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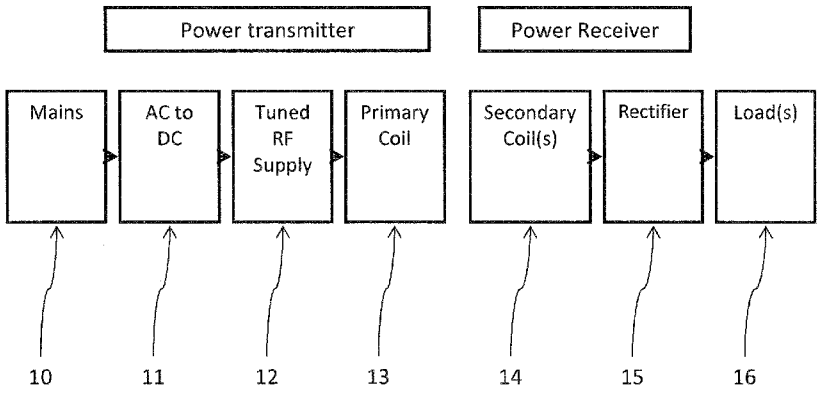


FIG. 1

(57) **Abstract**: Embodiments of the subject invention pertain to a method and apparatus for contactless power transfer. A specific embodiment relates to an impedance transformation network, a new class of load network for application to a contactless power system. Embodiments of the impedance transformation network enable a contactless power system to operate without encountering the common problems of: 1) over-voltage and/or under-voltage conditions; 2) over-power and/or under-power conditions; 3) power oscillations; and 4) high heat dissipation.

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DESCRIPTION

METHOD AND APPARATUS FOR CONTACTLESS POWER TRANSFER

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Serial No. 61/059,663, filed June 6, 2008, which is hereby incorporated by reference herein in its entirety, including any figures, tables, or drawings.

BACKGROUND OF INVENTION

In recent years, inductive charging technology has become a leading candidate to eliminate power cables. Inductive power systems and other contactless power systems typically use one or more transmitters to send power to one or more receivers. Electronic devices with contactless power receivers can be powered or charged by being positioned in close proximity to a contactless power transmitter. Such systems have been designed and implemented.

Contemporary contactless power systems are make use of switch-mode inverters, such as the Class, D, DE, E, E^{-1}, F, F^{-1}, EF, EF2, EF3, Phi. The switch-mode inverter converts DC voltage that is provided by a DC voltage source to into a high frequency signal that enables efficient coupling of one or more primary coils to one or more secondary coils. The secondary coils are ultimately connected to one more loads. In the case of a contactless power transfer system the load of an inverter is typically a portable electronic device or some other load device with a variable power requirement. In many instances the load has an input impedance that is variable. The load can use energy or it can be designed to store energy. The load can comprise a voltage regulator and / or a power management system for regulating and relaying the power to an energy consuming or energy storing element. The impedance of the load helps determine the loading condition.

A typical switch-mode inverter comprises an active device, a supply network, and a load network with output terminals for connecting to a load.

The active device is typically a transistor and operates as a switch. The switch alternates between a conductive and non-conductive state. A control signal from a gate drive or clock can be used to operate the switch. The switch is connected to a supply network and a load network. The switching of the active devices helps form an AC signal at the output of the load network.

The supply network relays power from a source the DC voltage source to a terminal of the active device. The DC voltage source can have an output voltage that is variable. The supply network can be a simple inductor and typically comprises passive components. In some cases it may comprise an active device or variable elements for active reconfiguration of the supply network. A reconfiguration of the supply network can be performed depending on the load conditions in order to optimize efficiency or regulate the power which is delivered from the source.

The load network relays power to the load device from a terminal of the active device and supply network. The load network typically comprises passive components. In some cases it may contain an active device or variable for active reconfiguration of the load network. A reconfiguration of the load network may be performed depending on the load conditions in order to optimize efficiency and / or regulate the power delivered to the load.

The load network includes one or more primary coils for inductively coupling to one or more secondary coils. Because of size mismatches and restrictions on the use of bulky core materials, the coupling between the primary and secondary coils can be weak thereby reducing efficiency, power delivery, or both.

In order to compensate for weak coupling between primary and secondary coils, typical inductive charge systems typically operate at frequencies greater than 50kHz. At these higher operating frequencies soft-switching inverters, such as the Class E, E^{-1}, are preferred because they are more efficient than hard-switching inverters. High efficiency is preferable for environmental and regulatory reasons as well as practical reasons such as minimizing heat dissipation.

Soft-switching describes a mode of operation where an active device, such as a transistor, will switch when either the voltage or current across the transistor is zero. Soft-switching eliminates losses that normally occur with hard switching due to switch capacitance and the overlap of voltage and current in the switch. For example, in the case of zero voltage switching, the voltage across a transistor to swings to zero before the device turns on and current flows. Likewise, at turn-off, the voltage differential across the active device swings to zero before it is driven to a non-conductive state.

A practical system is preferably capable of matching the power supplied to the power demanded by a load device. This is important because many load devices have variable power requirements. If the power delivered does not match power required, the excess energy can be dissipated as heat. A load device can have an input impedance that is variable because of a power requirement that is variable (see Figure 5 for a graph of resistance versus changing

time for a typical cell phone battery). The input impedance of the load device can change by an order of magnitude. The input impedance of a voltage regulator connected to a portable electronic device can change by two orders of magnitude. The variable impedance of a load device makes the implementation of contactless power system difficult.

The following two characteristics of soft-switched inverters found in typical contactless power system make the adaptation to a load device with a variable impedance challenging: 1. Most switch-mode inverters have high efficiency over a narrow range of impedances. As an example, a class E inverter typically operates under, high-efficiency soft-switched conditions over a factor of two in load impedance (see Figure 3) (Raab, 1978). (see Figure 2 for a graph of efficiency versus normalized resistance for typical switch-mode inverters); 2. The output power vs. load impedance relationship of a switch-mode inverter is different than the output power vs. load impedance relationship of a DC supply (See figure 4 for a graph of power delivery vs. load resistance for a DC supply and an inverter). Because of this, a load device's pre-existing power management control system can fail to appropriately regulate the power delivered to the load device which can lead to component failure.

Due to the above described characteristics a contactless power system is likely to encounter one or more of the following problems: 1) over-voltage and/or under-voltage conditions throughout the circuit; 2) excess or inadequate power delivery to individual loads 3) power oscillations; 4) heat problems; and 5) low efficiency.

Notably, a class D inverter architecture does not share the unfavorable characteristics and resulting problems of the other soft-switched inverters. Class D inverters are optimized for driving an impedance looking into the load network that has zero-phase angle (ZPA), and works for positive phase angles. Zero phase angle operation can be maintained by eliminating the reactance in a circuit of by using a combination of control functionalities, including, but not limited to, frequency, and tank circuit control (see Figures 7 and 8). A contactless power system with other soft-switched inverter architectures would be expected to make use of similar control functionality because of their sensitivity to the input impedance of the load(s). (Laouamer, R., *et al.*, " A multi-resonant converter for non-contact charging with electromagnetic coupling," in *Proc. 23rd International Conference on Electronics, Control and Instrumentation,* Nov 1997, Vol. 2, pp. 792 – 797; Abe, H., *et al.*, "A non-contact charger using a resonant converter with parallel capacitor of the secondary coil," in *Proc. Applied Power Electronics Conference and Exposition,* 15-19 Feb 1998, Vol. 1, pp. 136 – 141; Joung, G. B. *et al.*, "An energy transmission system for an artificial heart using leakage inductance compensation of transcutaneous transfor*mer," IEEE Transactions on Power*

Electronics, Vol. 13, pp. 1013 – 1022 Nov 1998; Lu, Y., *et al.*, "Gapped air-cored power converter for intelligent clothing power transfer," in *Proc. 7th International Conference on Power Electronics and Drive Systems,* 27-30 Nov. 2007, pp. 1578 – 1584; Jang, Y., *et al.*, "A contactless electrical energy transmission system for portable-telephone battery chargers," *IEEE Transactions on Industrial Electronics*, Vol. 3, pp. 520 – 527, June 2003; Wang, C., *et al.*, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer system," *IEEE Transactions on Industrial Electronics*, Vol. 51, pp. 148 – 157, Feb. 2004; Wang, C., *et al.*, "Investigating an LCL load resonant inverter for inductive power transfer applications," *IEEE Transactions on Power Electronics*, Vol. 19, pp. 995 – 1002, July 2004; Wang, C., *et al.*, "Design consideration for a contactless electric vehicle battery charger," *IEEE Transactions on Industrial Electronics*, Vol. 52, pp. 1308 – 1314, Oct. 2005) Control functionality adds to the cost and complexity of a system and detracts from the commercial viability.

To enable better control functionality and to ensure proper operation of the system, communication systems between the power supply and the load have been proposed (see Figures 6 and 9). Such communication systems also add undesirable cost to the system.

The previously described control functionality has been implemented in both contactless power transmitters and contactless power receivers. Control functionality in the receiver has been considered of particular importance when multiple loads require power from the same transmitter. To support multiple loads, it has been proposed that receiver units incorporate mechanisms such as, but not limited to, variable inductance and duty cycling. These mechanisms allow multiple loads to receive power from the same source by giving load devices a mechanism to protect themselves from over-voltage and/or current conditions (Figure 6). These mechanisms are of high importance because loads without such mechanisms will continue to receive power even when they no longer require power. The power will be dissipated as heat in the load device. Contemporary batteries will not charge at temperatures over 50°C. These systems also add undesirable cost to the system.

SUMMARY OF THE INVENTION

Embodiments of the subject invention pertain to a method and apparatus for contactless power transfer. A specific embodiment relates to an impedance transformation network, a new class of load network for application to a contactless power system. Embodiments of the impedance transformation network enables a contactless power system to operate without encountering the common problems of: 1) over-voltage and/or under-

voltage conditions; 2) over-power and/or under-power conditions; 3) power oscillations; and 4) high heat dissipation.

Embodiments of the impedance transformation network enables the contactless power system to avoid one or more of the four common problems described above, without any feedback, communication, and/or control functionality. The pre-existing power and battery charge management circuitry for a load, which may include a voltage regulator, can regulate the power output of a contactless power system under normal modes of operation. In accordance with embodiments of the invention, contactless power systems can be combined with very simple controls to improve the performance of the system. In this preferred mode of operation, a contactless power system can predictably and reliably deliver power to a load across a wide range of load impedances.

Embodiments of the invention provide one or more of, and a preferred embodiment of the invention provides each of, the following four functions:

1) Reactance shifting and phase angle control: a reactance is added to the resistance looking from the switch-mode supply through the load network. The reactance is shifted such that the phase angle looking from the switch-mode inverter into the load network is within a range that provides substantially soft-switching operation of the active device either when connected to or disconnected from one or more loads. Embodiments of the invention use the phase angle to control the power delivered by the inverter. Such embodiments can take advantage of the correlation between phase angle and load resistance. Changes in load resistance are transformed into a shift in the phase angle looking into the impedance transformation network. The output power response is more pronounced with respect to phase than with respect to load resistance (see Figure 12). This enables the invention to match power delivery and more closely mimic the response of a traditional DC supply (see Figure 13). In this method of operation, the contactless power system can deliver the necessary amount of power to the load. The soft-switching operation of the active device is preferably maintained for all load impedances.

If the inverter is designed for soft switching when the impedance looking into the load network from the active device is inductive, then the impedance transformation network is configured such that the impedance of the phase angle looking from the active device into the load network is positively correlated with the effective resistance of the load(s). If the effective resistance of the load increases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network increases. If the effective resistance of the load decreases, then the impedance transformation

network is configured such that the phase angle looking from the active device through the load network decreases. In a specific embodiment the reference phase angle is 40 degrees or greater, and in another 45 degrees or greater. In further embodiments, increases in load resistance can increase the phase angle up to 85 degrees.

If the inverter is designed for soft switching when the impedance looking into the load network from the active device is capacitive, than the impedance transformation network can be configured such that impedance of the phase angle looking from the active device into the load network is negatively correlated with the effective resistance requirement of the load. If the effective resistance of the load increases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network decreases. If the effective resistance of the load decreases, then the impedance transformation network is configured such that the phase angle looking from the active device through the load network increases.

The effective resistance is a combination of the resistances of the loads looking from the terminals of the secondary coils toward the load. The loads can be seen as in series or parallel. The loads can be seen as the series or parallel combination of the inverse of the individual load resistances. In the generalized form, the effective load resistance of any close proximity contactless power system via magnetic induction that incorporates m primary coils and n secondary coils can be described by:

$$Z_{in} = \{1_{1M}[\mathbb{Z}^{IV} - (\mathbb{Z}^{II})^T(\mathbb{Z}^{I})^{-1}\mathbb{Z}^{II}]^{-1}1_{M1}\}$$

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}^{III} & (\mathbb{Z}^{II})^T \\ \mathbb{Z}^{II} & \mathbb{Z}^{I} \end{bmatrix}$$

$$\mathbb{Z}_{ab} = \begin{cases} j\omega L_a + R_a & \text{for } a = b \\ j\omega M_{ab} & \text{otherwise} \end{cases}$$

$$\mathbb{Z}^{IV} = \mathbb{Z}^{III} + Z_{in}1_{MM}$$

Zin: Input impedance looking into the primary coil

1_{1M}: Vector of 1's of length M

1_{MM}: M X M matrix of 1's

Z: Impedance matrix

Z_{ab}: Element ab of the impedance matrix

Z^{I} : Sub-matrix of Z

Z^{II}: Sub-matrix of Z

Z^{III}: Sub-matrix of Z

M_{ab}: Mutual inductance between the a^{th} and b^{th} coil

j: imaginary number

a: coil index

b: coil index

ω: radian frequency

R_a: Parasitic resistance of the a^{th} coil

L_a: Self inductance of the a^{th} coil

Typically, the power requirement of the device is negatively correlated with load resistance. As the resistance of the load increases the power required by the load decreases.

2) Resistance isolation: the resistance looking from the switch-mode supply through the load network can be minimally affected by changes in load resistance (see Figure 10);

Embodiments of the invention can isolate the switch-mode supply from changes in load resistance in order to improve the predictability and stability of the output power. The isolation from changes can be accomplished by the implementation one or more filter networks such that the range of resistances presented by load appear much narrower at the output terminals of a switch-mode inverter. The switch-mode supply should see a resistance such that it is in a high efficiency mode of operation (see Figure 2).

3) Frequency filtering: a filter removes extra harmonics, effectively "cleaning" the power signal before it enters the primary or secondary coil. In one embodiment this frequency filter incorporates an inductor and a capacitor with a "low Q" value. In another embodiment this frequency filter incorporates an inductor and a capacitor, the filter being considered to have a high Q value.

4) Coupling: at least one primary coil in the load network is inductively coupled to one or more secondary coils of the same load network. The primary coils can be configured in a spiral configuration and maybe designed with a variable pitch in order to create an even

magnetic field distribution. The primary coils can be arranged in an array pattern with each coil in the array wound with an irregular shape so that the array has a substantially even magnetic field distribution. The secondary coils can be coupled to the primary coil in any position or orientation. The secondary coil can be adapted to attach to a load. In a preferred embodiment the secondary coil is adapted to attach to a portable electronic device. In specific embodiments, both the primary coil and the secondary coil are the same size to maximize coupling. In this example, and other specific embodiments, the receiver coil is significantly smaller than the primary coil, in order to allow the user to place the device in any orientation. It is desirable for the secondary coil to be much smaller than the primary coil, but the efficiency and power transfer capabilities start to degrade significantly if the receiver is too small, due to poor coupling. In this example the secondary is wound along a single path with minimal spacing between turns in order to minimize the occupied volume and ease integration.

The voltage and current characteristics of the primary coil and the secondary coil can be described using the following equations [7][12]:

$$V_1 = M_{11}\frac{dI_1}{dt} + M_{12}\frac{dI_2}{dt} \quad (1)$$

$$V_2 = M_{21}\frac{dI_1}{dt} + M_{22}\frac{dI_2}{dt} \quad (2)$$

$$M_{12} = k\sqrt{M_{11}M_{22}} \quad (3)$$

Where

V_1 is the voltage at the transmitting coil

I_1 is the current at the transmitting coil

V_2 is the voltage at the receiving coil

I_2 is the current at the receiving coil

M_{11} is the self inductance of the transmitting coil

M_{22} is the self inductance of the receiving coil

$M_{12} = M_{21}$ is the mutual inductance of the two coils

k is the coupling coefficient between the two coils

By Ohm's law:

$$Z_{tx} = R_{tx} + jX_{tx} = \frac{V_1}{I_1} \quad (4)$$

$$Z_{rx} = R_{rx} + jX_{rx} = \frac{V_2}{I_2} \quad (5)$$

Solving equations (1-3)

$$Z_{tx} = \frac{\omega^2 M_{12}^2 R_{rx}}{R_{rx}^2 + (\omega M_{22} + X_{rx})^2} + j\left(\omega M_{11} - \frac{\omega^2 M_{12}^2 (\omega M_{22} + X_{rx})}{R_{rx}^2 + (\omega M_{22} + X_{rx})^2}\right) \quad (6)$$

The above equations neglect any 2nd order effects such as skin depth and proximity effects. A more in-depth analysis accounting for the above effects can be utilized. In an embodiment, litz wires can be used to mitigate such effects to the extent that they do not create significant discrepancies.

By using the combination of resistance isolation and phase angle control, a reliable, stable transmitter can power a variable load. First, the inverter preferably will not fail or overheat when the secondary coil is removed from the primary coil. Although a load detection scheme can be used to turn off the transmitter and reduce unloaded power losses, it can still be desirable for the unloaded power consumption to be sufficiently low. Since the coil voltage is unique to each load resistance as shown in Figure 49, load detection and status can be easily acquired. To avoid false detection, the load detection and status can be verified by analyzing the supply current via a current sense resistor. Limiting unloaded power loss can be achieved by ensuring the unloaded transmitting load network has effective impedance similar to a high load resistance case (high impedance with large phase angle). From the schematic of the class E circuit in Figure 44, it can be deduced that most of the power lost is due to the primary coil and inductor parasitic resistances as they are in the path of power transfer. Therefore, one way to reduce the unloaded power loss is to use an inductor with lower parasitic resistance.

BRIEF DESCRIPTION OF DRAWINGS

The foregoing and other objects, features, and advantages of the present invention, as well as the invention itself, will be more fully understood from the following description of various embodiments, when read together with the accompanying drawings.

Figure 1 shows a typical contactless power system that uses an inverter to drive a primary coil that may couple to one or more secondary coils and loads.

Figure 2 shows the operating efficiency versus load resistance seen by an inverter (Class E) that is driving load resistances from .1 to 10, a span that reaches two orders of magnitude, where the high efficiency operating range for the inverter is identified, and the operating range of a typical portable electronic device is identified.

Figure 3 shows the power in (Pi) and power out (Po) versus load resistance seen by an inverter (Class E) that is driving load resistances from .1 to 10, a span that reaches two orders of magnitude, where the high efficiency operating range for the inverter is identified, and the operating range of a typical portable electronic device is identified.

Figure 4 shows the power delivered to a variable load resistance from two different sources: a tuned switch-mode inverter supply and a fixed voltage DC supply, illustrating that power delivered to the load across a range of impedances is very different depending on the source, and that the range of output power can be much smaller with switch-mode inverters.

Figure 5 shows the load resistance of a Motorola Razr during the charge cycle, illustrating that during the charge cycle, the resistance can change by greater than one order of magnitude.

Figure 6 shows a block diagram of a typical prior art contactless power system, including commonly proposed and implemented communication and control functionality.

Figure 7 shows a logic diagram, which is continued in Figure 8, of a typical prior art contactless power system, including commonly proposed and implemented control functionality.

Figure 8 shows a continuation of the logic diagram of Figure 7.

Figure 9 shows a block diagram of a typical prior art wireless power system with communication capability.

Figure 10 shows the correlation between load resistance and the resistance looking from the inverter in accordance with an embodiment of the subject method, where the load resistance is transformed such that the resistance seen by the switch-mode supply is relatively constant, and in particular, the resistance from the supply is seen as between 2 and 6 ohms while the resistance of the load is varied from 5-500 ohms.

Figure 11 shows the operating efficiency and power output of a class E inverter that is driving a fixed resistance with a phase angle ranging from -90 to 90 degrees, where the operating region for an embodiment of the invention is indicated.

Figures 12A and 12B show the power output of a class E inverter in response to variable load resistance and variable phase, respectively, showing a calculation of output range and compares them against each other.

Figure 13 shows the power delivered to a variable load resistance from three different sources: an inverter, a fixed voltage DC supply, and a switch-mode inverter operating in accordance with an embodiment of the invention.

Figure 14 shows the decoupling, or degradation of coupling efficiency between the load and the transmitter for various filter networks.

Figure 15 shows a block diagram of a system in accordance with an embodiment of the subject invention, where the block diagram shows the direction of power flow and the various networks that can be used.

Figure 16 shows a typical load resistance vs. time plot as seen from the input of a rectifier feeding into a device.

Figure 17 shows the real and reactive components of the impedance as seen looking into the receiver side impedance transformation network, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 18 shows the real and reactive components of the impedance as looking into the primary coil, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention .

Figure 19 shows the real and reactive components of the impedance as seen from the transmitter side load-transformation network, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 20 shows the real and reactive components of the impedance as seen from the transmitter-side, phase shift network, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 21 shows the phase angle of the impedance as it is seen from the inverter, where the impedance characteristic at this point is measured from a system operating in accordance with a preferred embodiment of the invention.

Figure 22 shows the actual power delivery and efficiency of a system that is operating in accordance with a preferred embodiment of the invention.

Figures 23A-23C show the actual power delivery and efficiency for another system in accordance with the invention. The experimental results are from a 12V supply system. Efficiency peaks at main power delivery band, which is approximately 25-100Ω load resistance, are shown. Power delivery drops rapidly after 100Ω, when the system goes into low load condition or trickle charge condition. Although the efficiency at high load resistance is poor, the absolute power loss is kept at about 1.75W, while power delivery continues to drop. This power loss is distributed in the system and little or no heat issues are observed (especially at the receiver) during the low load operation.

Figure 24 shows the phase angle of the impedance as it is seen from the inverter, where the impedance characteristic at this point is measured from a system operating in the non-preferred mode of operation.

