换器输出被求和变压器56进行合并，求和变压器56可以是三个物理上独立的变压器或在公共芯上具有六个绕组且三相的部分通量相消以使得更有效地使用芯材料的单个变压器。求和变压器56还提供与AC线的电隔离。三相线上的滤波器(图8中未示出)抑制转换器开关频率分量，从而引起新的功率因数为一的、低谐波失真三相负载。如现有技术图1所示，谐振网络20将转换器18与初级侧感应线圈22连接。初级侧感应线圈22与次级侧感应线圈24之间的磁耦合将初级侧能量传输至次级侧，在次级侧，能量被高频整流器26整流、被纹波滤波器28进行纹波滤波并且被用于对远端定位的电池30充电。谐振网络44使次级侧感应线圈24谐振，从而实现最大电流流动和最大能量传输。

[0051] 图9示出了图8的可替选实施方式，其中，求和变压器56被初级侧感应线圈22替代，其中初级侧感应线圈22被实现为与连接至次级侧整流器的次级侧感应线圈共享公共磁芯的三个独立且共位的感应线圈23。单独的DC-AC转换器18和关联的线频率整流器14通过谐振网络20来驱动三个初级线圈中的每个线圈。然后，电力求和作为初级线圈通量场之和而发生，使得不需要专用的组合变压器56。本领域技术人员将理解，图9的实施方式以添加两个初级线圈和两组谐振电容器为代价降低了组合变压器的尺寸、重量和成本。

[0052] 可以有利地在除谐振感应无线电力传输系统之外的设备中采用如本文中描述的Terman阻抗变换器网络的功率因数校正作用。这样的应用包括：

[0053] 有线——与无线相对的——电池充电；

[0054] 金属电镀；

[0055] 电化学处理如电解；

[0056] 感应加热；

[0057] 交流焊接；

[0058] 包括荧光和弧光照明的气体放电过程;以及

[0059] 向可以忍受全波整流的正弦直流电的负载提供根据交流源得到的直流电的任何其他应用。

[0060] 在无线感应电力传输的功率因数控制中,Terman阻抗变换网络被合并到无线传输的相互耦合的空心线圈对的T形等效电路中,其中,T形等效电路的一个元件是互感。本领域技术人员将理解,在非无线电力传输应用中,阻抗变换网络可以在三个离散的非相互耦接的部件处实现,从而显著提高了设计灵活性。

[0061] 在上面所论述的应用中,电力从AC源流向DC负载,并且设备向AC源提供具有接近一的功率因数的负载。本发明的教导同样适用于电力沿相反方向即从DC源流向AC负载并且设备提供接近一的功率因数的AC源的应用。反向电力流动设备得到作为将来自替代能源诸如光伏板和风力发电机的DC电力馈送至50Hz或60Hz的公用电网中的转换器的应用。

[0062] 图10示出了DC至AC转换器系统的概念性框图和关联的电压波形,该系统用于其中电力沿相反方向即从DC源流向AC负载并且设备提供接近一的功率因数的AC源的应用。如所示出的,图10的电路包括DC电源60,其后是提供线频率纹波滤波的并联纹波滤波电容器62。经线频率纹波滤波的DC电压被施加至高频DC至AC转换器64。在此上下文中高频意味着相对于线频率是高的。输出方波电压66被施加至Terman阻抗变换网络68的输入,Terman阻抗变换网络68提供随着阻抗变换网络的远端处的瞬时负载电压而变化的电压变换。

[0063] 在阻抗变换网络68的输出处的波形70是处于DC至AC转换器频率的被线频率正弦曲线进行包络调制的正弦波。高频整流器72将双极性正弦包络转换成单极性半正弦包络74。高频纹波滤波器网络76去除高频纹波,从而给出无纹波的线频率半正弦波形78。包括处于半波或全波桥配置的功率半导体开关的去整流网络80将波形78的每隔一个周期的极性反转以产生波形82,从而允许电力流入表示无限电网的恒定AC电压负载84。