Figure 25 shows the actual power delivery and efficiency of a system that is operating in the non- preferred mode of operation.

Figures 26A-26B show the instantaneous peak power loss for hard switching topologies, known in the art, as they are compared to soft-switching topologies, known in the art, where Figure 26A shows a "hard switching" topology power loss waveform for a bridge MOSFET (320 W/div) showing high instantaneous peak power loss during each switching cycle, and Figure 26B shows a "soft switching" topology power supply with the same rating as that in Figure 26A.

Figure 27 shows the real and reactive components of the impedance as seen looking into the receiver side impedance transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 28 shows the real and reactive components of the impedance as looking into the primary coil, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 29 shows the real and reactive components of the impedance as seen from the transmitter side load-transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 30 shows the real and reactive components of the impedance as seen from the transmitter-side, phase shift network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 31 shows the circuitry shown in Figure 68 with dotted lines, labeled A and B, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 32 shows the block diagram of Figure 15 with dotted lines, labeled A and B, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 31.

Figure 33 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 34 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 33.

Figure 35 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 36 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 35.

Figure 37 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 38 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 37.

Figure 39 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 40 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram

elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 39.

Figure 41 shows a typical inductive coupling system.

Figure 42 shows some of the possible topologies for a single-element transformation network.

Figure 43 shows some of the possible topologies for a single-element transformation network.

Figure 44 shows a typical Class E driver using parallel-parallel transformation network.

Figure 45 shows a dual channel class E driver that can be used in accordance with an embodiment of the invention.

Figure 46 shows an impedance response looking into receiver with different parallel capacitor value.

Figure 47 shows an optimum receiver capacitor value across a range of load resistances to achieve maximum R looking into the transmitter coil.

Figures 48A-48B show a coupling efficiency and transformed impedance looking into the primary coil.

Figure 49 shows a normalize primary coil voltage across a range of load resistances.

Figure 50 shows a load network reactance with different transmitter capacitor.

Figure 51 shows an amplitude and phase of impedance of unloaded transmitter load network with different C_{tx}.

Figure 52 shows an impedance looking into transmitter load network.

Figure 53 shows a phase looking into transmitter load network.

Figure 54 shows a power delivered into the transmitting load network if transmitter is an ideal sine voltage source.

Figure 55 shows a transistor drain voltage where C_{shunt} = 19nF.

Figure 56 shows a dual channel class E driver.

Figure 57 shows a primary coil – 10 turns (embedded into the table top) and secondary coil – 5 turns (taped up).

Figure 58 shows a power delivery and efficiency of 120V system with a peak power of 295W.

Figure 59 shows a temperature of transistor and inductor with natural convection cooling and forced cooling.

Figure 60 shows a dual channel class E with forced air cooling.

Figure 61 shows a waveform of the class E driver.

Figures 62A-62B show power delivered to load with respect to load resistance. Peak power occurs at approximately 50Ω load resistance for dual channel at 69W for dual channel and 75Ω for single channel at 10W for single channel.

Figure 63 shows system efficiency with respect to load resistance with both peak efficiency of 64.5% for single channel and 76% of dual channel at approximately 70Ω load resistance.

Figure 64 shows transmitter efficiency with respect to load resistance. Peak transmitter efficiency occurs across the band of 60Ω to 100Ω load resistance at 90% for dual channel and 79% for single channel.

Figure 65 shows system efficiency with respect to load resistance with both cases achieving high efficiency at heavy load and also illustratin that a single channel mode is more efficient at low power delivery state.

Figure 66 shows primary coil RMS voltage having a unique load resistance for each value.

Figure 67 shows receiver DC voltage converging to approximately 70V for dual channel and 37V for single channel.

Figure 68 shows a generalized contactless power system with a single transistor power amplifer in a single ended configuration.

Figure 69 shows a generalized contactless power system with two, single transistor power amplifiers in a push-pull configuration.

Figure 70 shows a generalized contactless power with a two transistor power amplifier in a single ended configuration.

Figure 71 shows a generalized contactless power system with two, two transistor power ampliferrs in a push-pull configuration.

Figure 72 shows different supply network configurations that are used to connect a DC supply voltage to a terminal of the active device of a power amplifier.

Figure 73 shows the functions of a impedance transformation network for a single ended system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 74 shows the functions of a impedance transformation network for a push-pull system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 75 shows various circuit elements arranged to achieve the fuction of reactance shifting. These circuit elements, or variants thereof, can add or remove the mangitude of reactance looking into the impedance transformation network. Inductive elements increase reactance. Capacitive elements decrease reactance.

Figure 76 shows various circuit elements arranged to achieve the fuction of frequency filtering. Two notch filters are shown that can remove unwanted harmonics from the signal. A combination of other filter types can be used to achieve frequency filtering.

Figure 77 shows various circuit elements arranged to adjust the correlation between the equivelent resistance and the phase of the load. Inductive elements will tend to result in a positive correlation between phase and load resistance. Capacitive elements will tend to result in a negative correlation between phase and load resistance. These elements can also serve the purpose of resistance compression.

Figure 78 shows primary to secondary coil configurations. The impedance transformation network may comprise a single primary and a single secondary. Alternatively, the impedance transformation network may comprise one or more primary coils coupled to one or more secondary coils. The inductance of the primary and/or secondary coil(s) can be used to compress resistance and change the phase vs. resistance relationship.

Figure 79 show various circuit elements arranged to compress the resistance seen looking into the impedance transformation network. Either capacitive or inductive elements can be used.

Figure 80 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 81 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 82 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 83 shows a typical configuration of an impedance tranformation network connected to an active device.

DETAILED DISCLOSURE

Contactless power systems typically use high frequency power electronics to deliver power to one or more loads. Figure 1 shows the fundamental components of many contactless power systems. A contactless power supply generally draws its power from the electrical grid through a standard wall outlet **10**. The power from the wall is typically AC so it is generally

converted to DC voltage by an AC to DC converter 11. In order to shrink the size of components it is desirable to work at a high frequency, so the DC voltage is switched by an inverter **12**. The high frequency signal, such as a high frequency voltage signal or high frequency current signal, is fed into one or more primary coils **13**. The high frequency signal may pass through one or more filters before it feeds in to the primary **13**. The primary coil **13** couples with one or more secondary coils **14**. The secondary coil **14** will receive the high frequency power signal and will feed that into a rectifier **15**, which will then output power to the load **16**. One or more filter networks may be present between the secondary coil **14**, rectifier **15**, and load **16**. Voltage regulation and battery charge management circuitry may be considered part of load **16**.

The incorporation of a switch-mode inverter can make it difficult to deliver the correct amount of power to the load or loads. This is partially attributable to the limited range of load resistances that enable high-efficiency operation. Figure 2 shows the high efficiency operating range **20** of an inverter as it compares to the operating range **21** of a typical battery operated device. The operating range of resistances of the battery operated device is substantially wider than the high efficiency operating range or the inverter. Figure 3 shows the relation of input power **34** and output power **33** of an inverter across a range of resistances. The lost power can be calculated by subtracting output power **33** from input power **34**. The power loss is significant outside the high efficiency operating region **31**.

Switch-mode inverters are difficult to implement in contactless power systems with variable loads because the output power response relative to load resistance is very different than a DC supply's output power response relative to load resistance. Figure 3 shows output power **33** increasing with load resistance until it reaches a center value and decreases again. This is different than a typical constant-voltage DC supply whose power delivery follows the relationship P=V^2/R. The difference is illustrated in Figure 4 where we can see that the power delivery from a DC supply **41** will decrease rapidly with an increase in load resistance. By contrast, the output power from an inverter **42** will increase with load resistance and will later drop as load resistance continues to increase. The drop in power delivery **42** is markedly slower than the drop in power delivery **41**. Although Figure 4 shows the curve for one example of a tuned switch-mode inverter supply, other tuned inverters can have different curves.

Portable electronic devices display a wide range of input resistances. Figure 5 shows the effective resistance **51** looking into a Motorola Razr during the charge cycle. Figure 5

shows the wide dynamic range of the load **52**, and in this case it is greater than one order of magnitude.

The aforementioned challenges of efficiency and power delivery can be overcome by implementing a variety of communications and controls. Figure 6 shows a contactless charging system that is an elaboration of the basic components and systems show in Figure 1. The grayed blocks are components that are found in a basic contactless power system. The white boxes are components that enhance the performance of a typical contactless power system. It show a transmitter control **60** which can alter the phase, duty cycle, frequency, tank circuit impedance, or rail voltage depending on loading conditions. There is a detection circuit **61** that draws information from various parts of the circuit and feeds that information back into the controller **60**. It show contactless communication links **62** on both the transmitter side **66** and receiver side **67**. The communication link can work in conjunction with the detection mechanisms **61** to help the controller **60** make the most appropriate adjustments to the system. The receiver side **67** also has a controller **63** which can adjust the resonant frequency, duty cycle **65**, or perform other functionality to regulate power being delivered to the load. A front end regulator **64** is added to provide an additional level of protection to the load.

With a system such as the one in Figure 6 in place, designers can implement control logic such as that shown in Figure 7 and Figure 8 taken from a prior art system. We can see from Figure 8 **433**, **434**, **436**, **438**, **440**, **442** some of the logic functionality that designers have built into contemporary contactless power systems. We can see from **432** that this system includes memory in order to achieve the desired functionality. Figure 9 shows another prior art system that uses a communication mechanism **91** on the receiver and a communication mechanism **90** on the transmitter. The communication, logic, and use of memory add additional cost to the system and require a large number of sensing points to be considered.

In order to stay within the high-efficiency operating region **20** and to match the power delivery of DC supply **41** several steps can be taken. Figure 10 shows the resistance seen by the switch-mode supply **100** as it compares to actual load resistance. From **100**, we can see that the resistance appears to vary from 2 to 6 ohms over a range from 5 to 500 ohms. This enables the switch-mode supply to stay in the high efficiency region **20** shown in Figure 2, regardless of load resistance.

Compressing the resistance will not solve the problem of improper power delivery. Figure 2 shows that if we keep the resistance in a narrowband, power output changes

minimally. In fact, the compression would exacerbate the power delivery discrepancy shown in Figure 4 where we see that power output response to load resistance from a switch-mode supply **42** does not match the power output response to load resistance from a constant voltage, DC supply. If too much power is delivered, the device may be destroyed, if too little is delivered it may not function.

In order to address the challenge, the phase angle of the load can be affected in order to affect the power output of the switch-mode supply, in accordance with embodiments of the invention. Figure 11 shows, for class E inverters, that an increase or decrease in phase correlates with an increase or decrease in output power. Input power **111** and output power **110** matched closely for a phase angle in the range of about +45 to +80 degrees. Even though efficiency **112** drops considerably as the phase angle approaches +90 degrees, the absolute power lost remains low. The use of phase angle control enables a +/-70% usable range of output power **113** with very low absolute power loss.

Embodiments of the invention use phase angle control to power a battery operated device. Conventional voltage regulators increase the resistance so that the power output of a DC supply is reduced **41**. Figures 12A-12B show, for class E inverters, the difference between using traditional resistance controlled output power vs. using phase controlled output power in accordance with embodiments of the invention. Referring to Figure 12A, in a resistance controlled scheme, input power **122** matches power out **123** for a very small dynamic range **125** of output power. This shows that varying the resistance is an ineffective way of controlling output power. The usable range of power levels for a resistance controlled scheme is only about +/- 9% **125** of the center value. Outside of this range the high absolute losses are high and can create harmful heat and wear and tear on components. Referring to Figure 12B, in a phase controlled scheme, input power **121** matches power out **120** for a much wider dynamic range of output power **124**. This shows that varying the phase dramatically increases the output power range. The usable range of power levels is +/- 70% **124** of the center value. Even though resistance may drop over this range, the absolute power losses are relatively low in this band **124**. Efficiency can be low, but total dissipated power is very low. The low absolute power loss avoids the problem of overheating and device damage.

By combining the resistance compression and the phase control, the contactless system can achieve a power output response to load resistance that is very similar to that of a conventional DC supply. Figure 13 shows the power output response of a DC supply **130**, an inverter **131**, and an inverter in accordance with an embodiment of the subject method of

operation **132**. The output power in response to load resistance of the inverter in accordance with the embodiment of the subject method of operation **132** is much closer to the output power a device should expect from a constant voltage DC supply **130**.

An additional challenge to designing and implementing a contactless power system is that multiple loads may draw power from a single source. This is problematic when different devices have different power requirements. For instance, a fully discharged cell phone may require 10-15 times the power of a fully charged cell phone. Embodiments of the subject method of operation can provide a mechanism to protect individual devices from damage if the power output exceeds the device requirement. Loads that no longer require power can be decoupled from the primary coil. De-coupling can include degradation in coupling efficiency so that the load is effectively isolated from the transmitter. This can be accomplished by using pre-existing voltage regulator behavior. As a voltage regulator increases the effective input resistance, coupling efficiency drops and vice-versa.

Figure 14 shows the decoupling effect for various receiver circuits. A parallel capacitor can be selected to tune the decoupling point, which is the point when efficiency of receiver is at 50%. For this case, the decoupling point for 100nF capacitor is at 700Ω, whereas the decoupling point for 150nF capacitor is at 320Ω. We can see that for various configurations **141**,**142**, **143** the rate of decoupling occurs at varying rates. **143** shows a curve that is a good fit for a single device charger that can regulate power output from the transmitter. **141** shows a curve that is good fit for a multi-device charger where individual loads may need to be isolated from the source. Although not shown in Figure 14, when the capacitor valve is changed the power received is also changed.

In order to accomplish this method of operation without any communication and control functionality, other than the pre-existing control found in today's voltage regulators, embodiments of the subject system can use a series of carefully tuned transformation networks that transform, compress, and shift the impedance of the load. Through these filter networks the resistance can be compressed, the phase angle manipulated, and the loads allowed to decouple from the primary.

Example 1:

A high power, high-efficiency contactless power transfer system using the impedance transformation network and has been designed and fabricated using the subject impedance transformation network. The contactless transfer system requires minimal control to achieve the desired power delivery profile across a wide range of load resistances, while maintaining high efficiency to which helps to prevent overheating of components. This embodiment of the

subject system includes more than one active device with independent gate drive to control power delivery. The system is able to achieve power delivery of 295W to a load of 50Ω with a DC voltage of 121.5V and current of 2.43A. The input current was current-limited at 3.25A. The system efficiency at maximum power output is 75.7%. The system operates at a minimum of 77% efficiency across load resistances ranging from 60Ω to 140Ω which corresponds to a high output power state. The system can be scaled to achieve higher output power if the current limit is removed. Higher efficiency and better power delivery can be achieved by using components with lower parasitic resistance.

The DC source voltage is the 600W CSI12005S power supply by Circuit Specialists, Inc rated at 120V at 5A. The active devices are transistors, specifically the transistors are part IRFP21N60L from International Rectifier.

A pair of coils was fabricated using 16 AWG magnet wire for the set-up. The primary coil is 21cm by 21cm with 10 turns with variable spacing between turns while the secondary coil is 13cm by 13cm with 5 turns wound along the same path. Figure 57 shows the primary coil embedded in plastic with the secondary coil placed on top. The primary and secondary coils are separated by a gap of 10mm. The primary coil is designed with the appropriate spacing between the turns to achieve only 5% power variation of the received power at all different locations. In this example, the coupling is approximately constant regardless of the receiver position provided that the entire secondary coil is within the outer perimeter of the primary coil. The self inductance of the primary coil is 31.95μH with a parasitic resistance of 0.32Ω and secondary coil is 12.52μH with a parasitic resistance of 0.2Ω. Mutual inductance between the coils is 7.454uH with a coupling coefficient of 0.373. The measurements were taken using the HP4192A LF Impedance Analyzer.

In order to reduce losses through parasitic resistance, low loss Polypropylene capacitors are used. In order to strike a balance between size and efficiency, 1140-101K-RC by Bourns Jw Miller is selected to be L_{out}. Since most of the losses of the transmitter are from the parasitic resistance of L_{out}, a larger and more efficient inductor can be replaced, if space permits. The fabricated dual channel driver with a dimension of 10cm x 8.5cm is shown in Figure 56. There are a lot of empty spaces; therefore its size can be further reduced. L_{out} takes up a significant amount of space due to the requirement for low parasitic resistance so as to maintain sufficiently high efficiency and power delivery.

Peak drain voltage is only 460V, which is approximately 25% lower than the rated voltage of the transistor used. Figure 58 shows the efficiency and power delivery of the 120V system with respect to load resistance. The power delivery of the system can be scaled by

varying the supply voltage as long as the DC power supply driving system is able to provide sufficient power and the drain voltage across the transistor stays within its breakdown voltage.

The efficiency of the single channel is approximately 10-15% lower for the same load resistance because the current is flowing through a single L_{out} inductor instead of a pair of them, which means the parasitic resistance is doubled, thus resulting in a low system and transmitter efficiency as shown in Figure 63 and Figure 64, respectively. However, when the system goes into light load mode or trickle charge mode, it would be desirable to go into the single channel mode. It can be seen from Figure 65 that the system efficiency is approximately 15% higher than the dual channel mode for delivering the same amount of power below 10W. Instead of operating at high load resistance for a dual channel mode resulting in high receiver DC voltage as shown in Figure 67, it is possible to achieve similar power delivery at much lower load resistance for a single channel mode resulting in lower receiver DC voltage as lower load resistance would result in higher system efficiency. In addition, a typical buck regulator has higher DC-DC efficiency when the input voltage is lower. Therefore, a load resistance detection scheme can be used to determine the switch over point from dual channel to single channel. It can be seen from Figure 62 that a power delivery of 10W occurs at 500Ω load resistance of the dual channel mode making it a good switch over point. It can be concluded that a 500Ω load resistance would translate to an approximate primary coil RMS voltage of 20V for the dual channel mode as shown in Figure 66. Likewise, if the power requirement for the single channel mode is too high, it can be switched to dual channel mode. It can be inferred from Figure 62 that the switch over point would be approximately 75Ω, which translates to a RMS coil voltage of 22V from Figure 65. The coil voltage can be read using an ADC where the DC voltage at the input of the ADC can be transformed from the coil voltage by rectification and stepping down using a potential divider.

In a specific embodiment, for size and efficiency considerations, capacitors can be used for the network. This is because resistors dissipate power and a low loss inductor would be large in size. Alternative embodiments can incorporate resistors and inductors. Although, a multi-element transformation network might achieve a more appropriate response, for simplicity and low components count, an embodiment of the system uses a single-element transformation network. Four topologies are shown in Figures 42 and 43.

A series capacitor only introduces a negative reactance and does not change the real part of the impedance. A parallel capacitor affects both the real and imaginary part of the

impedance. For simplicity, the receiver input impedance can be modeled using a variable resistor load such that equation (7) illustrates the transformation performed by the parallel capacitor.

$$Z_{rx} = \frac{R}{1+\omega^2 C^2 R^2} - j\frac{\omega C R^2}{1+\omega^2 C^2 R^2} \qquad (7)$$

Equation (7) shows that the resistance is "compressed" non-linearly by a factor of $1/(1+\omega^2 C^2 R^2)$. Thus, the effective resistance decreases with increasing load resistance. At high load resistance, the transformed resistance is small. Therefore, a significant part of the power received is dissipated across the secondary coil as heat. This phenomenon is actually desirable if the receiver is in a state that requires very little power or during trickle charge. Therefore, it has a "decoupling" effect regulating the power delivery with increasing load resistance. However, this should preferably occur only when the transmitter is designed to use limited power at this state of operation as heating would become an issue if too much power is being dissipated across the secondary coil. By using a parallel capacitor, a reactive term can be introduced. The reactive term decreases nonlinearly from null with increasing load resistance with an asymptote of $-1/\omega C$, which can be useful in compensating the secondary coil inductance.

From equation (6) it can be observed that the resistance looking into the transmitter coil can be reduced significantly with the increase of resistance looking from the receiver coil into the receiver. Due to loose coupling between the coils, the resistance looking into the primary coil can be further reduced as the mutual inductance can be relatively low. If the total resistance looking into the primary coil is comparable to the parasitic resistance of the primary coil, limited power is transmitted to the receiver as most of the power would be dissipated across the primary coil as heat. Therefore, it would be preferred for a power transmission via loosely coupled coils to have a parallel capacitor on the secondary coil. By substituting equation (7) into equation (6),

$$Z_{ex} = \left(\frac{\omega^2 M_{12}^2 \left(\frac{R}{1+\omega^2 C^2 R^2} \right)}{\left(\frac{R}{1+\omega^2 C^2 R^2} \right)^2 + \left(\omega M_{22} - \frac{\omega C R^2}{1+\omega^2 C^2 R^2} \right)^2} \right) + j \left(\omega M_{11} - \frac{\omega^2 M_{12}^2 \left(\omega M_{22} - \frac{\omega C R^2}{1+\omega^2 C^2 R^2} \right)}{\left(\frac{R}{1+\omega^2 C^2 R^2} \right)^2 + \left(\omega M_{22} - \frac{\omega C R^2}{1+\omega^2 C^2 R^2} \right)^2} \right) \quad (8)$$

For the transmitter transformation network, a series or parallel topology can be used. However, to maintain an ideal efficiency above 95%, the allowable variation of load resistance of an ideal class E inverter can be kept within +55% and -37% [F. H. Raab, "Effects of circuit variations on the class E tuned power amplifier," *IEEE Journal of Solid-State Circuits*, vol. 13, pp. 239 – 247, Apr 1978.]. Therefore, if the variation of resistance with respect to load resistance looking into the transmitter is too large, it can be preferable to use a parallel capacitor instead of a series capacitor. A capacitor value can be selected that ensures that the transmitter would not suffer immediate failure when there is no secondary coil as well as having an increasing reactance trend with increasing load resistance. Having an increasing reactance trend with increasing load resistance can ensure the preferred power delivery trend.

Figure 15 shows an example configuration of a system that can work in this mode of operation in accordance with an embodiment of the subject invention. Other circuit configurations can also be utilized to work in this mode of operation in accordance with the subject invention. The grayed boxes, which include an AC/DC converter **150**, switch-mode inverter **151**, primary coil **154**, secondary coil **156**, rectifier stage **158**, regulator stage **159**, and load **1500**, are components of a typical contactless power system, for example, as shown in Figure 1. In order to achieve the method of operation in accordance with the subject invention, this system uses four transformation networks, including receiver-side impedance transformation network **157**, coupling network **155**, transmitter-side impedance transformation network **153**, phase shift network **152**. Measuring the impedance at probe points looking into the rectifier stage **1503**, receiver-side impedance transformation network **1504**, primary coil **1505**, transmitter-side impedance transformation network **1506**, and phase shift network **1507**, facilitate a better understanding of the operation.

Figure 16 shows a simulated load resistance vs. time **160** measured looking into the rectifier stage from probe **1503**. The swing from 0-500 ohms is well outside usable operating

range of an inverter **20** and **31**, shown in Figure 2 and Figure 3, respectively. It would be desirable to compress the resistance into a useable operating range **20**, **31**. At this stage there is no reactive component which is introduced by the impedance transformation network **157** in order to use the phase angle method of power control in accordance with embodiments of the invention.

Figure 17 shows the transformed load resistance **170** looking into the receiver-side impedance transformation stage from probe **1504**. The objective of this stage is to achieve the decoupling effect shown in Figure 14. This decoupling effect is automatic decoupling where the degradation of coupling efficiency between the contactless power transmitter and the load(s) effectively decouples the receiver from the transmitter. Figure 17 also shows the reactive component **171** introduced by the impedance transformation network **157**. The introduction of the reactive component **171** compresses the resistance looking into the receiver in order to stay within the useable operating range of the inverter identified in Figure 2. Additional reactive components will be further added on the transmitter side for implementing the phase-angle method of control in accordance with the invention. At this stage the reactive component **171** decreases with respect to load resistances, which means that phase angle is decreasing with respect to load resistance. From Figure 11, we can see that the working range **114** requires an increase in phase angle for inductive load, to reduce power output. Impedance transformation networks **153** on the transmitter side can compensate from the phase angle introduced by the impedance transformation network **157**.

Figure 18 shows the impedance transformation that is the result of the coupling network **155** and is measured looking into the primary coil **154** from probe **1505**. The objective is to maximize the real part **170** shown in Figure 17, which has been compressed to the point where parasitic losses would become less dominant. Increasing the resistance can improve the efficiency of the circuit. The real part **180** is much greater at this stage and has been increased to maximize power delivery through to the secondary coil **156** and minimize the losses from other parasitic upstream stages closer to the wall outlet, or AC/DC **150**. The negative aspect, however, is that magnitude change of the real component **180** is too large when compared to the working region of a switch-mode supply **20**and **31,** shown in Figure 2 and Figure 3, respectively. This can be corrected by the upstream transformation networks, such as impedance transformation network **153**. The reactive component **181** still trends downward with load resistance and can also be corrected by upstream transformation networks.

Figure 19 shows the impedance transformation that is the result of impedance transformation network **153** and is measured looking into the impedance transformation network **153** from probe **1506**. The objective is to compress the real component **180** such that it falls within the operating range **20**and **31**, defined in Figure 2 and Figure 3, respectively. The second objective is to transform the reactive component **181** such that the increase in load resistance increases the reactive component and phase angle. The real part **190** is compressed back within the operating range of a switch-mode inverter **20** and **31**. The reactive part **191** has been corrected such that it trends upward with increasing load resistance. This corresponds to an increasing phase angle and decreased power delivery as load resistance increases. The reactive part **191** is negative at this stage and this would correspond to a negative phase angle. From Figure 11, it can be seen, for a class E inverter, that a negative phase angle corresponds with poor efficiency and high actual power losses. The same is true for class D and Phi inverters. The trend is undesirable at this stage because an increase in phase angle on the negative slope of **110** would increase power output. The reactive component can be shifted by phase shift network **152**, for example, so that is falls within the working region **114**.

Figure 20 shows the impedance transformation that is the result of the phase shift network **152** and is measured looking into the phase shift network **152** from probe **1507**. The objective is to keep the real part **190** in the operating range of the switch-mode inverter and shift the reactive part **191** into the operating range of the switch-mode inverter. The real part **200** is within the operating range of resistances of a switch-mode inverter **20** and **31**, from Figure 2 and Figure 3, respectively. The reactive part **201** now falls in the correct operating region **114** shown in Figure 11. Confirmation that the phase angle and trend are correct can be shown by converting **200** and **201** into a phase angle plot, as shown in Figure 21. The phase angle **210** is within the operating region **114** and increases with respect to load resistance. The phase angle **210** has a dip at very low impedances and in specific embodiments the initial dip in phase can be avoided.

Figure 22 shows actual experimental data taken from the system shown in Figure 15. After the 30 Ohm inflection point **220**, power output decreases with load impedance and the system achieves high operating efficiency. Because a typical portable electronic device will operate at impedances greater than 30 ohms when the supply voltage is sufficiently high, this is an example of a preferred power delivery vs. load resistance vs. efficiency plot.

Example 2:

A primary coil parallel capacitor value in a specific embodiment can meet two

constraints.

Figure 24 offers a contrast to the preferred phase angle vs. load resistance trend shown in Figure 21. The reference phase angle is approximately 80 degrees and decreases with load resistance. The phase angle **240** decreases with load resistance.

Figure 25 shows the result of this mode of operation when there are no communication and control mechanisms in place. The power output increases with load resistance, which is exactly opposite the response of a fixed voltage DC supply **130** which is shown in Figure 13.

Figure 27 shows the real and reactive components of the impedance as seen looking into the receiver side impedance transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 28 shows the real and reactive components of the impedance as looking into the primary coil, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 29 shows the real and reactive components of the impedance as seen from the transmitter side load-transformation network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figure 30 shows the real and reactive components of the impedance as seen from the transmitter-side, phase shift network, where the impedance characteristic at this point is measured from a system operating in an undesirable range.

Figures 31-40 show a variety of ways that the components of various embodiments of the subject invention can be located, for example proximate the transmitter coil, proximate the receiver coil, or separate from both.

Figure 31 shows the circuitry shown in Figure 68 with dotted lines, labeled A and B, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 32 shows the block diagram of Figure 15 with dotted lines, labeled A and B, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 31.

Figure 33 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 34 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 33.

Figure 35 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 36 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 35.

Figure 37 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 38 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 37.

Figure 39 shows the circuitry shown in Figure 68 with dotted lines, labeled A, B, C, and D, around portions of the circuitry to show one embodiment of how the circuitry can be split between a transmitter unit, for example a transmitter pad, and a receiver unit.

Figure 40 shows the block diagram of Figure 15 with dotted lines, labeled A, B, C, and D, around portions of the block diagram elements to show how the block diagram elements can be split between a transmitter unit, for example a transmitter pad, and a receiver unit, in accordance with the embodiment shown in Figure 39.

Figure 41 shows a typical inductive coupling system.

Figures 42-83 show various components and systems or subsystems that can be utilized with various embodiments of the invention, and/or data corresponding to various embodiments of the invention.

Figure 42 shows some of the possible topologies for a single-element transformation network.

Figure 43 shows some of the possible topologies for a single-element transformation network.

Figure 44 shows a typical Class E driver using parallel-parallel transformation network.

Figure 45 shows a dual channel class E driver that can be used in accordance with an embodiment of the invention.

Figure 46 shows an impedance response looking into receiver with different parallel capacitor value.

Figure 47 shows an optimum receiver capacitor value across a range of load resistances to achieve maximum R looking into the transmitter coil.

Figures 48A-48B show a coupling efficiency and transformed impedance looking into the primary coil.

Figure 49 shows a normalize primary coil voltage across a range of load resistances.

Figure 50 shows a load network reactance with different transmitter capacitor.

Figure 51 shows an amplitude and phase of impedance of unloaded transmitter load network with different C_{tx}.

Figure 52 shows an impedance looking into transmitter load network.

Figure 53 shows a phase looking into transmitter load network.

Figure 54 shows a power delivered into the transmitting load network if transmitter is an ideal sine voltage source.

Figure 55 shows a transistor drain voltage where C_{shunt} = 19nF.

Figure 56 shows a dual channel class E driver.

Figure 57 shows a primary coil – 10 turns (embedded into the table top) and secondary coil – 5 turns (taped up).

Figure 58 shows a power delivery and efficiency of 120V system with a peak power of 295W.

Figure 59 shows a temperature of transistor and inductor with natural convection cooling and forced cooling.

Figure 60 shows a dual channel class E with forced air cooling.

Figure 61 shows a waveform of the class E driver.

Figures 62A-62B show power delivered to load with respect to load resistance. Peak power occurs at approximately 50Ω load resistance for dual channel at 69W for dual channel and 75Ω for single channel at 10W for single channel.

Figure 63 shows system efficiency with respect to load resistance with both peak efficiency of 64.5% for single channel and 76% of dual channel at approximately 70Ω load resistance.

Figure 64 shows transmitter efficiency with respect to load resistance. Peak transmitter efficiency occurs across the band of 60Ω to 100Ω load resistance at 90% for dual channel and 79% for single channel.

Figure 65 shows system efficiency with respect to load resistance with both cases achieving high efficiency at heavy load and also illustratin that a single channel mode is more efficient at low power delivery state.

Figure 66 shows primary coil RMS voltage having a unique load resistance for each value.

Figure 67 shows receiver DC voltage converging to approximately 70V for dual channel and 37V for single channel.

Figure 68 shows a generalized contactless power system with a single transistor power amplifer in a single ended configuration.

Figure 69 shows a generalized contactless power system with two, single transistor power amplifiers in a push-pull configuration.

Figure 70 shows a generalized contactless power with a two transistor power amplifier in a single ended configuration.

Figure 71 shows a generalized contactless power system with two, two transistor power ampliferrs in a push-pull configuration.

Figure 72 shows different supply network configurations that are used to connect a DC supply voltage to a terminal of the active device of a power amplifier.

Figure 73 shows the functions of a impedance transformation network for a single ended system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 74 shows the functions of a impedance transformation network for a push-pull system in block diagram format. The fucntional blocks are arranged in no particular order and there can be multiples of the same functional blocks.

Figure 75 shows various circuit elements arranged to achieve the fuction of reactance shifting. These circuit elements, or variants thereof, can add or remove the mangitude of reactance looking into the impedance transformation network. Inductive elements increase reactance. Capacitive elements decrease reactance.

Figure 76 shows various circuit elements arranged to achieve the fuction of frequency filtering. Two notch filters are shown that can remove unwanted harmonics from the signal. A combination of other filter types can be used to achieve frequency filtering.

Figure 77 shows various circuit elements arranged to adjust the correlation between the equivelent resistance and the phase of the load. Inductive elements will tend to result in a positive correlation between phase and load resistance. Capacitive elements will tend to result in a negative correlation between phase and load resistance. These elements can also serve the purpose of resistance compression.

Figure 78 shows primary to secondary coil configurations. The impedance transformation network may comprise a single primary and a single secondary. Alternatively, the impedance transformation network may comprise one or more primary coils coupled to one or more secondary coils. The inductance of the primary and/or secondary coil(s) can be used to compress resistance and change the phase vs. resistance relationship.

Figure 79 show various circuit elements arranged to compress the resistance seen looking into the impedance transformation network. Either capacitive or inductive elements can be used.

Figure 80 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 81 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 82 shows a typical configuration of an impedance tranformation network connected to an active device.

Figure 83 shows a typical configuration of an impedance tranformation network connected to an active device.

Specific embodiments pertain to a method and a circuit for inductive power transfer, incorporating an impedance transformation network, where the impedance transformation network has an input port for coupling to an active device for creating a signal at a selected operating frequency, an output port for coupling to a load having a variable impedance; and a reactive network coupled between the input port and the output port, where the reactive network includes a primary coil; and a secondary coil, where the primary coil is inductively coupled to the secondary coil, where when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is inductive and negatively correlated with the amount of power delivered to the load. A real part of the impedance looking into the impedance transformation network through the input port can be in a range between a minimum real part and a maximum real part. The maximum real part can be less than or

equal to one order of magnitude greater than the minimum real part. Further embodiments can incorporate at least one additional input port, at least one additional output port, at least one additional primary coil, and/or at least one additional secondary coil. The output port can be adapted for coupling to at least two loads.

In an embodiment, the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with the resistance of the load. In another embodiment, the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load. In a specific embodiment, the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load, wherein when the impedance looking to the primary coil, Zin, is explained by:

$$Z_{in} = \{1_{1M}[\mathbb{Z}^{IV} - (\mathbb{Z}^{II})^T(\mathbb{Z}^{I})^{-1}\mathbb{Z}^{II}]^{-1}1_{M1}\}$$

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}^{III} & (\mathbb{Z}^{II})^T \\ \mathbb{Z}^{II} & \mathbb{Z}^{I} \end{bmatrix}$$

$$\mathbb{Z}_{ab} = \begin{cases} j\omega L_a + R_a & \text{for } a = b \\ j\omega M_{ab} & \text{otherwise} \end{cases}$$

$$\mathbb{Z}^{IV} = \mathbb{Z}^{III} + Z_{in}1_{MM}$$

Zin: Input impedance looking into the primary coil

1_{1M}: Vector of 1's of length M

1_{MM}: M X M matrix of 1's

Z: Impedance matrix

Z_{ab}: Element ab of the impedance matrix

Z^{I} : Sub-matrix of Z

Z^{II}: Sub-matrix of Z

Z^{III}: Sub-matrix of Z

M_{ab}: Mutual inductance between the a^{th} and b^{th} coil

j: imaginary number

a: coil index

b: coil index

ω: radian frequency

R_a: Parasitic resistance of the a^{th} coil

L_a: Self inductance of the a^{th} coil

The reactive network can have at least one shunt network with a negative reactance that is connected between a first terminal of the secondary coil and a second terminal of the secondary coil. The at least one shunt network with a negative reactance can have a capacitor. The active device can have a transistor. In a specific embodiment, active device includes a switching component that operates substantially as a switch; and a capacitance in parallel with the switching component. The input port can be coupled to a voltage source or input port can be coupled to a current source. A supply network can be connected between the input port and a voltage source, where the supply network includes at least one inductor. The supply network connected between the input port and a voltage source can be configured to reject harmonics not intended to reach the load. In specific embodiments, the supply network connected between the input port and a voltage source can include elements of the supply network, load network, and the active device so as to represent at least one class D inverter or variant, at least one class DE inverter or variant, at least one class E inverter or variant, at least one class E^{-1} inverter or variant at least one class F inverter or variant, at least one class F^{-1} inverter or variant, at least one class EF^{-1} inverter or variant, or at least one class Phi inverter or variant.

The signal from the active device can be an AC signal and/or a periodic signal. When the active device is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero voltage-switching of the active device occurs. Regarding this range, in specific embodiments switching of the active device can occur when the voltage is within a range of 10% of a peak voltage and zero voltage, switching of the active device can occur when the voltage is within a range of 5% of a peak voltage and zero voltage, and/or switching

of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage.

In another embodiment, when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs. Regarding this range, in specific embodiments, switching of the active device occurs when the slope of the voltage is within a range of -1 and +1, switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1. In a further specific embodiment, when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching and substantially zero voltage derivation switching of the active device occurs. Such switching of the active device can occur when the voltage is within a range of 10% of a peak voltage and zero and when the slope of the voltage is within a range of -1 and +1, when the voltage is within a range of 5% of a peak voltage and zero and when the slope of the voltage is within a range of -0.5 and +0.5, and/or when the voltage is within a range of 1% of a peak voltage and zero and when the slope of the voltage is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero voltage-switching of the active device occurs. Switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero voltage, switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero voltage, and/or switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage. When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range

such that substantially zero voltage derivative switching of the active device occurs. Switching of the active device occurs when the slope of the voltage is within a range of -1 and +1, switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current-switching of the active device occurs. Switching of the active device occurs when the current is within a range of 10% of a peak current and zero current, switching of the active device occurs when the current is within a range of 5% of a peak current and zero current, and/or switching of the active device occurs when the current is within a range of 1% of a peak current and zero current. When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current derivative switching of the active device occurs. Switching of the active device occurs when the slope of the current is within a range of -1 and +1, switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port can be within a range such that substantially zero current-switching of the active device occurs. Switching of the active device occurs when the current is within a range of 10% of a peak current and zero current, switching of the active device occurs when the current is within a range of 5% of a peak current and zero current, and/or switching of the active device occurs when the current is within a range of 1% of a peak current and zero current. When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port can be within a range such that

substantially zero current derivative switching of the active device occurs. Switching of the active device occurs when the slope of the current is within a range of -1 and +1, switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5, and/or switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

When the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage is coupled to the input port, and the load is coupled to the output port, the real part of the impedance looking into the impedance transformation network through the input port can be within a range such that the maximum real part of the impedance looking into the impedance transformation network through the input port is no more than two orders of magnitude greater than the minimum real part of the impedance looking into the impedance transformation network through the input port. A supply network can be connected between the input port and a voltage source, where the supply network is configured to reject harmonics not intended to reach the load. At least one load having a time-dependent impedance connected to the output port. In another embodiment, the system can be adapted least one load having a time dependent non-negative real resistance can be connected to the output port. In a specific embodiment where the phase angle of the impedance looking into the impedance transformation network through the input port is inductive, the phase angle of the impedance looking into the impedance transformation network through the input port is between 40 and 85 degrees.

In an embodiment with a shunt network connected between the first terminal of the secondary coil and the second terminal of the secondary coil, where the shunt network has a negative reactance, the shunt network can be configured such that the resistance looking from the secondary coil towards the load is between an upper bound and a lower bound, wherein the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and minimum resistance. In specific embodiments, the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, or the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms. In a further specific embodiment, the at least one shunt network has a

negative reactive value such that the phase angle looking into the primary coil is positively correlated with the load resistance. In a further specific embodiment, the at least one shunt network is configured to have a negative reactive value such that the phase angle looking into the primary coil is negatively correlated with the load resistance, where the reactive network further utilizes at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil, the at least one additional shunt network having a positive reactive value such that the phase angle looking into the impedance transformation network through the input port is positively correlated with the load resistance.

The reactive network can further include at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil.

The reactive network can include at least one reactive component connected to the primary coil, where the at least one reactive component has a reactance that shifts the phase angle looking into the impedance transformation network through the input port can be within a range such that substantially zero-voltage switching of the active device occurs. In specific embodiments, the impedance transformation network is configured such that the range of resistances looking into the impedance transformation network through the input port is between an upper bound and a lower bound, where the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and the minimum load resistance. In various embodiments, the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms, and the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms.

The at least one filter network having a positive reactance can be connected in series with the primary coil, where a reactance of the at least one filter network divided by a resistance looking from the filter network towards the load has a value between 1.5 and 10.

The impedance transformation network can be configured to couple to two active devices via a single input port. The input port can have at least two input ports for coupling to at least two active devices.

A rectifier can be positioned between the impedance transformation network and the load.

The primary coil can be connected in series with at least one reactive component and the secondary coil can be connected in series with at least one additional reactive component. In another embodiment, the primary coil is connected in series with at least one reactive component and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil. In yet another embodiment, at least one other reactive component is connected between a first terminal of the primary and a second terminal of the primary coil and the secondary coil is connected in series with at least one additional reactive component. In further embodiments, at least one other reactive component is connected between a first terminal of the primary coil and a second terminal of the primary coil and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

The primary coil can be a single primary coil inductively coupled to at least two secondary coils. In another embodiment, at least two primary coils are inductively coupled to the secondary coils. In various other embodiments, m primary coils are inductively coupled to n secondary coils, where $m>1$ and $n>1$.

A specific embodiment relates to a circuit for inductive power transfer having an impedance transformation network, incorporating an input port for coupling to an active device for creating a signal at a selected operating frequency, an output port for coupling to a load having a variable impedance; and a reactive network coupled between the input port and the output port, wherein the reactive network has a primary coil; and a secondary coil, where the primary coil is inductively coupled to the secondary coil, such that when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is capacitive and positively correlated with the amount of power delivered to the load.

Another embodiment pertains to a circuit for inductive power transfer, having a primary impedance transformation network, where the primary impedance transformation network has an input port for coupling to a active device that creates a signal at a selected operating frequency, a primary coil for coupling to a secondary coil, and a reactive network coupled to the input port and coupled to the primary coil, where the reactive network incorporates at least one capacitor, and at least one inductor, such that when the primary coil

is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is inductive and negatively correlated with the amount of power inductively transferred from the primary coil.

Another embodiment relates to a circuit for inductive power transfer, having a primary impedance transformation network, where the primary impedance transformation network includes an input port for coupling to an one active device that creates a signal at a selected operating frequency, a primary coil for coupling to a secondary coil, a reactive network coupled to the input port and coupled to the primary coil, where the reactive network incorporates at least one capacitor, at least one inductor, such that when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is capacitive and positively correlated with the amount of power inductively transferred from the primary coil.

A further embodiment pertains to a circuit for inductive power transfer, having a secondary side impedance transformation network, where the secondary side impedance transformation network incorporates at least one secondary coil for coupling to at least one primary coil, at least one output port for coupling to at least one load having a variable impedance; and a secondary side reactive network coupled to the output port and coupled to the secondary coil, where the reactive network incorporates at least one capacitor, such that when the secondary coil is coupled to the primary coil, where the primary coil is coupled to a primary side reactive network, where the primary side reactive network has an input port for connection to at least one active device that creates a signal at a selected operating frequency, the a phase angle of an impedance looking into the primary side reactive network through the input port is inductive and positively correlated with the amount of power inductively transferred from the primary coil.

A further embodiment is directed to a circuit for inductive power transfer, having a secondary side impedance transformation network, wherein the secondary side impedance transformation network has at least one secondary coil for coupling to at least one primary coil, at least one output port for coupling to at least one load having a variable impedance; and a secondary side reactive network coupled to the at least one output port and coupled to the at least one secondary coil, wherein the reactive network includes at least one capacitor, such that when the secondary coil is coupled to the primary coil, where the primary coil is coupled to a primary side reactive network, where the primary side reactive network has an

input port for connection to at least one active device that creates a signal at a selected operating frequency, the a phase angle of an impedance looking into the primary side reactive network through the input port is capacitive and negatively correlated with the amount of power inductively transferred from the primary coil.