[0064] 三相AC电网负载如图11所示与三个独立的DC至AC转换器串接纳,每个串与添加有隔离变压器90的单相转换器串相同。每个串驱动一起构成AC三相恒压负载92的三个AC恒压负载之一。隔离变压器90提供与AC负载92的电隔离。DC源94可以是三个等电压的如图10所示的独立DC电源或者三个DC源节点可以连在一起并且由单个DC电源馈电。滤波电容器96滤除如果不滤除的话将会存在于DC源节点处的120Hz半正弦电流变化。元件和操作另外与图10的电路配置相同。

[0065] 本领域技术人员将理解,本发明不限于无线电力装置应用。除了无线感应充电应用之外,本发明还可以应用于输电行业以外的用途,如AC感应马达、马达控制器、谐振电力供应、工业感应加热、熔化、焊接和表面硬化装备、焊接装备、电力变压器、电子物品监视装备、感应烹饪用具和炉子、其他工业装备、包括通过插入式充电器插入式充电的其他应用以及其他非电池充电应用如电化学、电镀和所有其他可以以来自单相线源的半正弦电流波形或由多相线源之和得到的降低纹波的波形来操作的负载。这些实施方式和其他这样的实施方式被认为包括在由所附权利要求书限定的本发明的范围内。

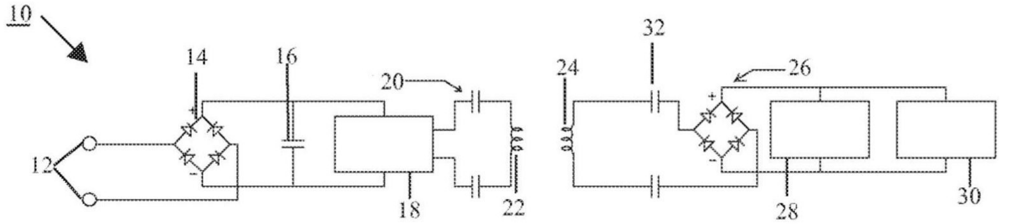


图1现有技术

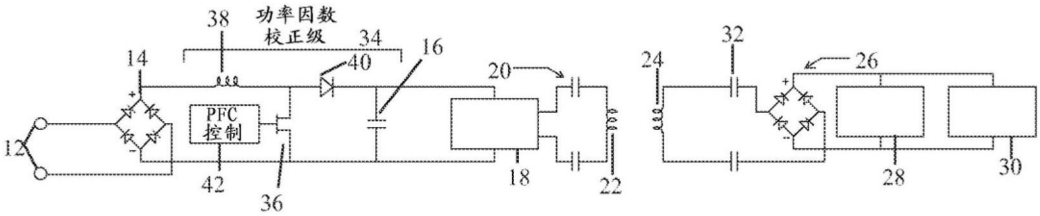


图2现有技术

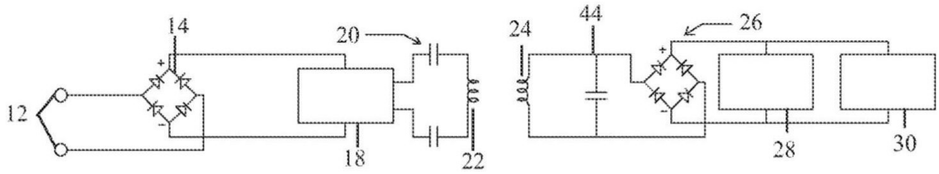


图3

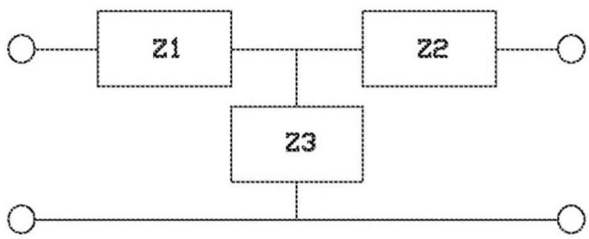


图4

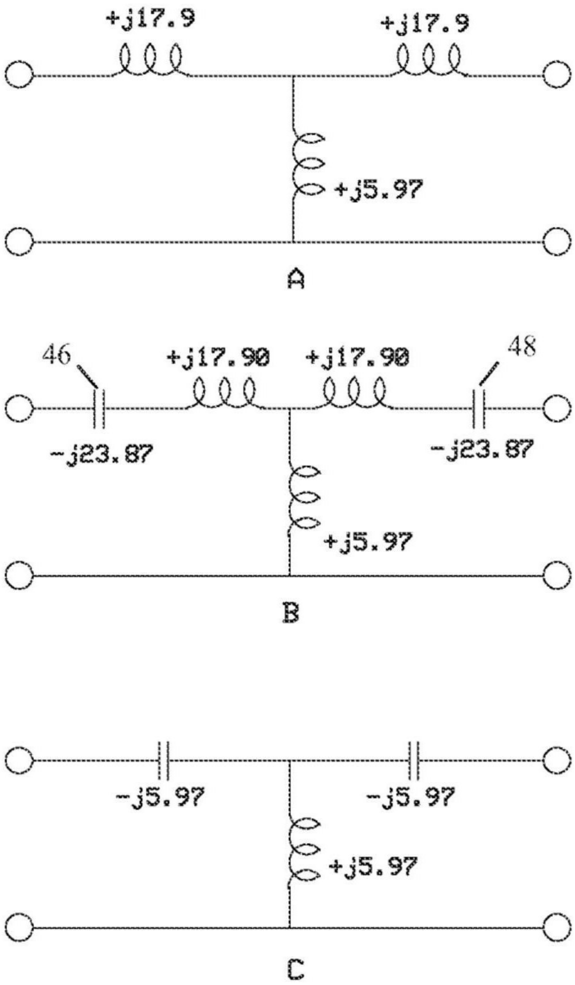

+j17.9
+j17.9
+j5.97
A
46
+j17.90
+j17.90
48
-j23.87
-j23.87
+j5.97
B
-j5.97
-j5.97
+j5.97
C

图5

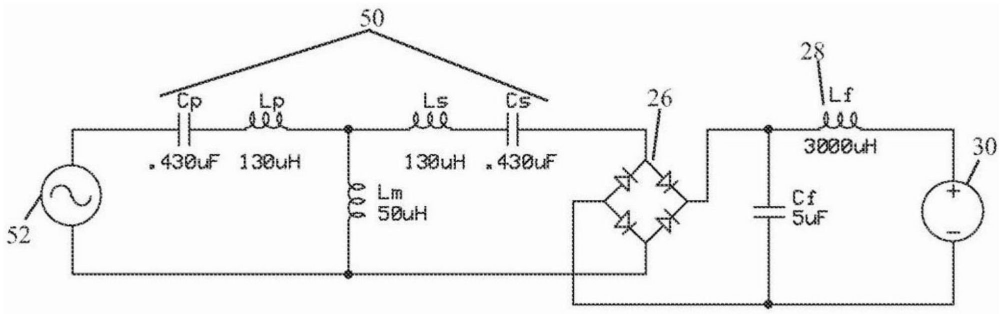
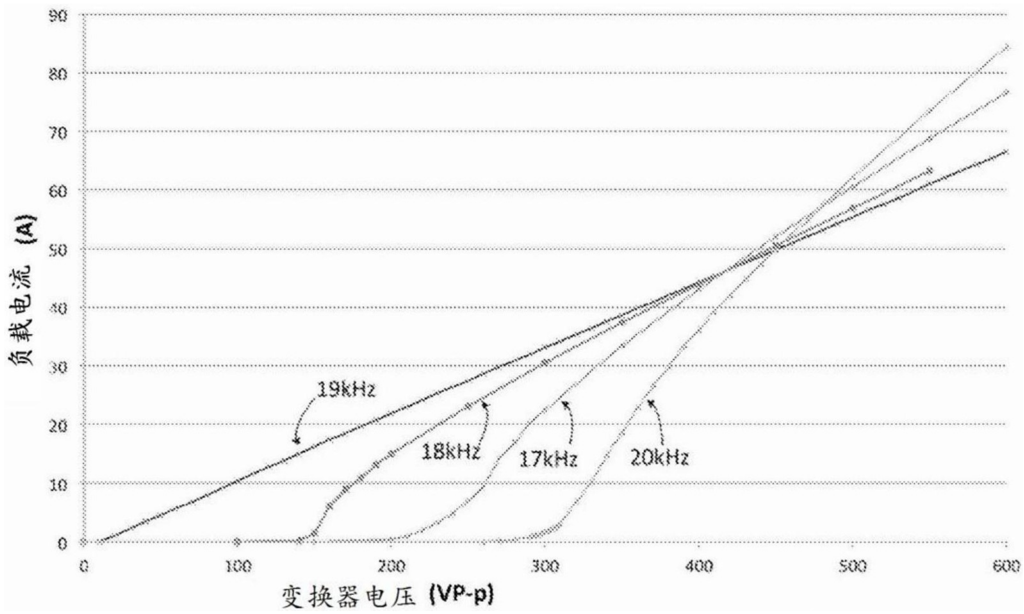
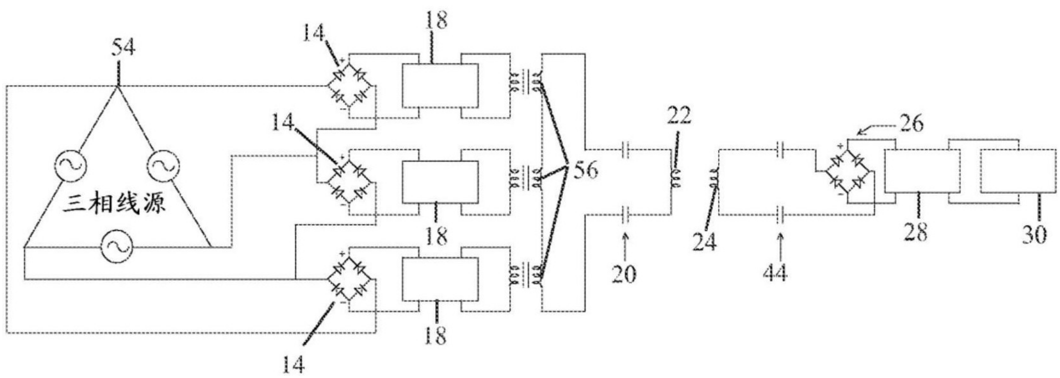