An embodiment of the invention is directed to an apparatus for wireless power transfer, having a rectifier stage, where the rectifier stage is adapted to interconnect with a load; a first impedance transformation network (FITN), where the first impedance transformation network interconnects with the rectifier stage and transforms the impedance looking into the rectifier stage such that the impedance looking into the FITN is such that the load decouples from the primary coil; a secondary coil, where the secondary coil is interconnected with the FITN such that the power coupled from the primary coil to the secondary coil is received by the FITN; a primary coil, where the primary coil is positioned with respect to the secondary coil such that the primary coil is coupled to the secondary coil, wherein the interaction between the primary coil and secondary coil is such that the impedance looking into the primary coil has a resistance large enough to maximize power delivery through to the secondary coil; a second impedance transformation network (SITN), where the SITN interconnects with the primary coil and transforms the impedance looking into the primary coil such that the resistance looking into the SITN toward the load is within a usable operating range of the tuned switch-mode inverter, large enough to maximize power delivery through to the secondary coil; a phase shifting network, where the phase shifting network interconnects with the SITN and transforms the impedance looking into the SITN such that the impedance looking into the phase shifting network has a resistance in the operating range of the tuned switch-mode inverter and a reactive part in the operating range of the tuned switch-mode inverter; a tuned switch-mode inverter, where the tuned switch-mode inverter is interconnected with the phase shifting network; and a power source, where the power source is interconnected with the tuned switch-mode inverter. In this embodiment, the load can have a load resistance that can range from 0 to 500 ohms.

An embodiment is an apparatus for wireless power transfer, having a rectifier stage, where the rectifier stage is adapted to interconnect with a load; a secondary coil, where the secondary coil is interconnected with the rectifier stage; a primary coil, where the primary coil is coupled to the secondary coil; a tuned switch-mode supply, wherein the tuned switch-mode supply is interconnected to the primary coil; a power supply, where the power supply supplies power to the tuned switch-mode supply; a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and a second circuitry interconnected

between the secondary coil and the rectifier stage, such that power output to the load decreases as the impedance of the load increases.

Another embodiment is an apparatus for wireless power transfer, having a rectifier stage, where the rectifier stage is adapted to interconnect with a load; a secondary coil, where the secondary coil is interconnected with the rectifier stage; a primary coil, where the primary coil is coupled to the secondary coil; a tuned switch-mode supply, where the tuned switch-mode supply is interconnected to the primary coil; a power supply, where the power supply supplies power to the tuned switch-mode supply; a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and a second circuitry interconnected between the secondary coil and the rectifier stage, such that power output to the load is adjusted as the phase angle of the load changes.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application.

CLAIMS

1. A circuit for inductive power transfer, comprising:

an impedance transformation network, wherein the impedance transformation network comprises:

an input port for coupling to an active device for creating a signal at a selected operating frequency,

an output port for coupling to a load having a variable impedance; and

a reactive network coupled between the input port and the output port, wherein the reactive network comprises:

a primary coil;

a secondary coil, wherein the primary coil is inductively coupled to the secondary coil, wherein when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is inductive and negatively correlated with the amount of power delivered to the load.

2. The circuit according to claim 1, wherein a real part of the impedance looking into the impedance transformation network through the input port is in a range between a minimum real part and a maximum real part.

3. The circuit according to claim 2, wherein the maximum real part is less than or equal to one order of magnitude greater than the minimum real part.

4. The circuit according to claim 1, further comprising at least one additional input port.

5. The circuit according to claim 1, further comprising at least one additional output port.

6. The circuit according to claim 1, further comprising at least one additional primary coil.

7. The circuit according to claim 1, further comprising at least one additional secondary coil.

8. The circuit according to claim 1, wherein the output port is for coupling to at least two loads.

9. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with the resistance of the load.

10. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load.

11. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is positively correlated with an equivalent resistance of the load, wherein when the impedance looking to the primary coil, Zin, is explained by:

$$Z_{in} = \{1_{1M}[\mathbb{Z}^{IV} - (\mathbb{Z}^{II})^T(\mathbb{Z}^I)^{-1}\mathbb{Z}^{II}]^{-1}1_{M1}\}$$

$$\mathbb{Z} = \begin{bmatrix} \mathbb{Z}^{III} & (\mathbb{Z}^{II})^T \\ \mathbb{Z}^{II} & \mathbb{Z}^I \end{bmatrix}$$

$$\mathbb{Z}_{ab} = \begin{cases} j\omega L_a + R_a & \text{for } a = b \\ j\omega M_{ab} & \text{otherwise} \end{cases}$$

$$\mathbb{Z}^{IV} = \mathbb{Z}^{III} + Z_{in}1_{MM}$$

Zin: Input impedance looking into the primary coil

1_{1M}: Vector of 1's of length M

1_{MM}: M X M matrix of 1's

Z: Impedance matrix

Z_{ab}: Element ab of the impedance matrix

Z^{I} : Sub-matrix of Z

Z^{II}: Sub-matrix of Z

Z^{III}: Sub-matrix of Z

M_{ab}: Mutual inductance between the a^{th} and b^{th} coil

j: imaginary number

a: coil index

b: coil index

ω: radian frequency

R_a: Parasitic resistance of the a^{th} coil

L_a: Self inductance of the a^{th} coil

12. The circuit according to claim 1, wherein the reactive network further comprises at least one shunt network with a negative reactance that is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

13. The circuit according to claim 12, wherein the at least one shunt network with a negative reactance comprises a capacitor.

14. The circuit according to claim 1, wherein the active device comprises a transistor.

15. The circuit according to claim 1 wherein the active device comprises:

a switching component that operates substantially as a switch; and

a capacitance in parallel with the switching component.

16. The circuit according to claim 1 wherein the input port is coupled to a voltage source.

17. The circuit according to claim 1, wherein the input port is coupled to a current source.

18. The circuit according to claim 1 comprising a supply network connected between the input port and a voltage source, wherein the supply network comprises at least one inductor.

19. The circuit according to claim 1 comprising a supply network connected between the input port and a voltage source, wherein the supply network is configured to reject harmonics not intended to reach the load.

20. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class D inverter or variant.

21. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class DE inverter or variant.

22. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class E inverter or variant.

23. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class E^{-1} inverter or variant.

24. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class F inverter or variant.

25. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class F^{-1} inverter or variant.

26. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class EF^{-1} inverter or variant.

27. The circuit according to claim 1, comprising a supply network connected between the input port and a voltage source, wherein the elements of the supply network, load network, and the active device represent at least one class Phi inverter or variant.

28. The circuit according to claim 1, wherein the signal is an AC signal.

29. The circuit according to claim 1, wherein the signal is a periodic signal.

30. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching of the active device occurs.

31. The circuit according to claim 30, wherein switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero voltage.

32. The circuit according to claim 30, wherein switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero voltage.

33. The circuit according to claim 30, wherein switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage.

34. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs.

35. The circuit according to claim 34, wherein switching of the active device occurs when the slope of the voltage is within a range of -1 and +1.

36. The circuit according to claim 34, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5.

37. The circuit according to claim 34, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1.

38. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching and substantially zero voltage derivation switching of the active device occurs.

39. The circuit according to claim 38, wherein switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero and when the slope of the voltage is within a range of -1 and +1.

40. The circuit according to claim 38, wherein switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero and when the slope of the voltage is within a range of -0.5 and +0.5.

41. The circuit according to claim 38, wherein switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero and when the slope of the voltage is within a range of -0.1 and +0.1.

42. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage-switching of the active device occurs.

43. The circuit according to claim 42, wherein switching of the active device occurs when the voltage is within a range of 10% of a peak voltage and zero voltage.

44. The circuit according to claim 42, wherein switching of the active device occurs when the voltage is within a range of 5% of a peak voltage and zero voltage.

45. The circuit according to claim 42, wherein switching of the active device occurs when the voltage is within a range of 1% of a peak voltage and zero voltage.

46. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero voltage derivative switching of the active device occurs.

47. The circuit according to claim 46, wherein switching of the active device occurs when the slope of the voltage is within a range of -1 and +1.

48. The circuit according to claim 46, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.5 and +0.5.

49. The circuit according to claim 46, wherein switching of the active device occurs when the slope of the voltage is within a range of -0.1 and +0.1.

50. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current-switching of the active device occurs.

51. The circuit according to claim 50, wherein switching of the active device occurs when the current is within a range of 10% of a peak current and zero current.

52. The circuit according to claim 50, wherein switching of the active device occurs when the current is within a range of 5% of a peak current and zero current.

53. The circuit according to claim 50, wherein switching of the active device occurs when the current is within a range of 1% of a peak current and zero current.

54. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current derivative switching of the active device occurs.

55. The circuit according to claim 54, wherein switching of the active device occurs when the slope of the current is within a range of -1 and +1.

56. The circuit according to claim 54, wherein switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5.

57. The circuit according to claim 54, wherein switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

58. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, a real component of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current-switching of the active device occurs.

59. The circuit according to claim 58, wherein switching of the active device occurs when the current is within a range of 10% of a peak current and zero current.

60. The circuit according to claim 58, wherein switching of the active device occurs when the current is within a range of 5% of a peak current and zero current.

61. The circuit according to claim 58, wherein switching of the active device occurs when the current is within a range of 1% of a peak current and zero current.

62. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage source is coupled to the input port, and the load is coupled to the output port, the phase angle of the impedance looking into the impedance transformation network through the input port is within a range such that substantially zero current derivative switching of the active device occurs.

63. The circuit according to claim 62, wherein switching of the active device occurs when the slope of the current is within a range of -1 and +1.

64. The circuit according to claim 62, wherein switching of the active device occurs when the slope of the current is within a range of -0.5 and +0.5.

65. The circuit according to claim 62, wherein switching of the active device occurs when the slope of the current is within a range of -0.1 and +0.1.

66. The circuit according to claim 1, wherein when the active device creating a signal at the selected operating frequency is coupled to the input port, a voltage is coupled to the input port, and the load is coupled to the output port, the real part of the impedance looking into the impedance transformation network through the input port is within a range such that the maximum real part of the impedance looking into the impedance transformation network through the input port is no more than two orders of magnitude greater than the minimum real part of the impedance looking into the impedance transformation network through the input port.

67. The circuit according to any of claims 27 – 31, comprising a supply network connected between the input port and a voltage source, wherein the supply network is configured to reject harmonics not intended to reach the load.

68. The circuit according to claim 1, comprising at least one load connected to the output port, the load having a time-dependent impedance.

69. The circuit according to claim 1, comprising at least one load connected to the output port, the load having a time dependent non-negative real resistance.

70. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is inductive.

71. The circuit according to claim 1, wherein the phase angle of the impedance looking into the impedance transformation network through the input port is between 40 and 85 degrees.

72. The circuit according to claim 12, wherein the shunt network is configured such that the resistance looking from the secondary coil towards the load is between an upper bound and a lower bound, wherein the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and minimum resistance.

73. The circuit according to claim 72, wherein the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

74. The circuit according to claim 72, wherein the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

75. The circuit according to claim 72, wherein the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

76. The circuit according to claim 72, wherein the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms.

77. The circuit according to claim 12, wherein the at least one shunt network has a negative reactive value such that the phase angle looking into the primary coil is positively correlated with the load resistance.

78. The circuit according to claim 12, wherein the at least one shunt network is configured to have a negative reactive value such that the phase angle looking into the primary coil is negatively correlated with the load resistance, wherein the reactive network further comprises at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil, wherein the at least one additional shunt network has a positive reactive value such that the phase angle looking into the impedance transformation network through the input port is positively correlated with the load resistance.

79. The circuit according to claim 1, wherein the reactive network further comprises at least one additional shunt network connected between a first terminal of the primary coil and a second terminal of the primary coil.

80. The circuit according to claim 78, wherein the at least one additional shunt network has a positive reactive value such that the phase angle looking into the impedance transformation network through the input port is positively correlated with the load resistance.

81. The circuit according to claim 1, wherein the reactive network comprises at least one reactive component connected to the primary coil, wherein the at least one reactive component has a reactance that shifts the phase angle looking into the impedance transformation network through the input port is within a range such that substantially zero-voltage switching of the active device occurs.

82. The circuit according to claim 1, wherein impedance transformation network is configured such that the range of resistances looking into the impedance transformation network through the input port is between an upper bound and a lower bound, wherein the difference between the upper bound and lower bound is less than the difference between the maximum load resistance and the minimum load resistance.

83. The circuit according to claim 82, wherein the upper bound is 1000 ohms and the lower bound is .01 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

84. The circuit according to claim 82, wherein the upper bound is 10 ohms and the lower bound is 1 ohm when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

85. The circuit according to claim 82, wherein the upper bound is 10,000 ohms and the lower bound is 500 ohms when the maximum load resistance is 100,000 ohms and the minimum load resistance is 1 ohms.

86. The circuit according to claim 82, wherein the upper bound is 1,000,000 ohms and the lower bound is 800,000 ohms when the maximum load resistance is 10,000,000 ohms and the minimum load resistance is 1 ohms.

87. The circuit according to claim 1, wherein at least one filter network having a positive reactance is connected in series with the primary coil, wherein a reactance of the at least one filter network divided by a resistance looking from the filter network towards the load has a value between 1.5 and 10.

88. The circuit according to claim 1, wherein the impedance transformation network is configured to couple to two active devices via a single input port.

89. The circuit according to claim 1, wherein the input port comprises at least two input ports for coupling to at least two active devices.

90. The circuit according to claim 1, wherein the load is resistive.

91. The circuit according to claim 1, wherein the load is reactive.

92. The circuit according to claim 1, wherein the load comprises resistive and reactive components.

93. The circuit according to claim 1, wherein a rectifier is positioned between the impedance transformation network and the load.

94. The circuit according to claim 93, wherein the load comprises a portable electronic device.

95. The circuit according to claim 94, wherein the load comprises:
a voltage regulator;
a power management system; and
a battery.

96. The circuit according to claim 1, wherein the primary coil is connected in series with at least one reactive component and the secondary coil is connected in series with at least one additional reactive component.

97. The circuit according to claim 1, wherein the primary coil is connected in series with at least one reactive component and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

98. The circuit according to claim 1, wherein at least one other reactive component is connected between a first terminal of the primary and a second terminal of the primary coil and the secondary coil is connected in series with at least one additional reactive component.

99. The circuit according to claim 1, wherein at least one other reactive component is connected between a first terminal of the primary coil and a second terminal of the primary coil and at least one additional reactive component is connected between a first terminal of the secondary coil and a second terminal of the secondary coil.

100. The circuit according to claim 1, wherein the primary coil is a single primary coil inductively coupled to at least two secondary coils.

101. The circuit according to claim 1, wherein the at least two primary coils are inductively coupled to the secondary coils.

102. The circuit according to claim 1, wherein m primary coils are inductively coupled to n secondary coils, where $m>1$ and $n>1$.

103. A circuit for inductive power transfer, comprising:

an impedance transformation network, wherein the impedance transformation network comprises:

an input port for coupling to an active device for creating a signal at a selected operating frequency,

an output port for coupling to a load having a variable impedance; and

a reactive network coupled between the input port and the output port, wherein the reactive network comprises:

a primary coil;

a secondary coil, wherein the primary coil is inductively coupled to the secondary coil, wherein when the output is coupled to the load having a variable impedance and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the impedance transformation network through the input port is capacitive and positively correlated with the amount of power delivered to the load.

104. A circuit for inductive power transfer, comprising:

a primary impedance transformation network, wherein the primary impedance transformation network comprises:

an input port for coupling to a active device that creates a signal at a selected operating frequency,

a primary coil for coupling to a secondary coil

a reactive network coupled to the input port and coupled to the primary coil, wherein the reactive network comprises:

at least one capacitor

at least one inductor

wherein when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is inductive and negatively correlated with the amount of power inductively transferred from the primary coil.

105. A circuit for inductive power transfer, comprising:

a primary impedance transformation network, wherein the primary impedance transformation network comprises:

an input port for coupling to an one active device that creates a signal at a selected operating frequency,

a primary coil for coupling to a secondary coil

a reactive network coupled to the input port and coupled to the primary coil, wherein the reactive network comprises:

at least one capacitor

at least one inductor

wherein when the primary coil is coupled to the secondary coil and the input port is coupled to the active device that creates a signal at the selected operating frequency, a phase angle of an impedance looking into the primary impedance transformation network through the input port is capacitive and positively correlated with the amount of power inductively transferred from the primary coil.

106. A circuit for inductive power transfer, comprising:

a secondary side impedance transformation network, wherein the secondary side impedance transformation network comprises:

at least one secondary coil for coupling to at least one primary coil

at least one output port for coupling to at least one load having a variable impedance; and

a secondary side reactive network coupled to the output port and coupled to the secondary coil, wherein the reactive network comprises:

at least one capacitor

wherein when the secondary coil is coupled to the primary coil wherein the primary coil is coupled to a primary side reactive network

wherein the primary side reactive network comprises an input port for connection to at least one active device that creates a signal at a selected operating frequency

the a phase angle of an impedance looking into the primary side reactive network through the input port is inductive and positively correlated with the amount of power inductively transferred from the primary coil.

107. A circuit for inductive power transfer, comprising:

a secondary side impedance transformation network, wherein the secondary side impedance transformation network comprises:

at least one secondary coil for coupling to at least one primary coil

at least one output port for coupling to at least one load having a variable impedance; and

a secondary side reactive network coupled to the at least one output port and coupled to the at least one secondary coil, wherein the reactive network comprises:

at least one capacitor

wherein when the secondary coil is coupled to the primary coil wherein the primary coil is coupled to a primary side reactive network

wherein the primary side reactive network comprises an input port for connection to at least one active device that creates a signal at a selected operating frequency

the a phase angle of an impedance looking into the primary side reactive network through the input port is capacitive and negatively correlated with the amount of power inductively transferred from the primary coil.

108. An apparatus for wireless power transfer, comprising:

a rectifier stage, wherein the rectifier stage is adapted to interconnect with a load;

a first impedance transformation network (FITN), wherein the first impedance transformation network interconnects with the rectifier stage and transforms the impedance looking into the rectifier stage such that the impedance looking into the FITN is such that the load decouples from the primary coil;

a secondary coil, wherein the secondary coil is interconnected with the FITN such that the power coupled from the primary coil to the secondary coil is received by the FITN;

a primary coil, wherein the primary coil is positioned with respect to the secondary coil such that the primary coil is coupled to the secondary coil, wherein the interaction between the primary coil and secondary coil is such that the impedance looking into the primary coil has a resistance large enough to maximize power delivery through to the secondary coil;

a second impedance transformation network (SITN), wherein the SITN interconnects with the primary coil and transforms the impedance looking into the primary coil such that the resistance looking into the SITN toward the load is within a usable operating range of the

tuned switch-mode inverter, large enough to maximize power delivery through to the secondary coil;

a phase shifting network, wherein the phase shifting network interconnects with the SITN and transforms the impedance looking into the SITN such that the impedance looking into the phase shifting network has a resistance in the operating range of the tuned switch-mode inverter and a reactive part in the operating range of the tuned switch-mode inverter;

a tuned switch-mode inverter, wherein the tuned switch-mode inverter is interconnected with the phase shifting network; and

a power source, wherein the power source is interconnected with the tuned switch-mode inverter.

109. The apparatus according to claim 108, wherein the load has a load resistance that can range from 0 to 500 ohms.

110. An apparatus for wireless power transfer, comprising:

a rectifier stage, wherein the rectifier stage is adapted to interconnect with a load;

a secondary coil, wherein the secondary coil is interconnected with the rectifier stage;

a primary coil, wherein the primary coil is coupled to the secondary coil;

a tuned switch-mode supply, wherein the tuned switch-mode supply is interconnected to the primary coil;

a power supply, wherein the power supply supplies power to the tuned switch-mode supply;

a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and

a second circuitry interconnected between the secondary coil and the rectifier stage, wherein power output to the load decreases as the impedance of the load increases.

111. An apparatus for wireless power transfer, comprising:

a rectifier stage, wherein the rectifier stage is adapted to interconnect with a load;

a secondary coil, wherein the secondary coil is interconnected with the rectifier stage;

a primary coil, wherein the primary coil is coupled to the secondary coil;

a tuned switch-mode supply, wherein the tuned switch-mode supply is interconnected to the primary coil;

a power supply, wherein the power supply supplies power to the tuned switch-mode supply;

a first circuitry interconnected between the tuned switch-mode supply and the primary coil; and

a second circuitry interconnected between the secondary coil and the rectifier stage, wherein power output to the load is adjusted as the phase angle of the load changes.

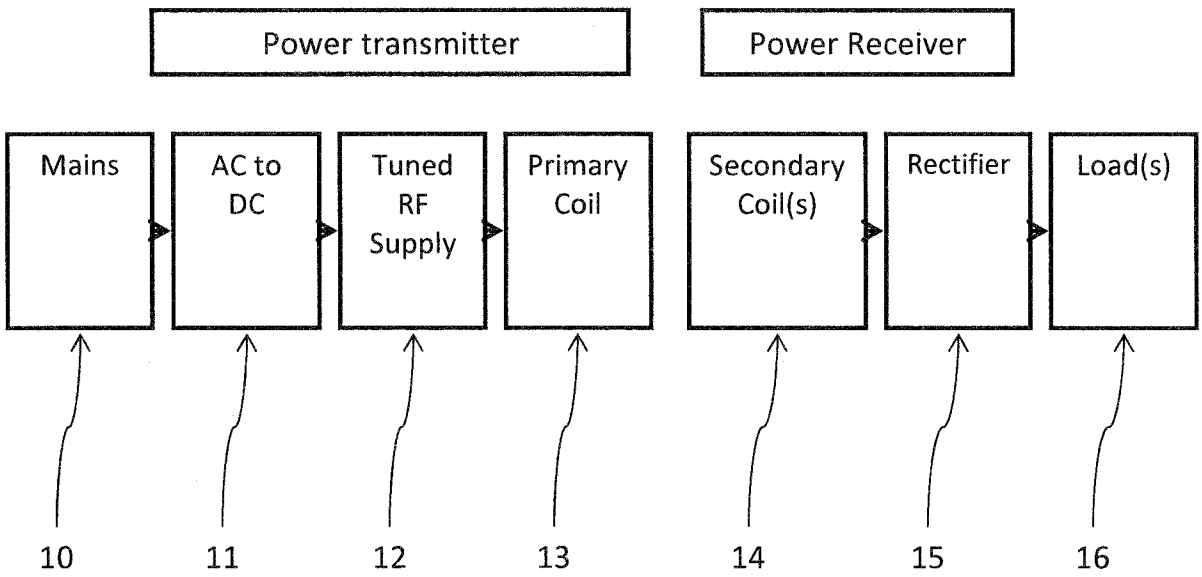

Power transmitter
Power Receiver
Mains
AC to DC
Tuned RF Supply
Primary Coil
Secondary Coil(s)
Rectifier
Load(s)
10
11
12
13
14
15
16

FIG. 1

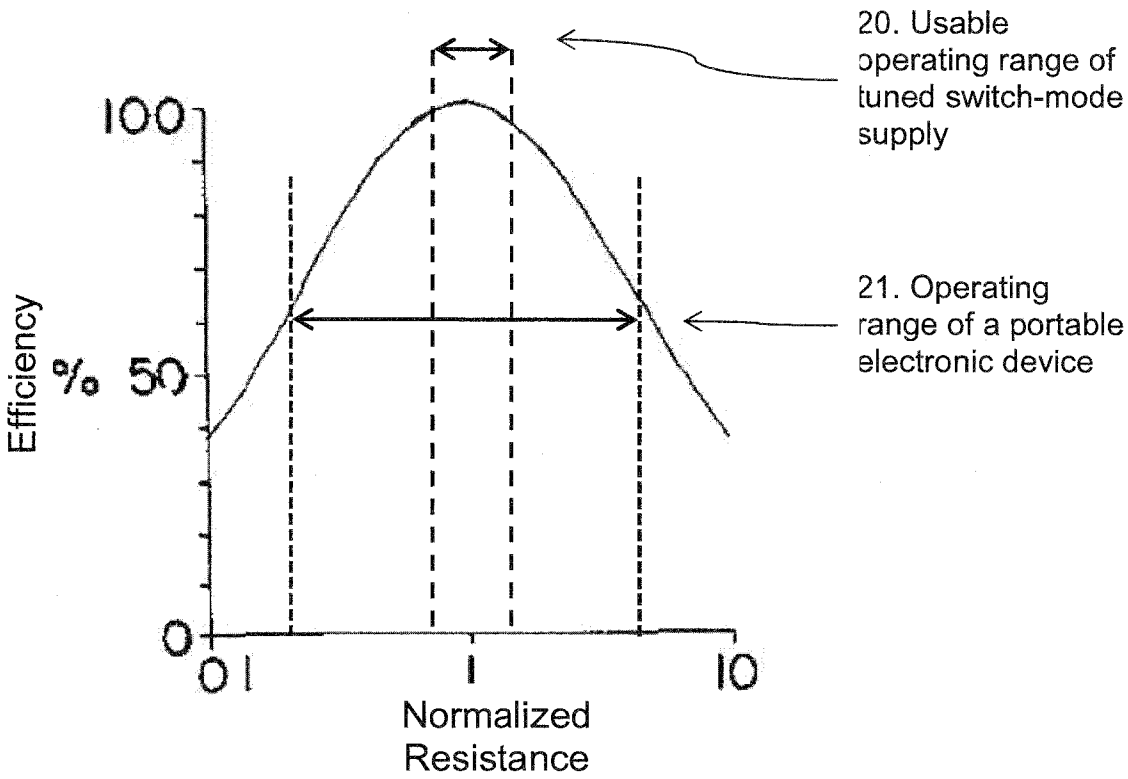

20. Usable operating range of tuned switch-mode supply
21. Operating range of a portable electronic device
100
Efficiency
% 50
0
0.1
1
10
Normalized Resistance

FIG. 2

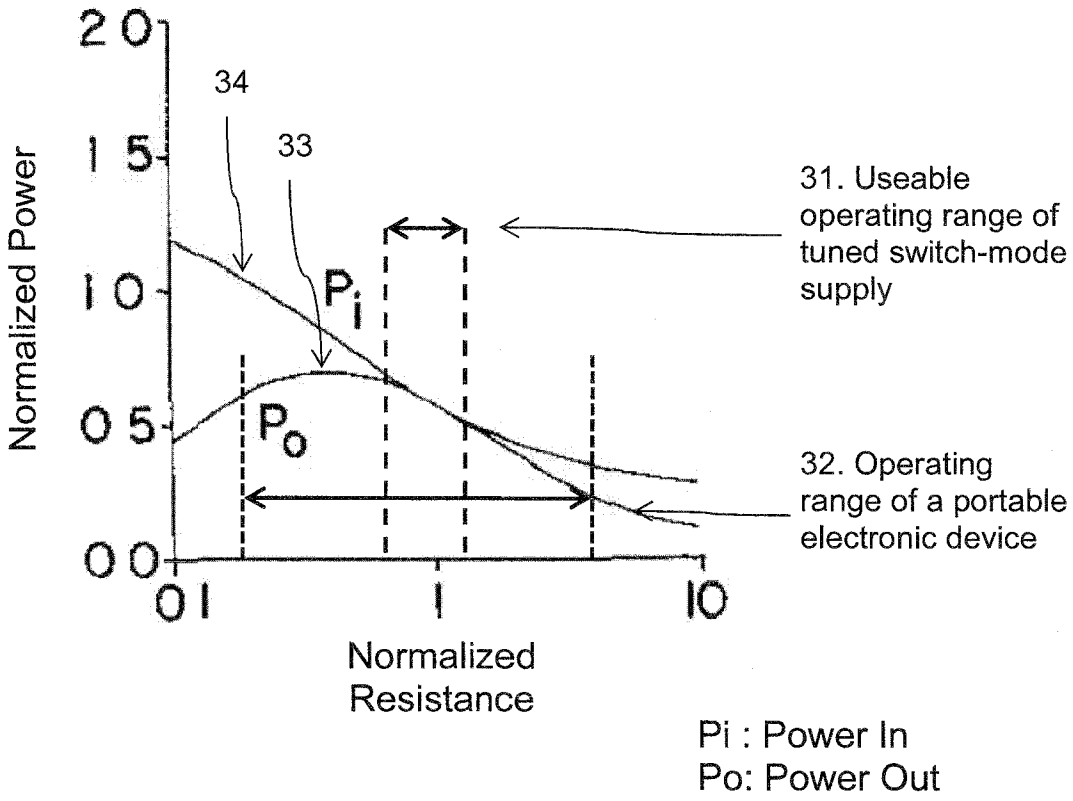

20
15
10
05
00
Normalized Power
34
33
Pi
Po
31. Useable operating range of tuned switch-mode supply
32. Operating range of a portable electronic device
01
1
10
Normalized Resistance
Pi : Power In
Po: Power Out

FIG. 3

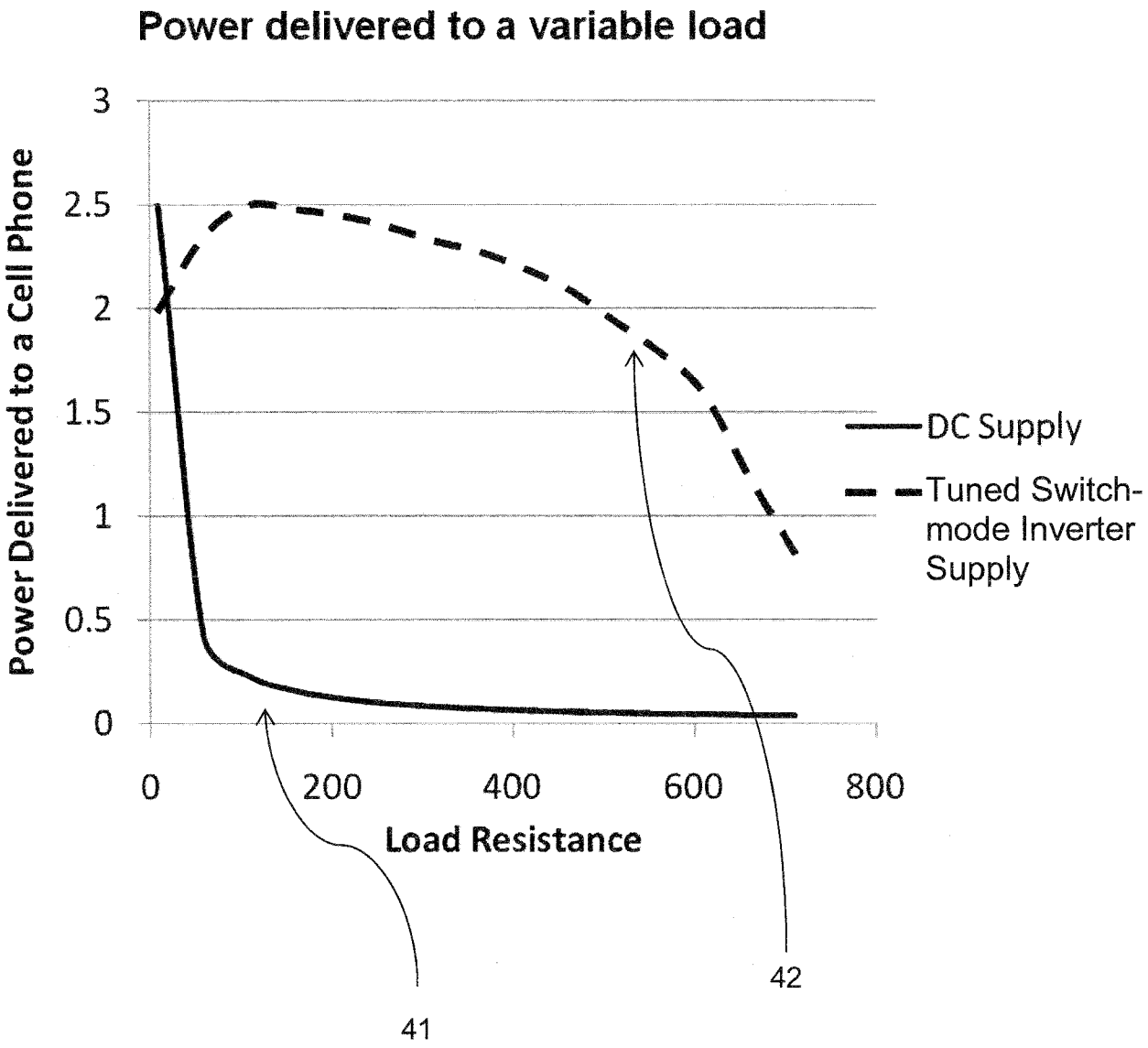

Power delivered to a variable load
Power Delivered to a Cell Phone
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
Load Resistance
DC Supply
Tuned Switch-mode Inverter Supply
41
42

FIG. 4

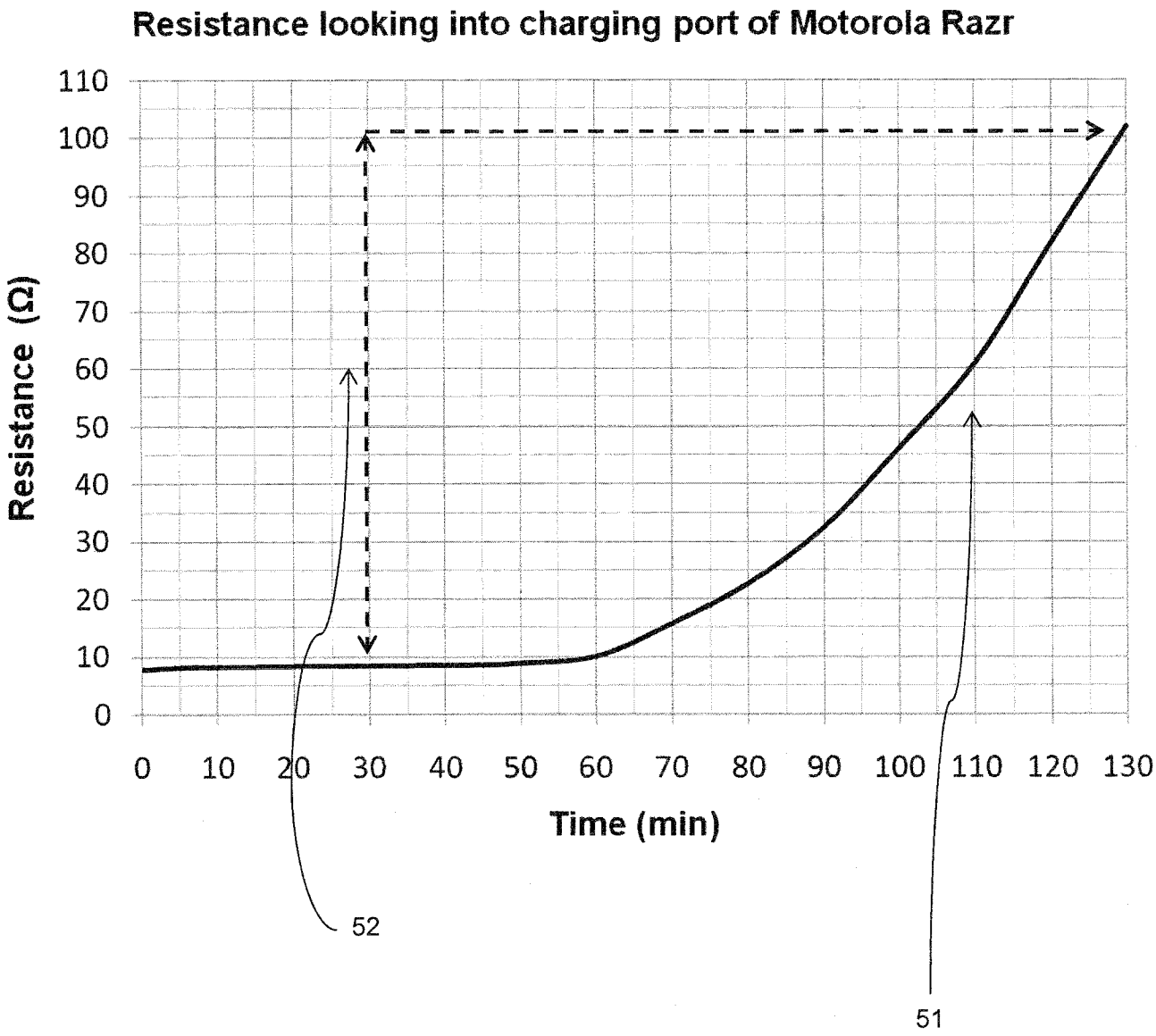

Resistance looking into charging port of Motorola Razr
Resistance (Ω)
110
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Time (min)
52
51

FIG. 5

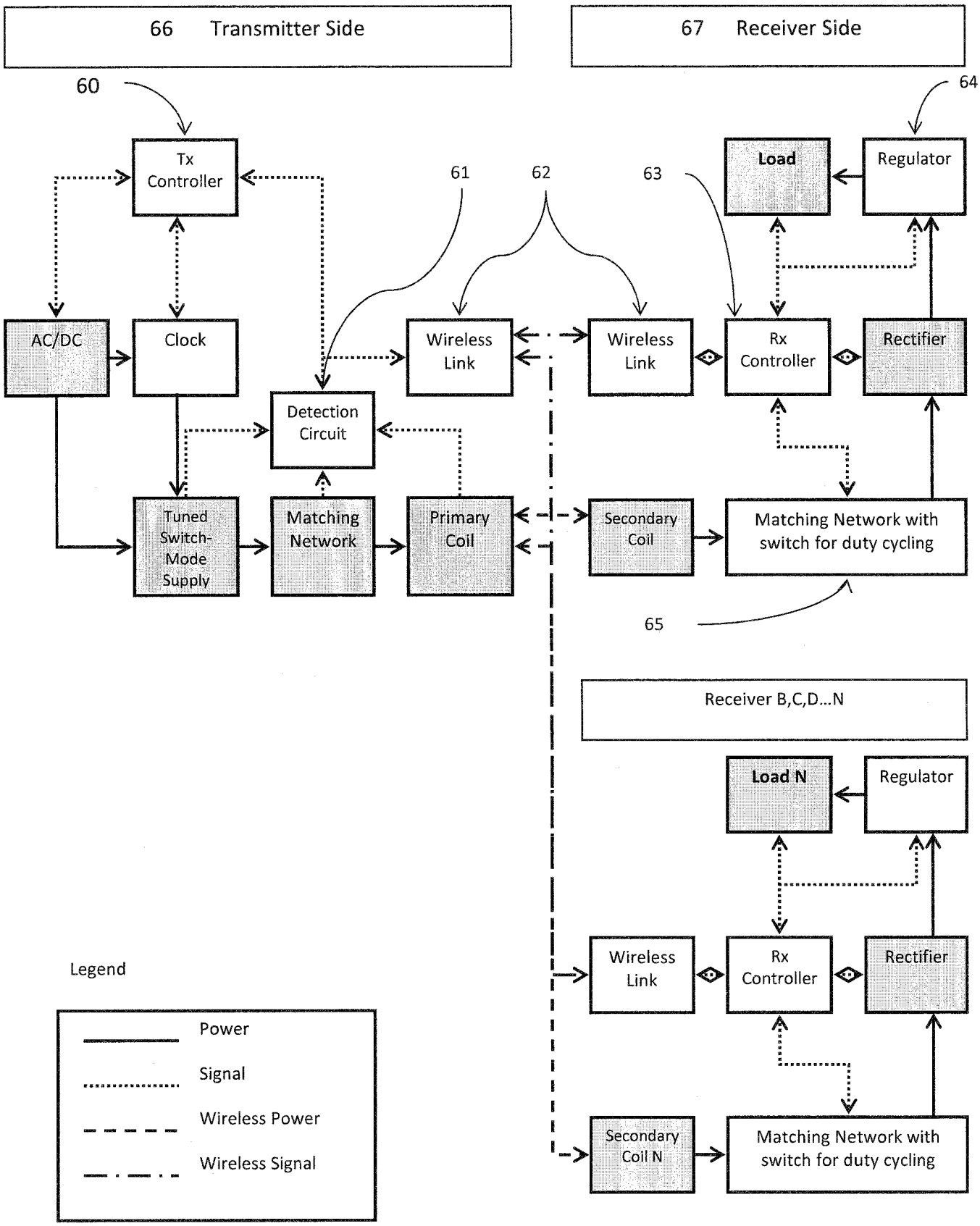
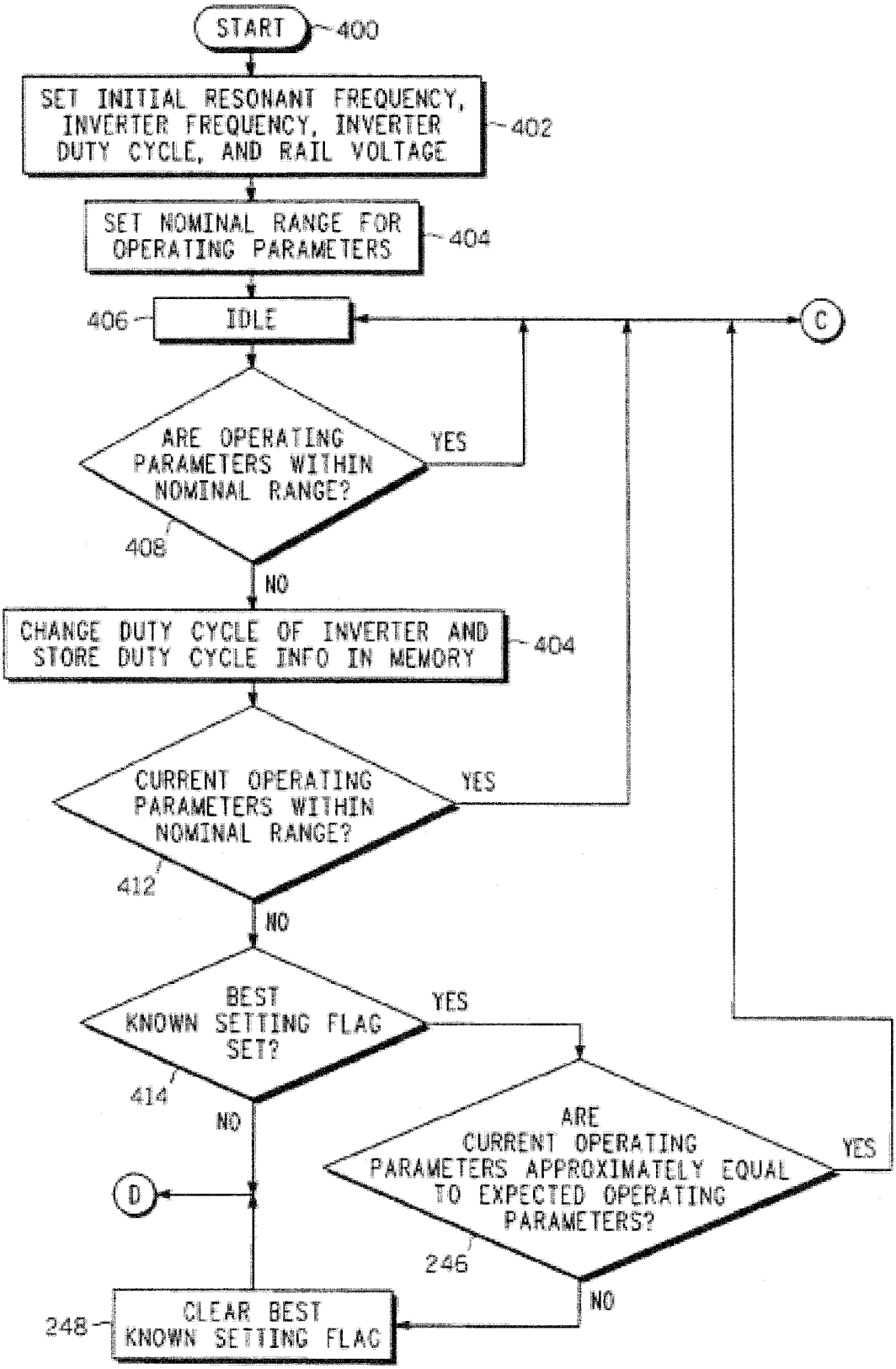
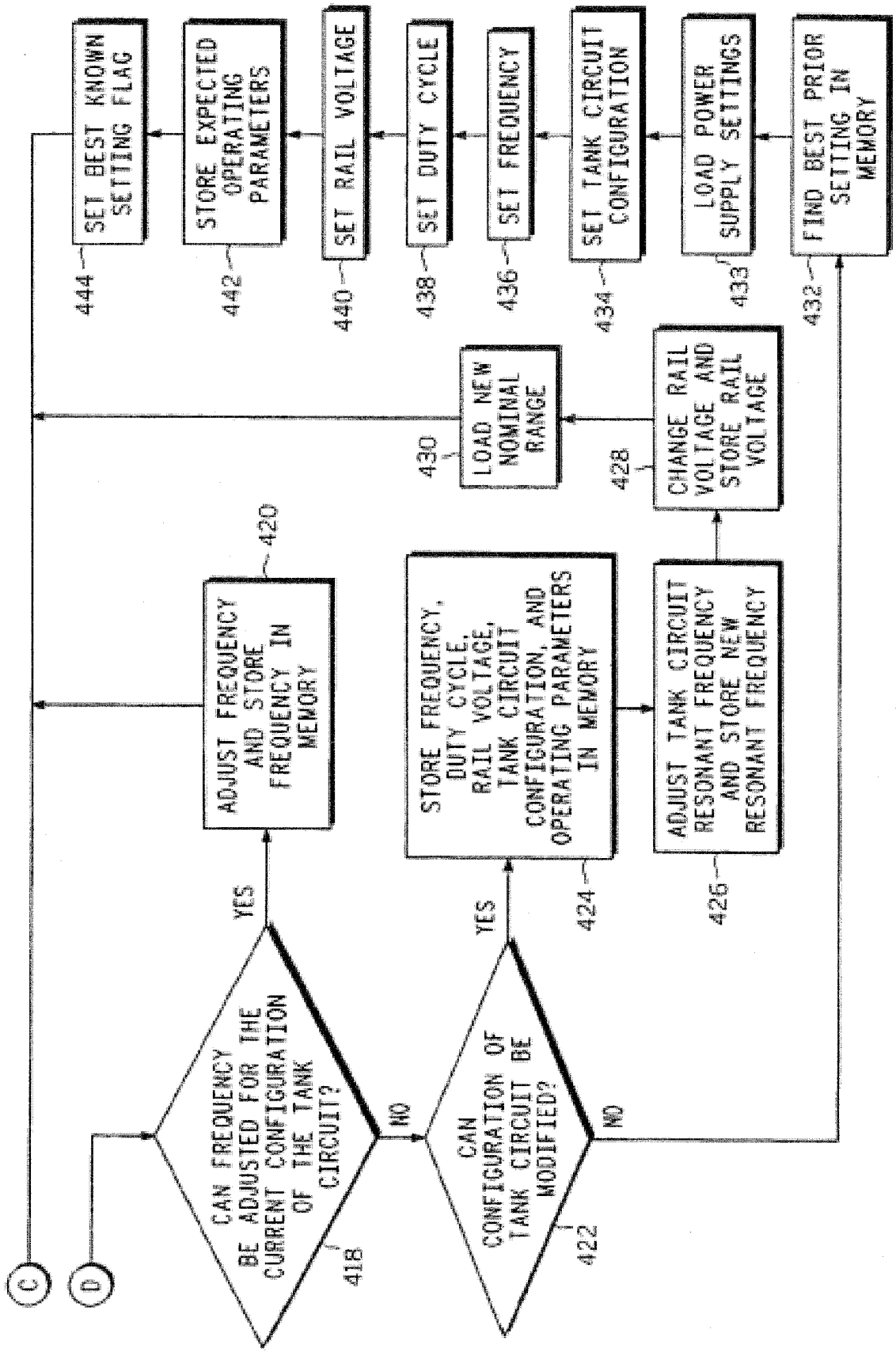