50
Cp
Lp
Ls
Cs
.430uF
130uH
130uH
.430uF
Lm
50uH
52
26
28
Lf
3000uH
Cf
5uF
30

图6



负载电流 (A)
变换器电压 (VP-p)
19kHz
18kHz
17kHz
20kHz

图7



54
三相线源
14
18
56
22
26
20
24
44
28
30

图8

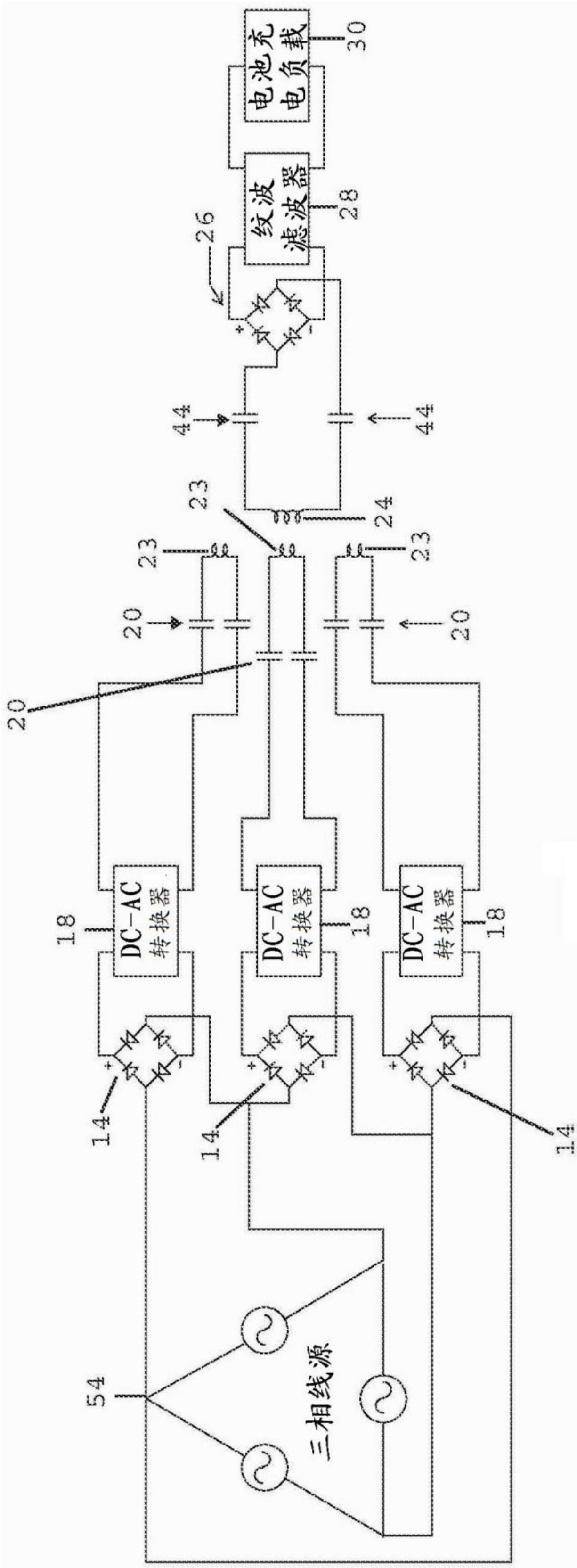

电池充电负载
30
纹波滤波器
28
26
44
44
23
24
23
23
20
20
20
DC-AC转换器
18
18
18
14
14
14
54
三相线源

图9

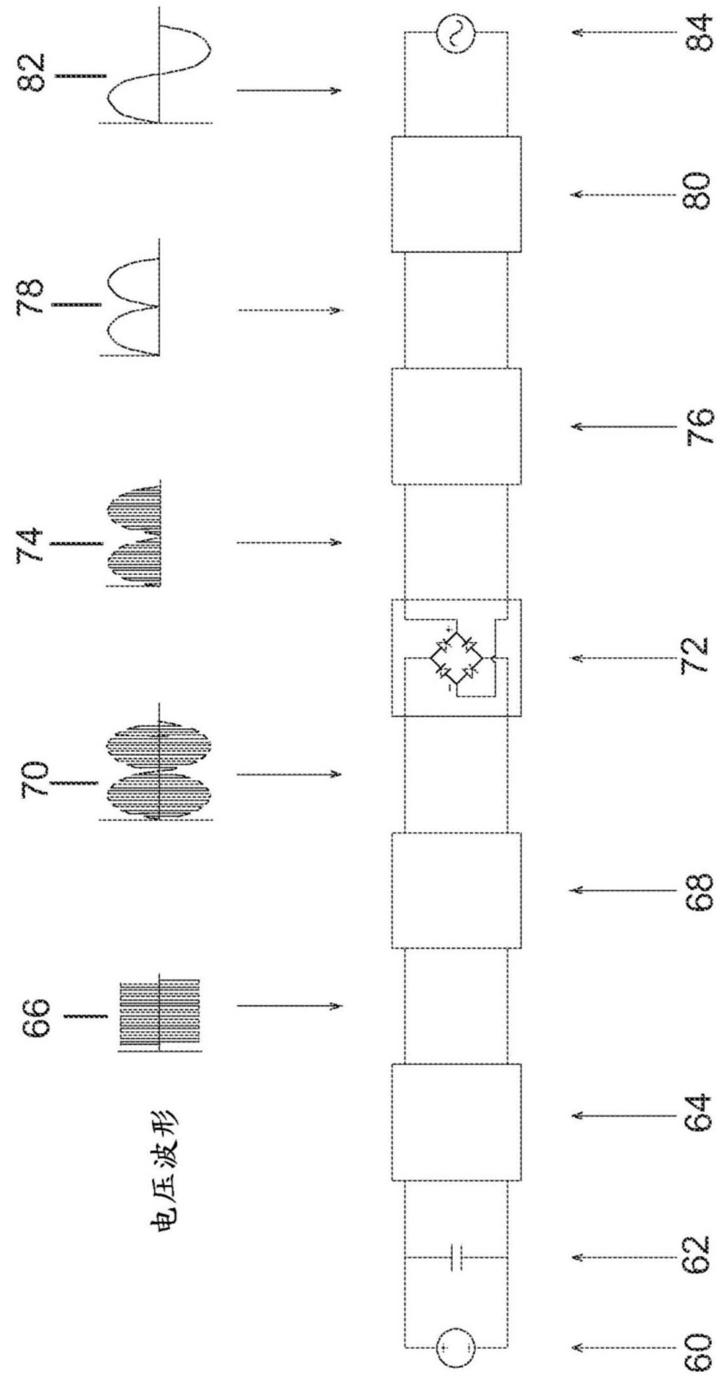