66 Transmitter Side
67 Receiver Side
60
64
Tx Controller
61
62
63
Load
Regulator
AC/DC
Clock
Wireless Link
Wireless Link
Rx Controller
Rectifier
Detection Circuit
Tuned Switch-Mode Supply
Matching Network
Primary Coil
Secondary Coil
Matching Network with switch for duty cycling
65
Receiver B,C,D...N
Load N
Regulator
Wireless Link
Rx Controller
Rectifier
Secondary Coil N
Matching Network with switch for duty cycling
Legend
Power
Signal
Wireless Power
Wireless Signal

FIG. 6



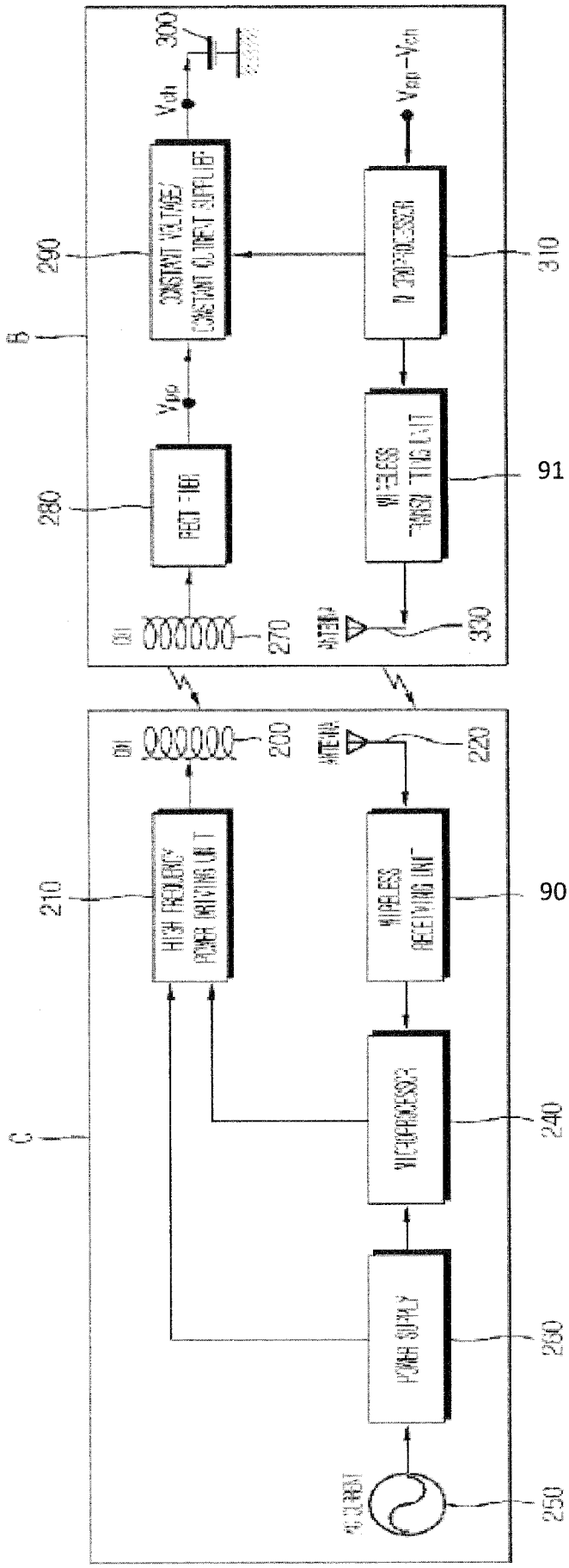
(PRIOR ART)

FIG. 7



(PRIOR ART)

FIG. 8



(PRIOR ART)

FIG. 9

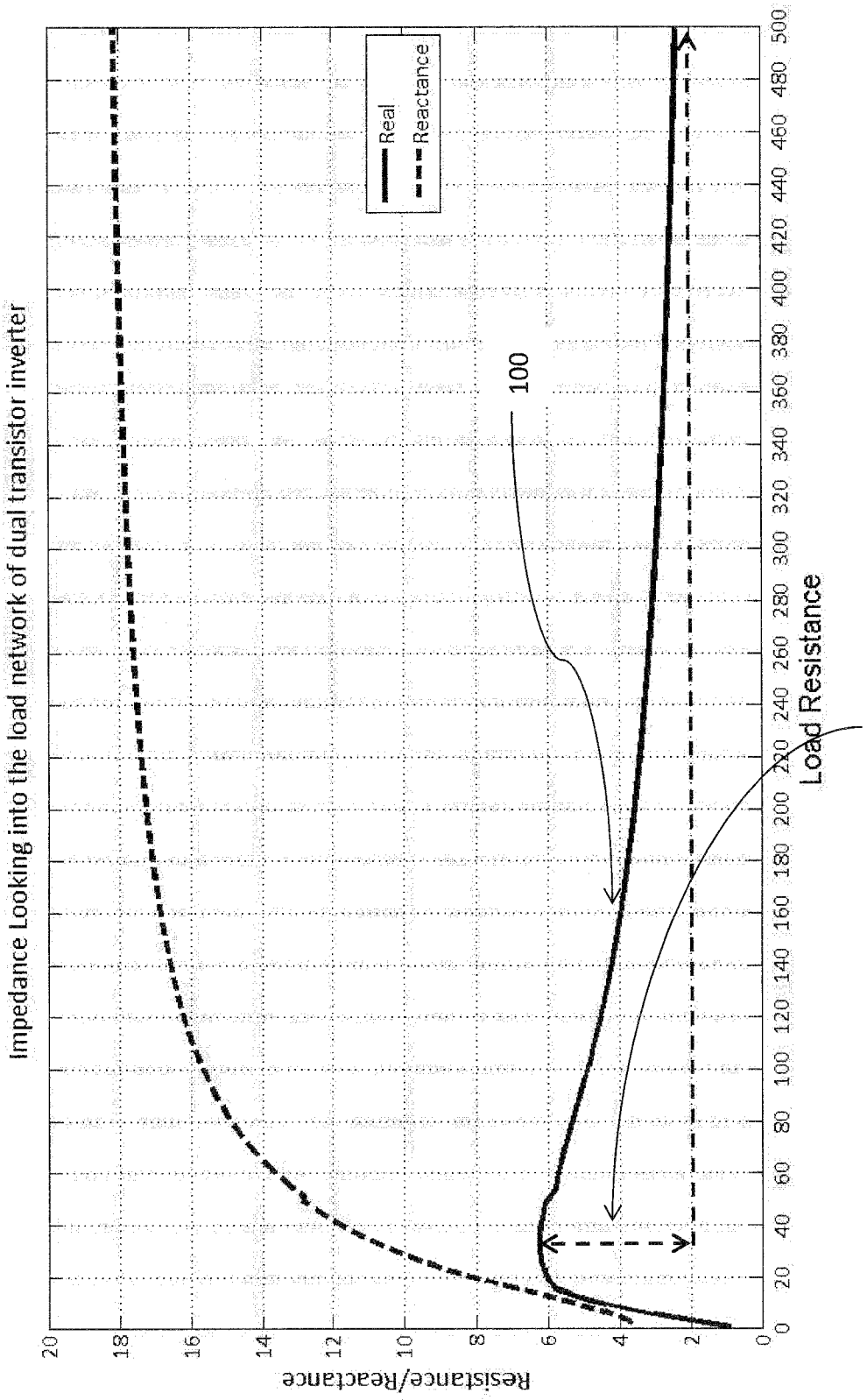

Impedance Looking into the load network of dual transistor inverter
Real
Reactance
100
Resistance/Reactance
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
2
4
6
8
10
12
14
16
18
20

FIG. 10

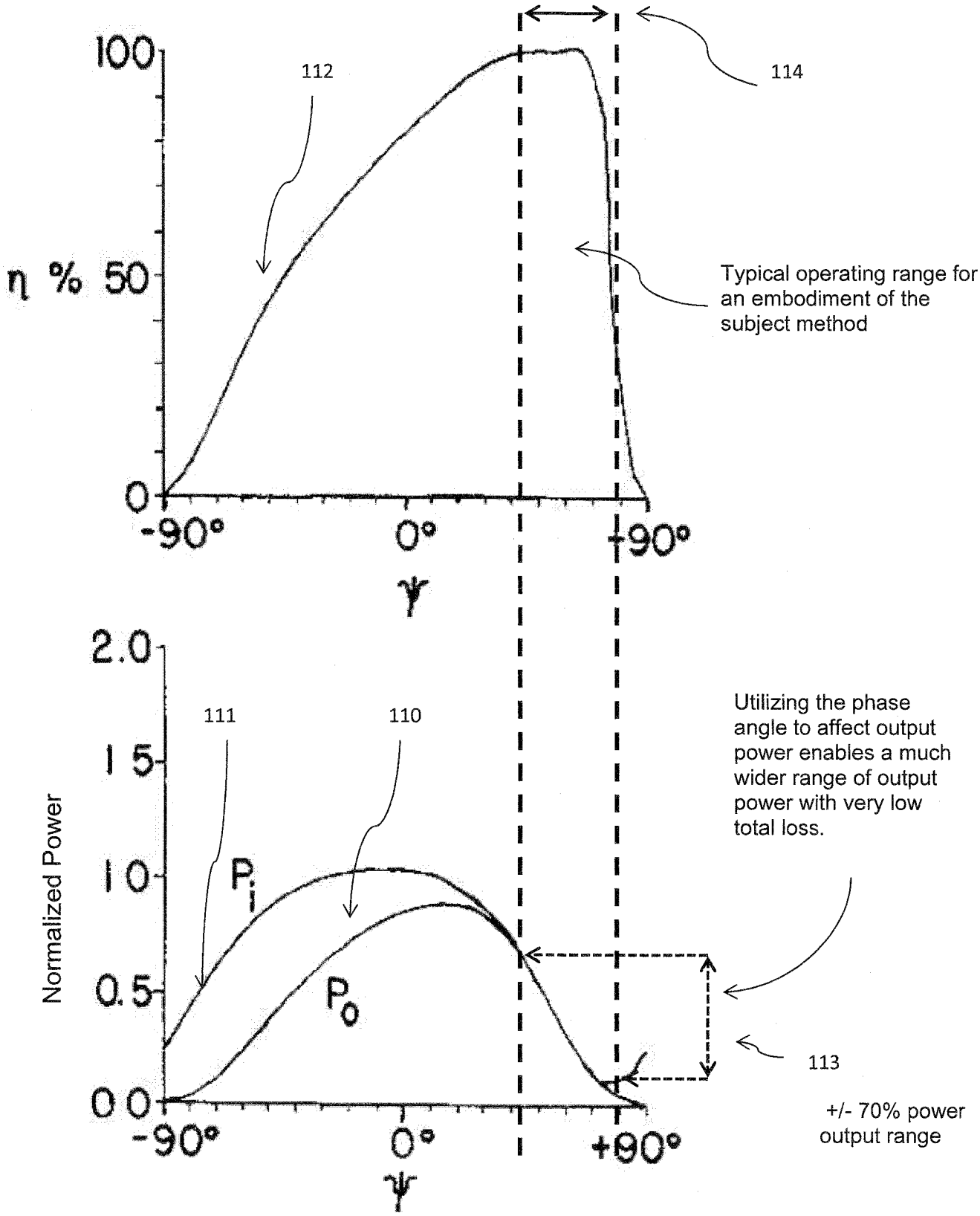

100
η % 50
0
-90°
0°
+90°
ψ
112
114
Typical operating range for an embodiment of the subject method
2.0
1.5
1.0
0.5
0.0
Normalized Power
111
110
P_i
P_o
Utilizing the phase angle to affect output power enables a much wider range of output power with very low total loss.
113
+/- 70% power output range

FIG. 11

127 Resistance controlled power delivery

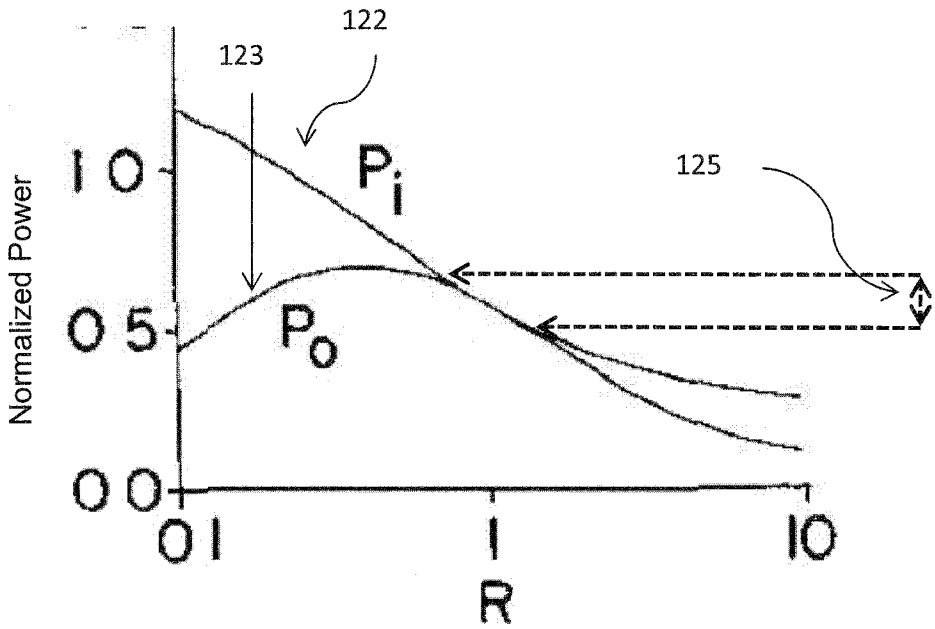


FIG. 12A

126 Phase controlled power delivery

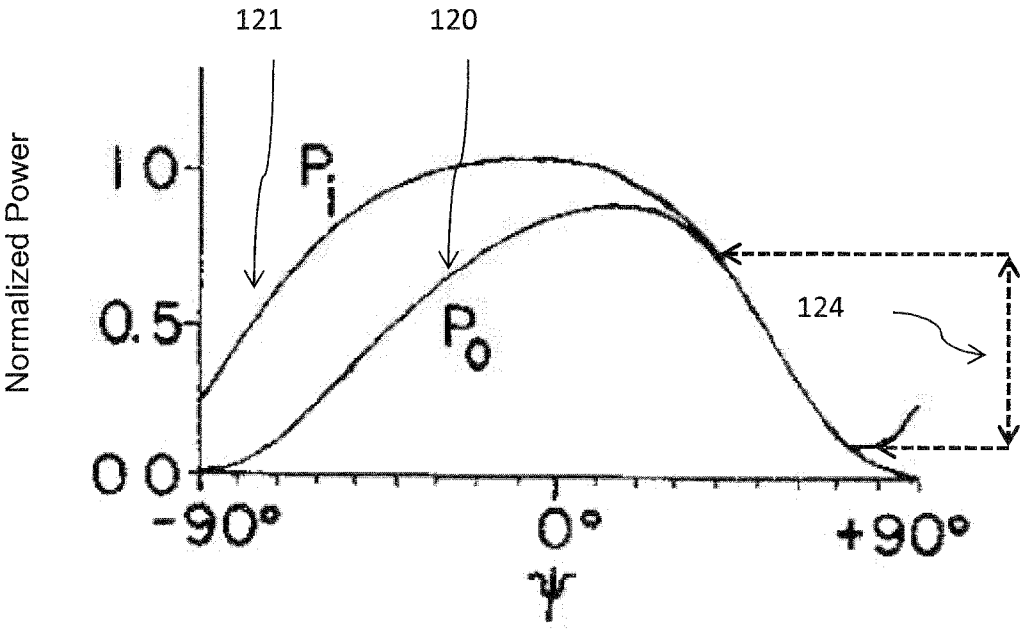


FIG. 12B

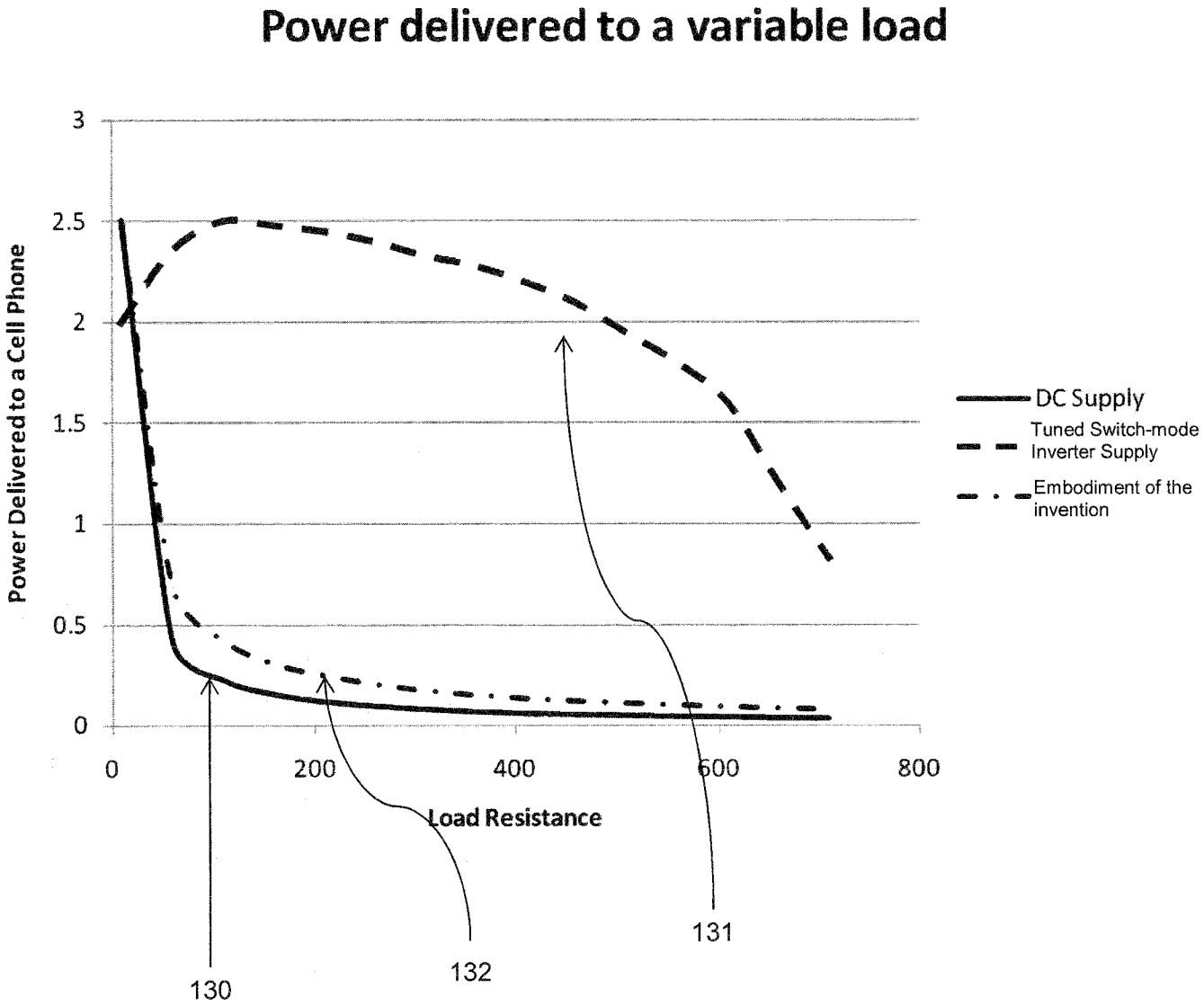

Power delivered to a variable load
Power Delivered to a Cell Phone
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
Load Resistance
DC Supply
Tuned Switch-mode Inverter Supply
Embodiment of the invention
130
132
131

FIG. 13

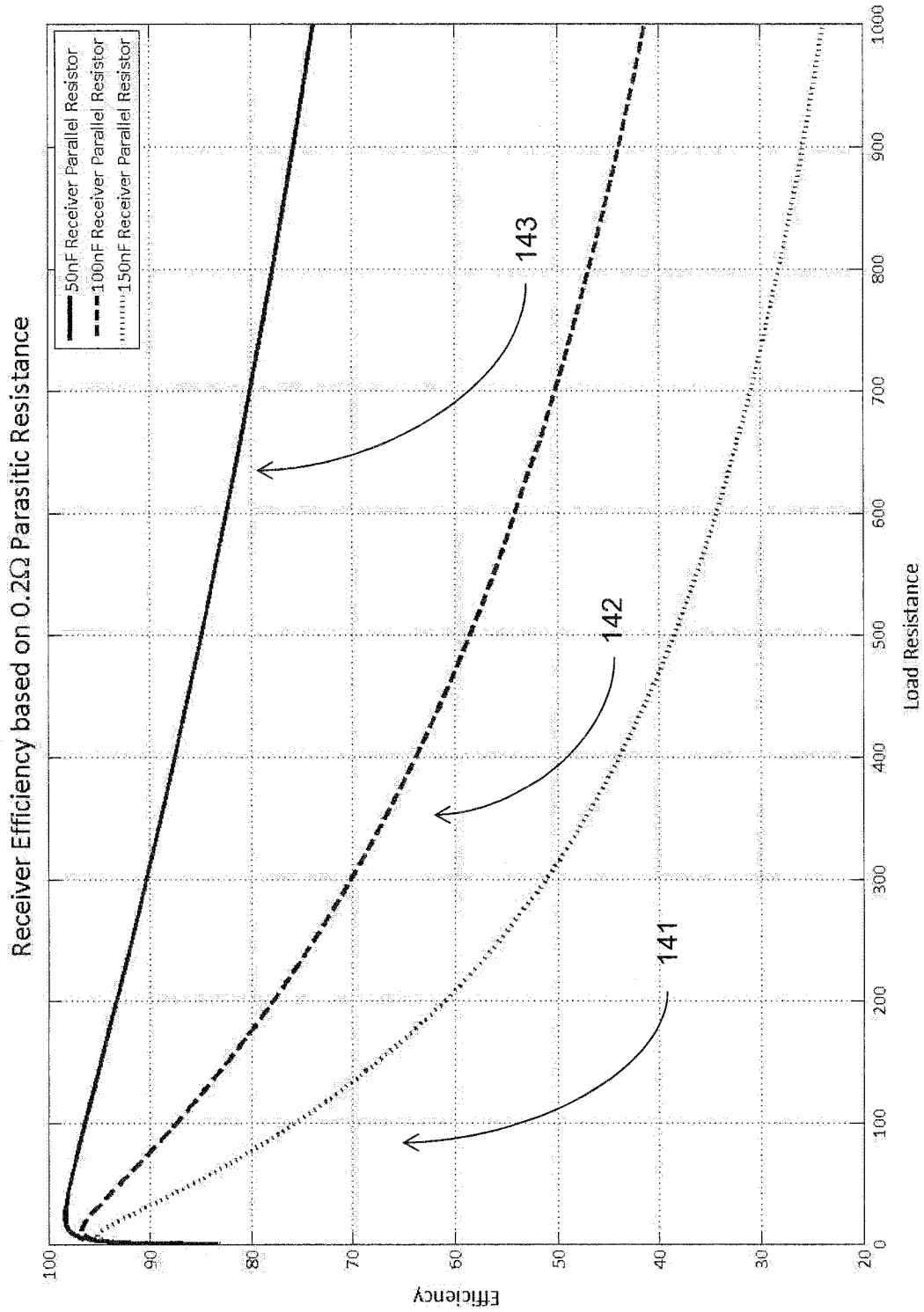

Receiver Efficiency based on 0.2Ω Parasitic Resistance
50nF Receiver Parallel Resistor
100nF Receiver Parallel Resistor
150nF Receiver Parallel Resistor
143
142
141
Efficiency
Load Resistance
100
90
80
70
60
50
40
30
20
0
100
200
300
400
500
600
700
800
900
1000

FIG. 14

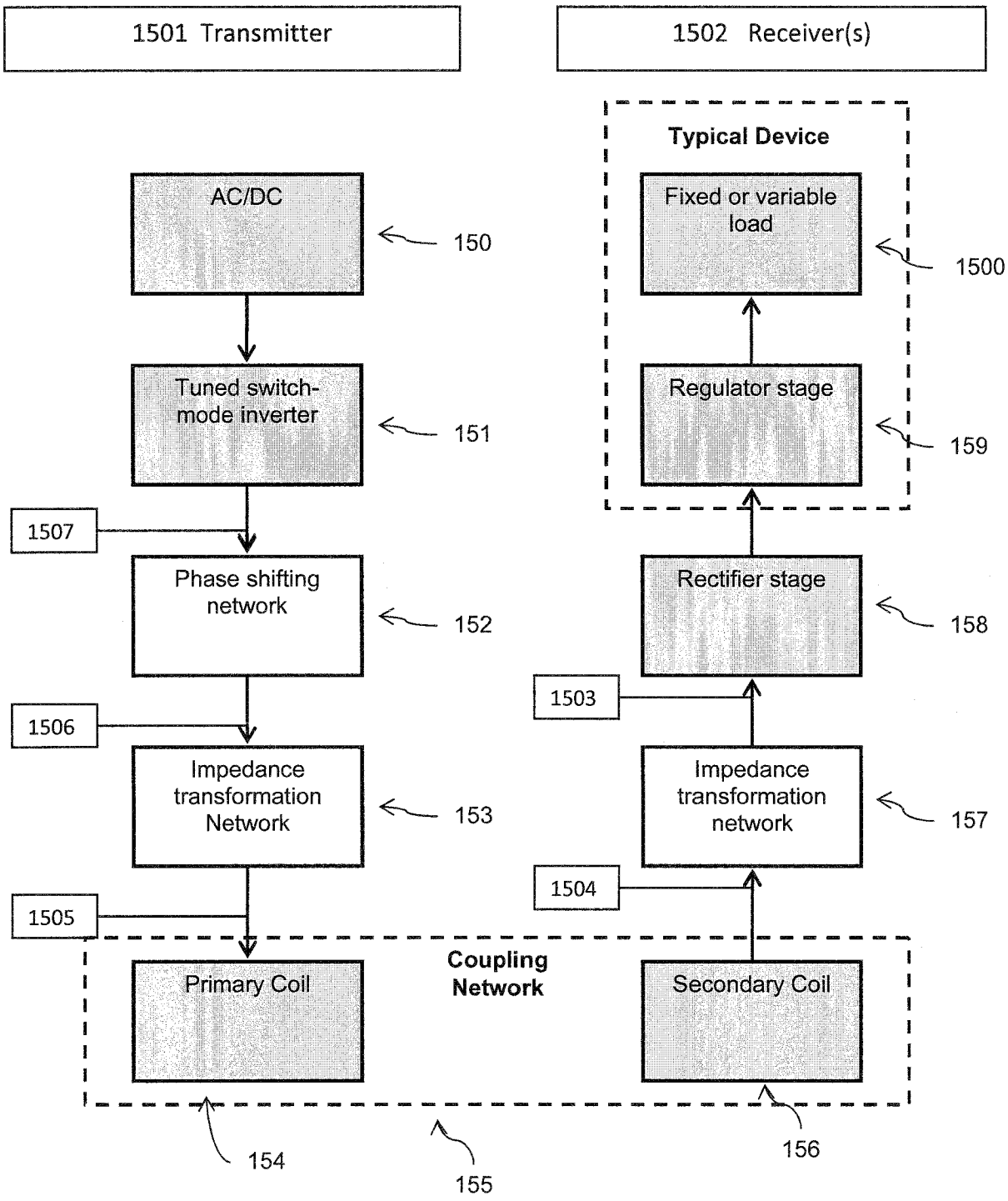

1501 Transmitter
1502 Receiver(s)
Typical Device
AC/DC
150
Fixed or variable load
1500
Tuned switch-mode inverter
151
Regulator stage
159
1507
Phase shifting network
152
Rectifier stage
158
1503
1506
Impedance transformation Network
153
Impedance transformation network
157
1504
1505
Coupling Network
Primary Coil
Secondary Coil
154
155
156

FIG. 15

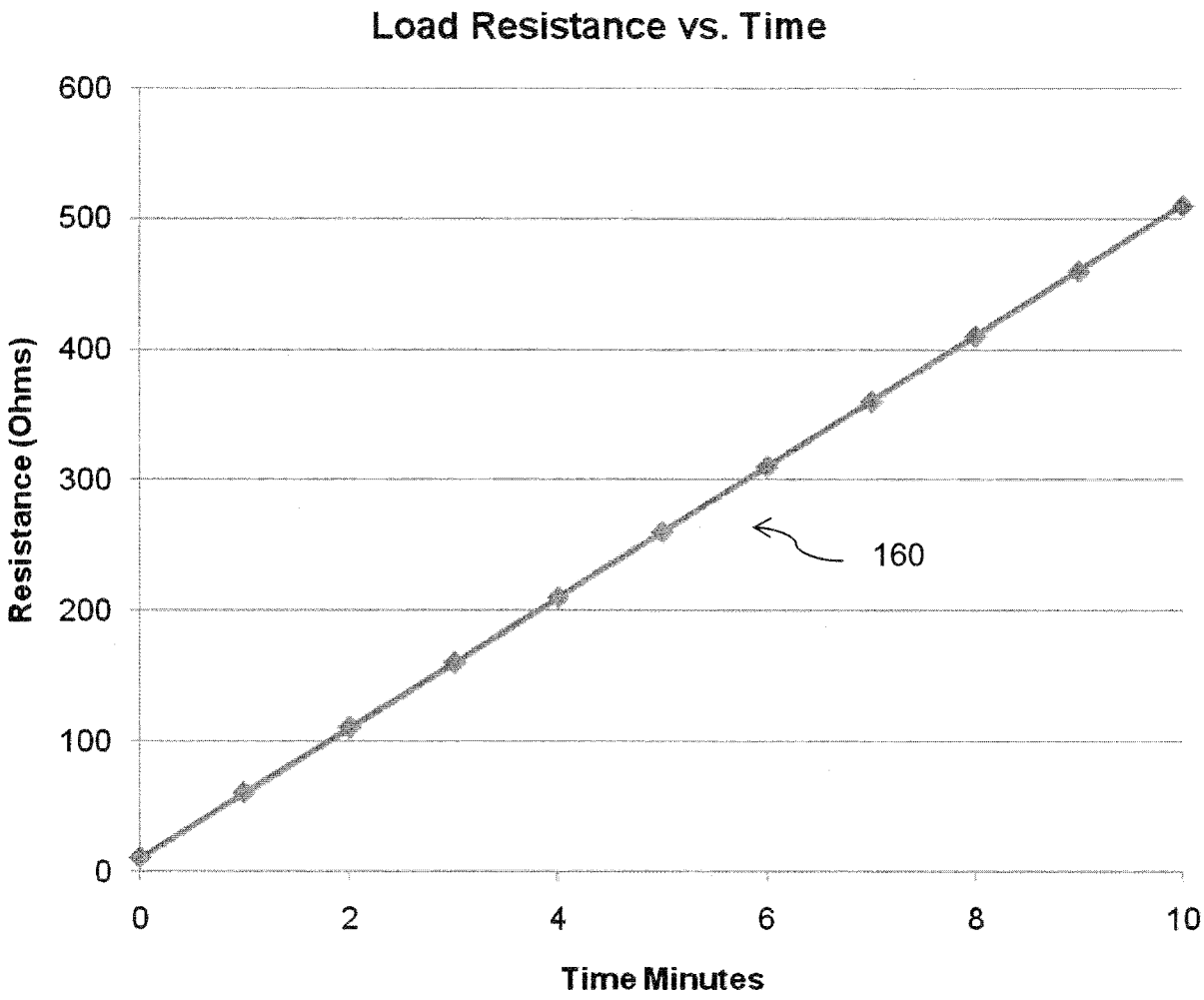

Load Resistance vs. Time
600
500
400
300
200
100
0
Resistance (Ohms)
0
2
4
6
8
10
Time Minutes
160

FIG. 16

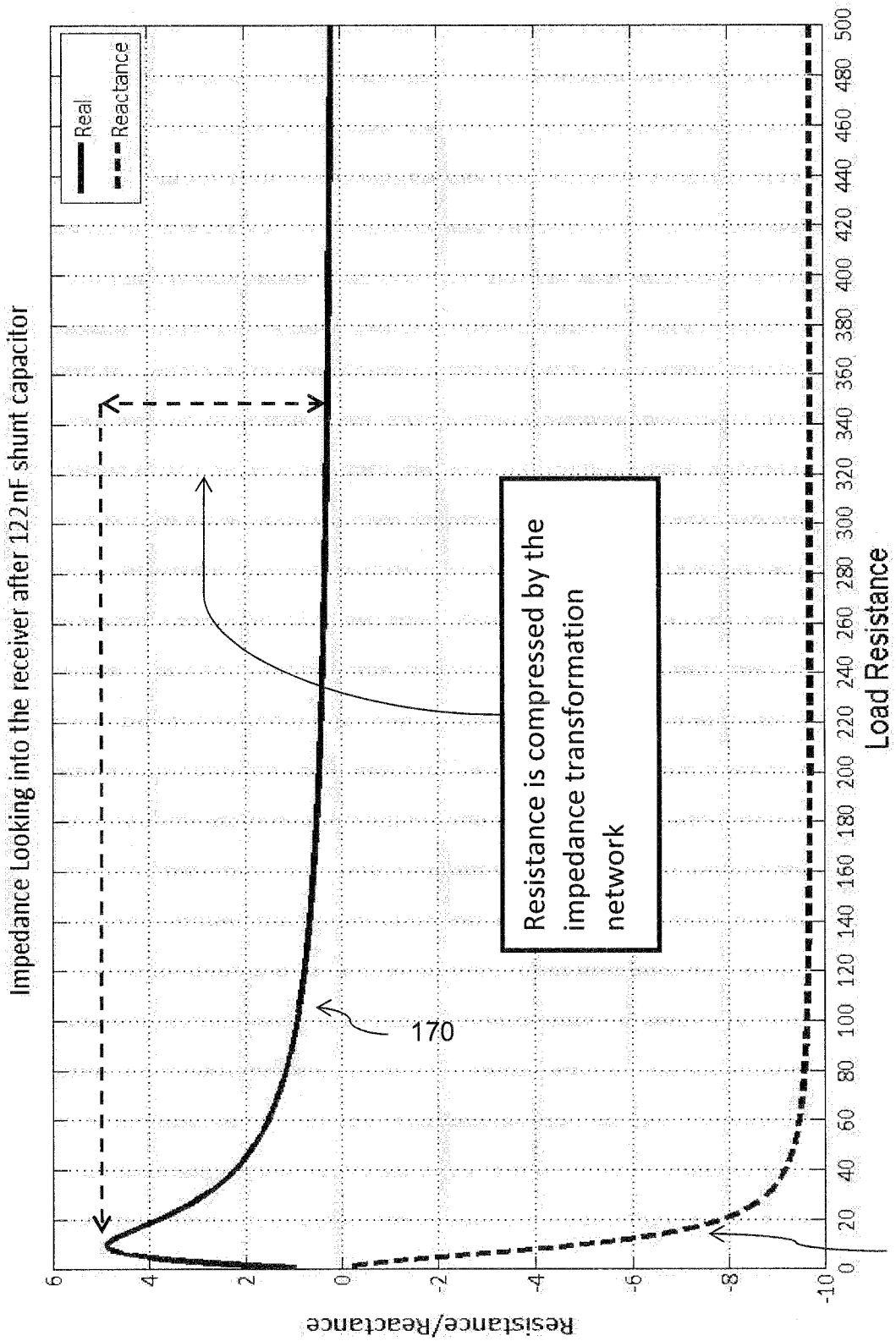

Impedance Looking into the receiver after 122nF shunt capacitor
Real
Reactance
Resistance is compressed by the impedance transformation network
170
171
Resistance/Reactance
Load Resistance
6
4
2
0
-2
-4
-6
-8
-10
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 17

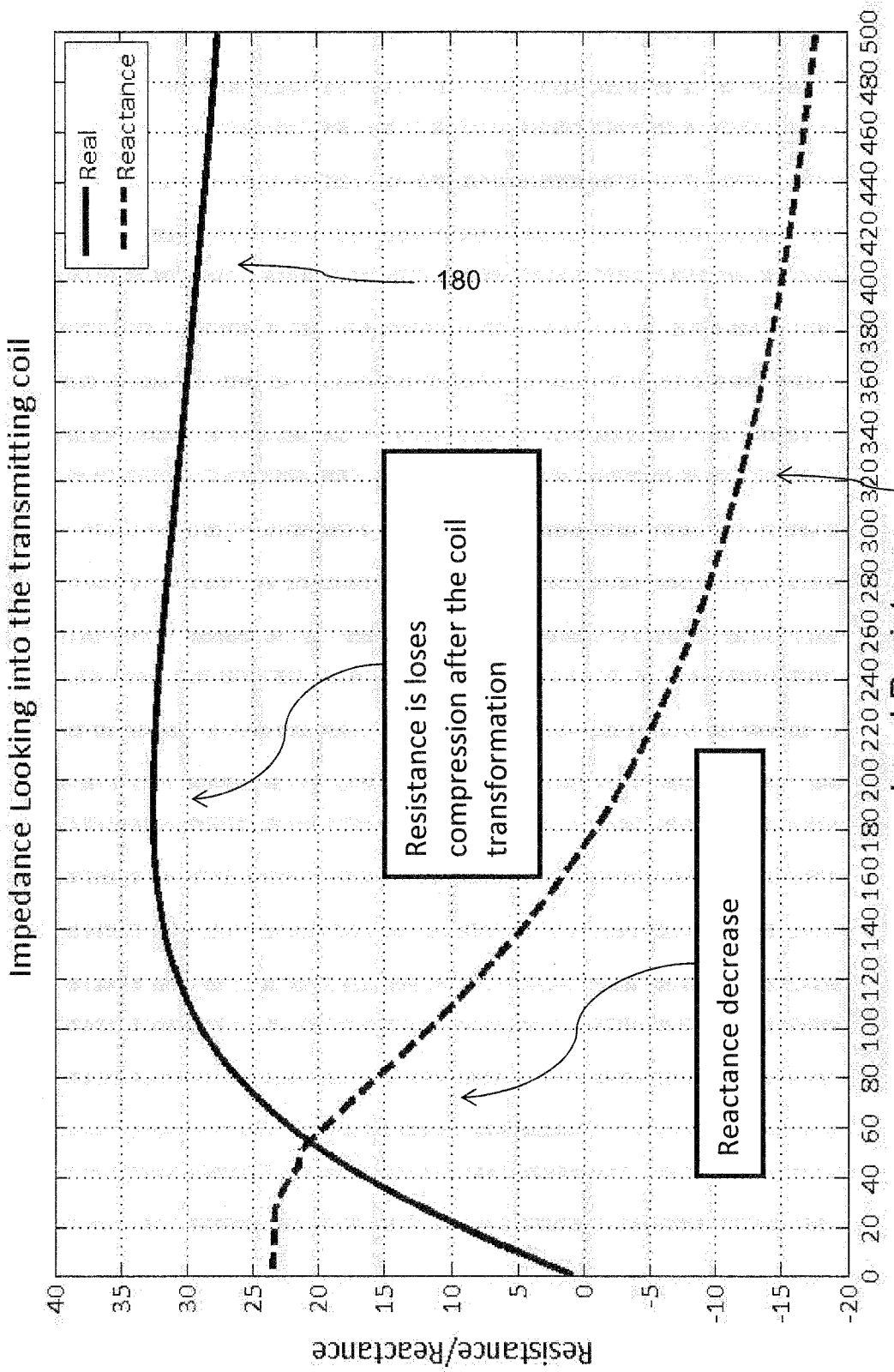

Impedance Looking into the transmitting coil
Real
Reactance
180
181
Resistance is loses compression after the coil transformation
Reactance decrease
Resistance/Reactance
Load Resistance
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500