图10

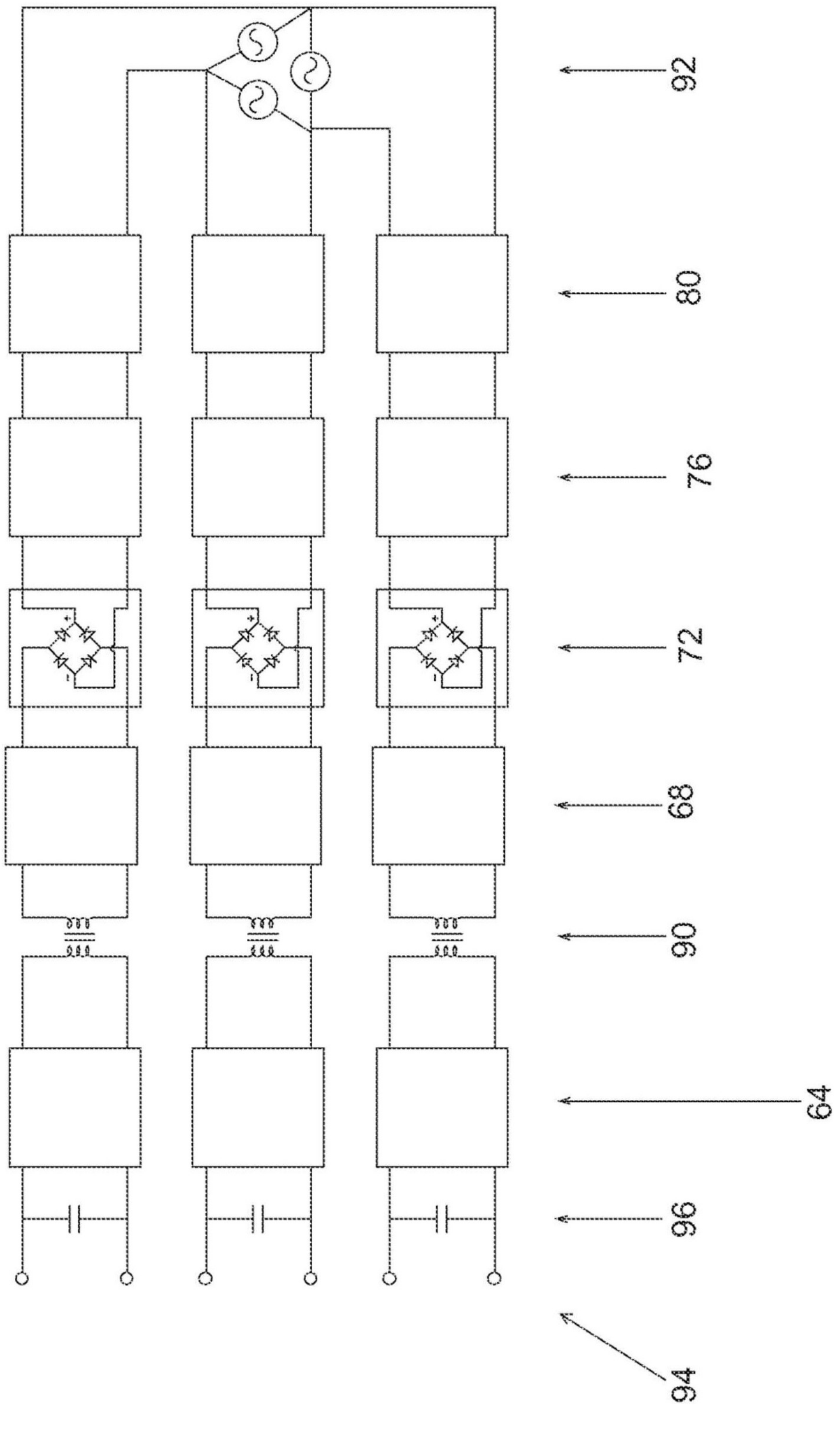


图11