FIG. 18

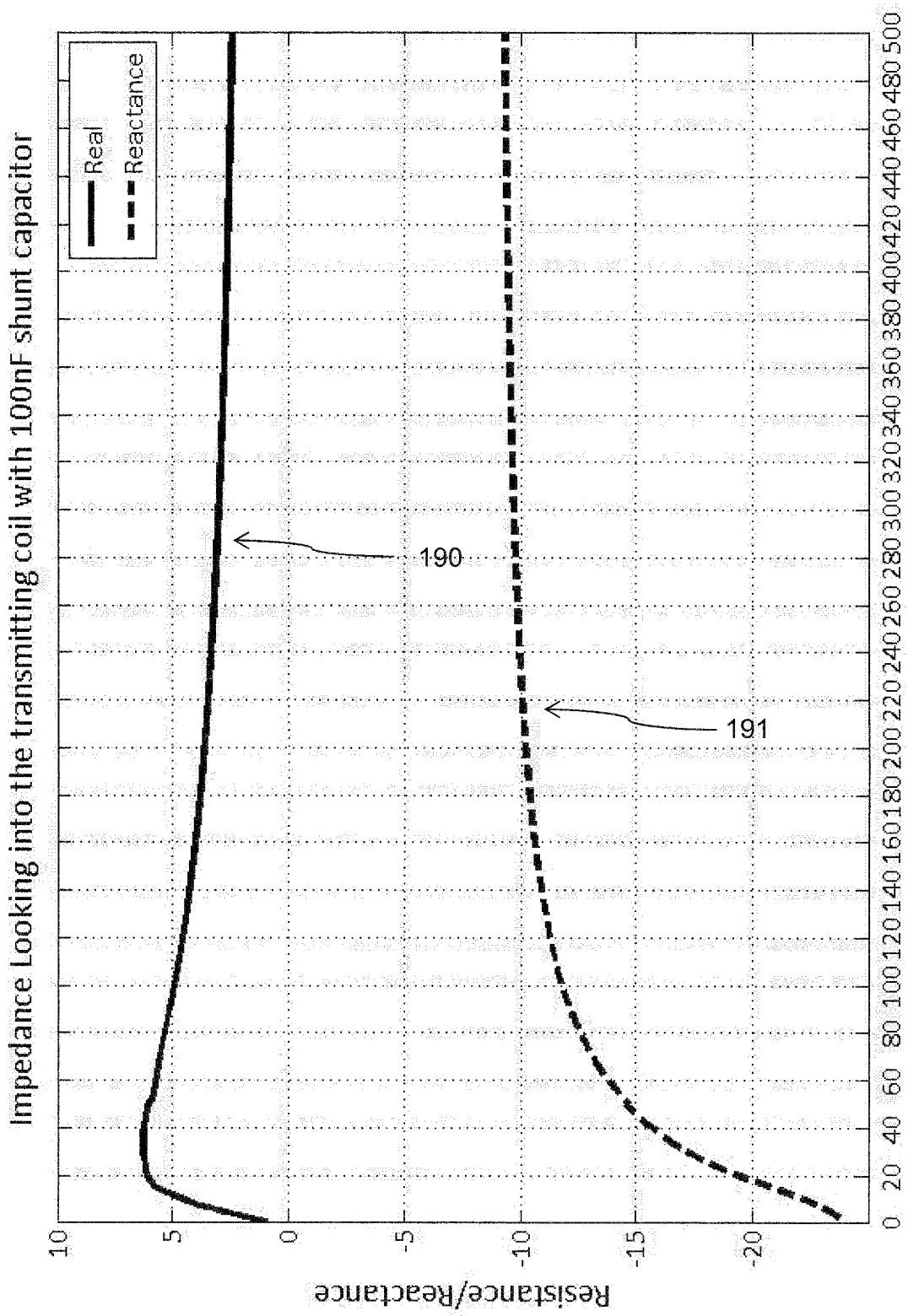

Impedance Looking into the transmitting coil with 100nF shunt capacitor
Real
Reactance
190
191
Resistance/Reactance
Load Resistance
10
5
0
-5
-10
-15
-20
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500

FIG. 19

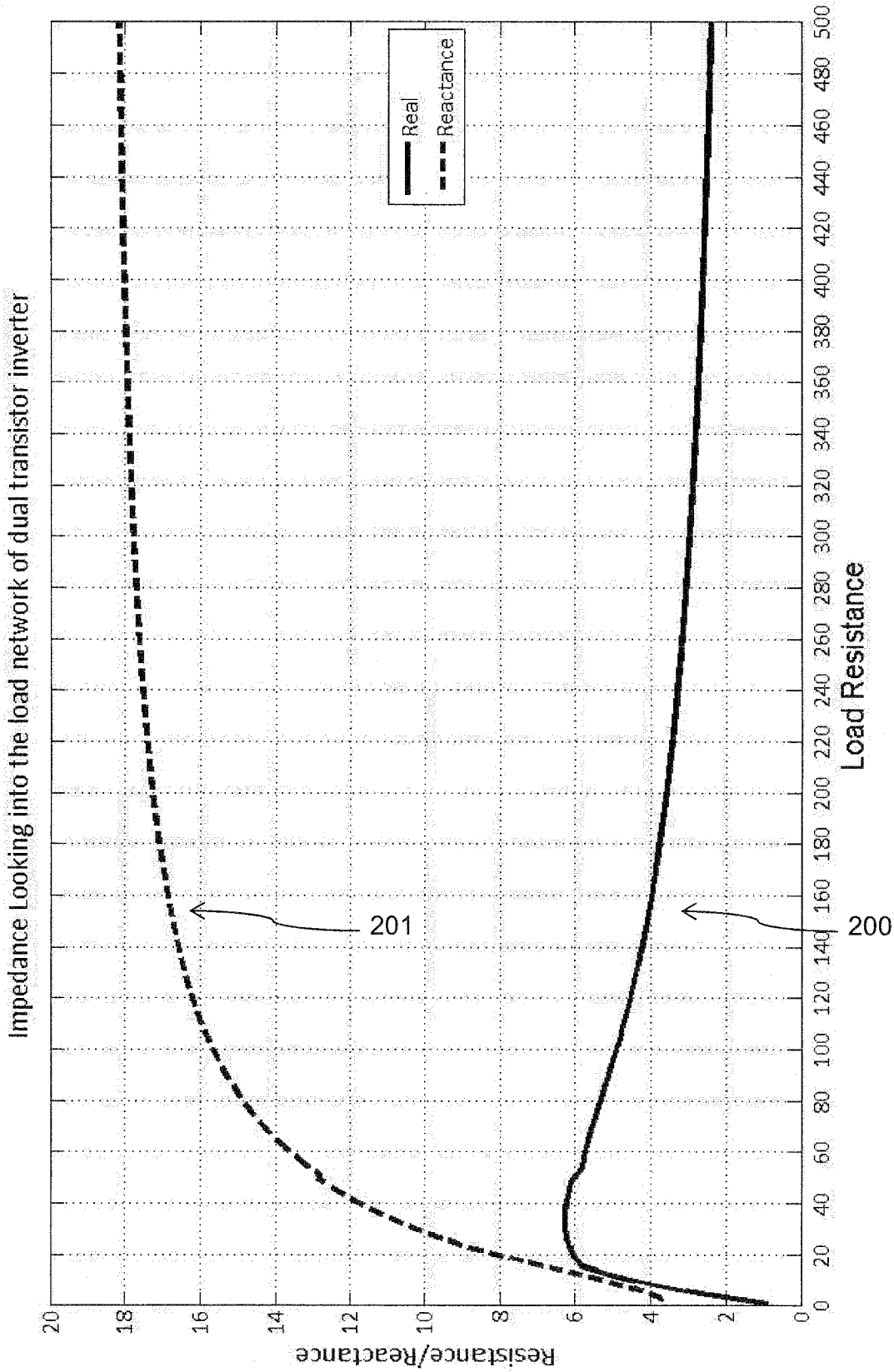

Impedance Looking into the load network of dual transistor inverter
Real
Reactance
201
200
Resistance/Reactance
Load Resistance
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
2
4
6
8
10
12
14
16
18
20

FIG. 20

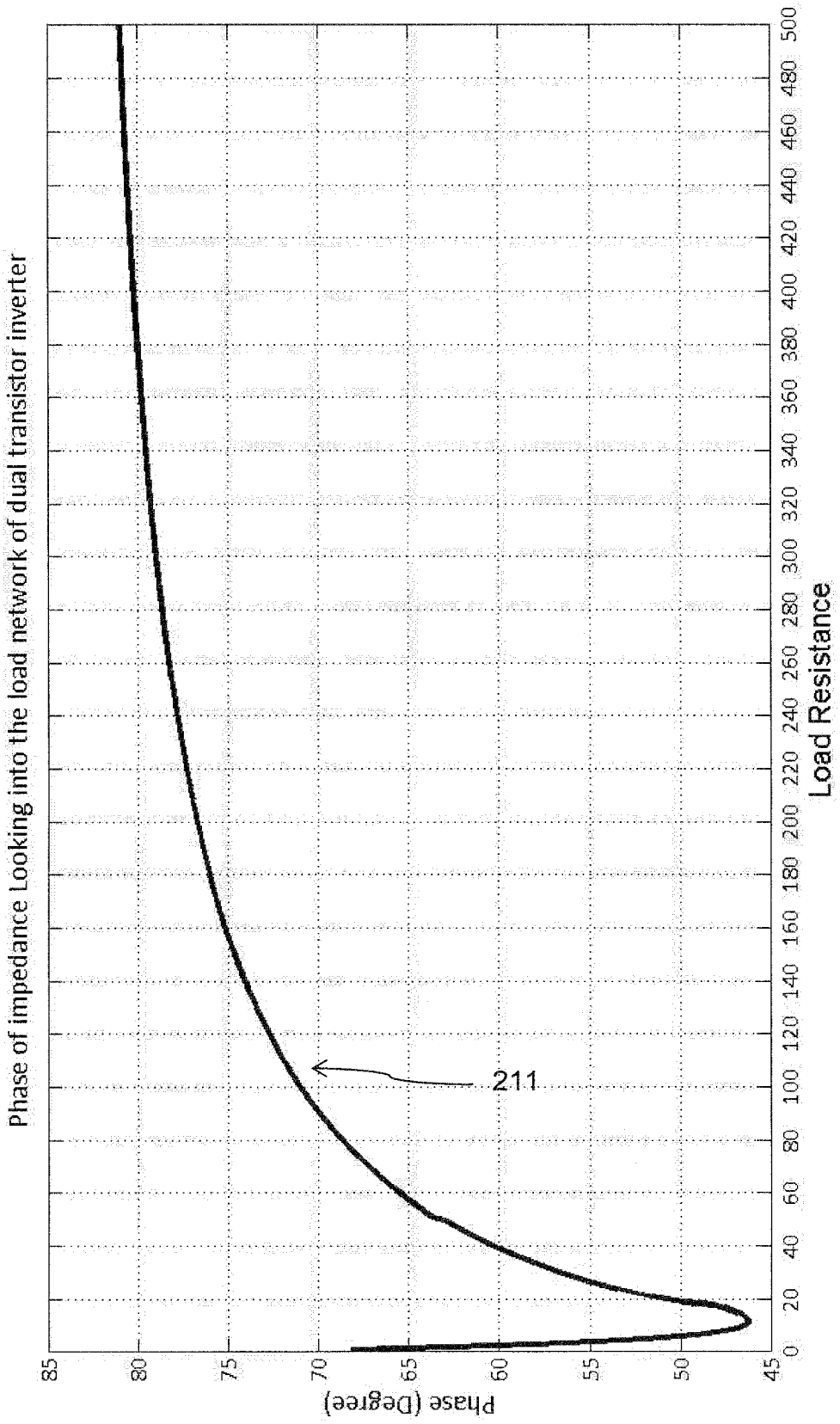

Phase of impedance Looking into the load network of dual transistor inverter
Phase (Degree)
Load Resistance
211
85
80
75
70
65
60
55
50
45
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 21

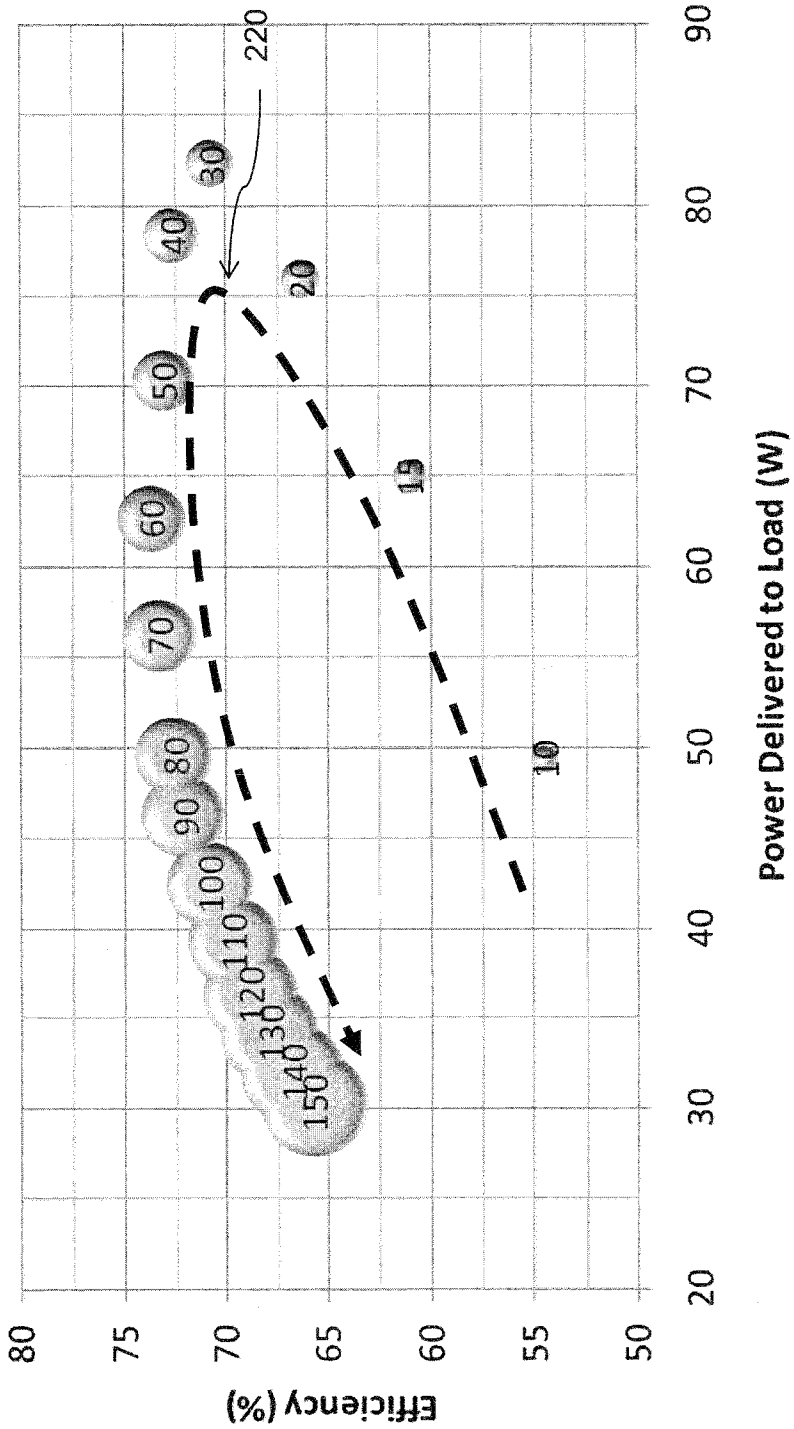

Efficiency (%)
80
75
70
65
60
55
50
Power Delivered to Load (W)
20
30
40
50
60
70
80
90
220
30
40
50
60
70
80
90
100
110
120
130
140
150
20
15
10

FIG. 22

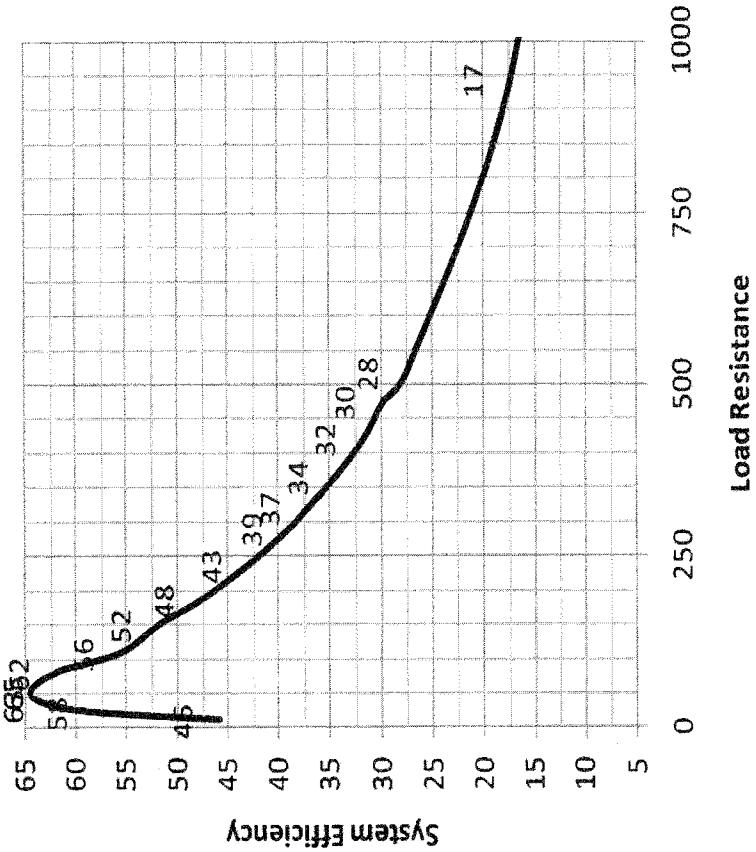


FIG. 23B

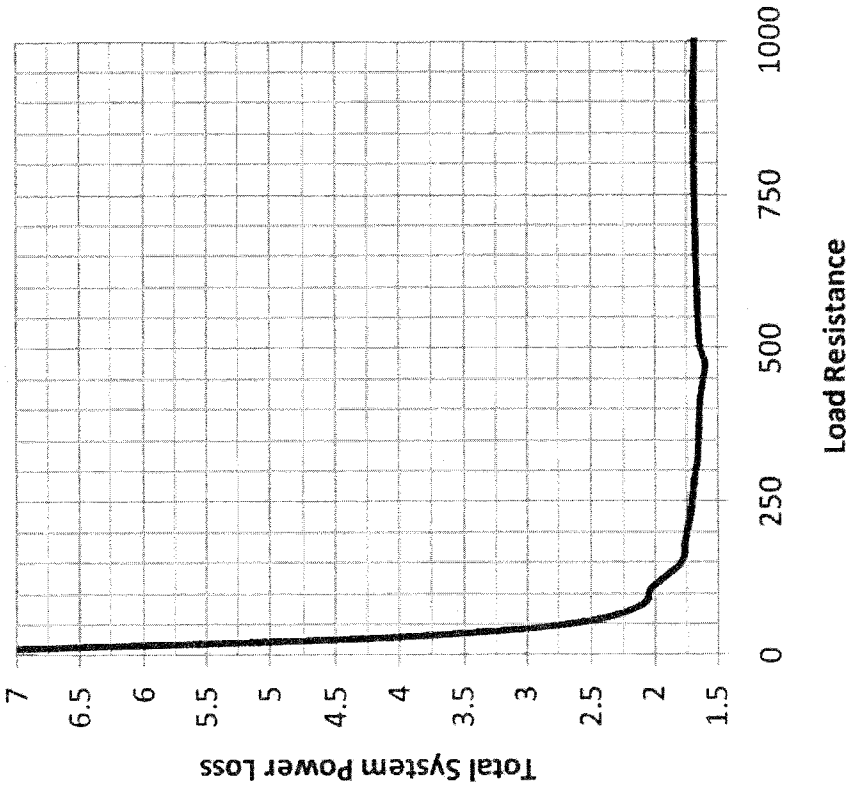


FIG. 23A

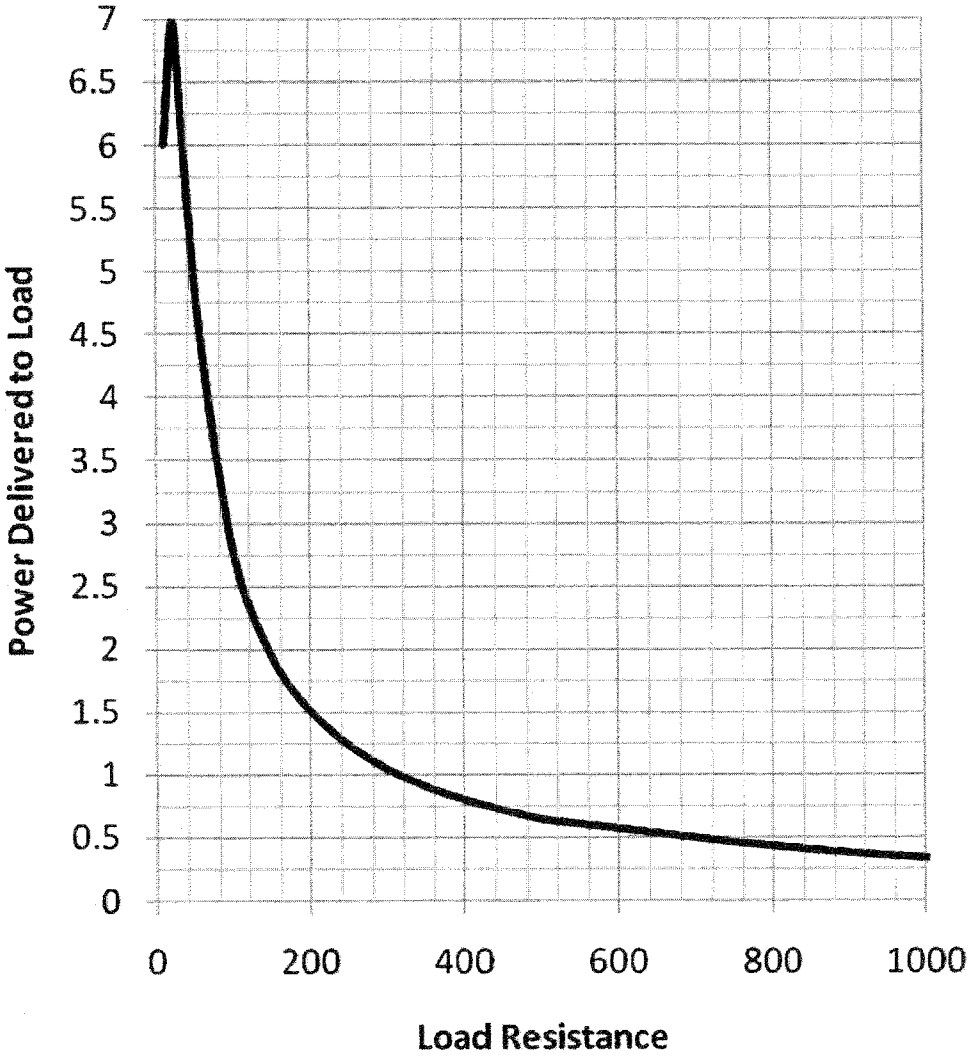

Power Delivered to Load
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
200
400
600
800
1000
Load Resistance

FIG. 23C

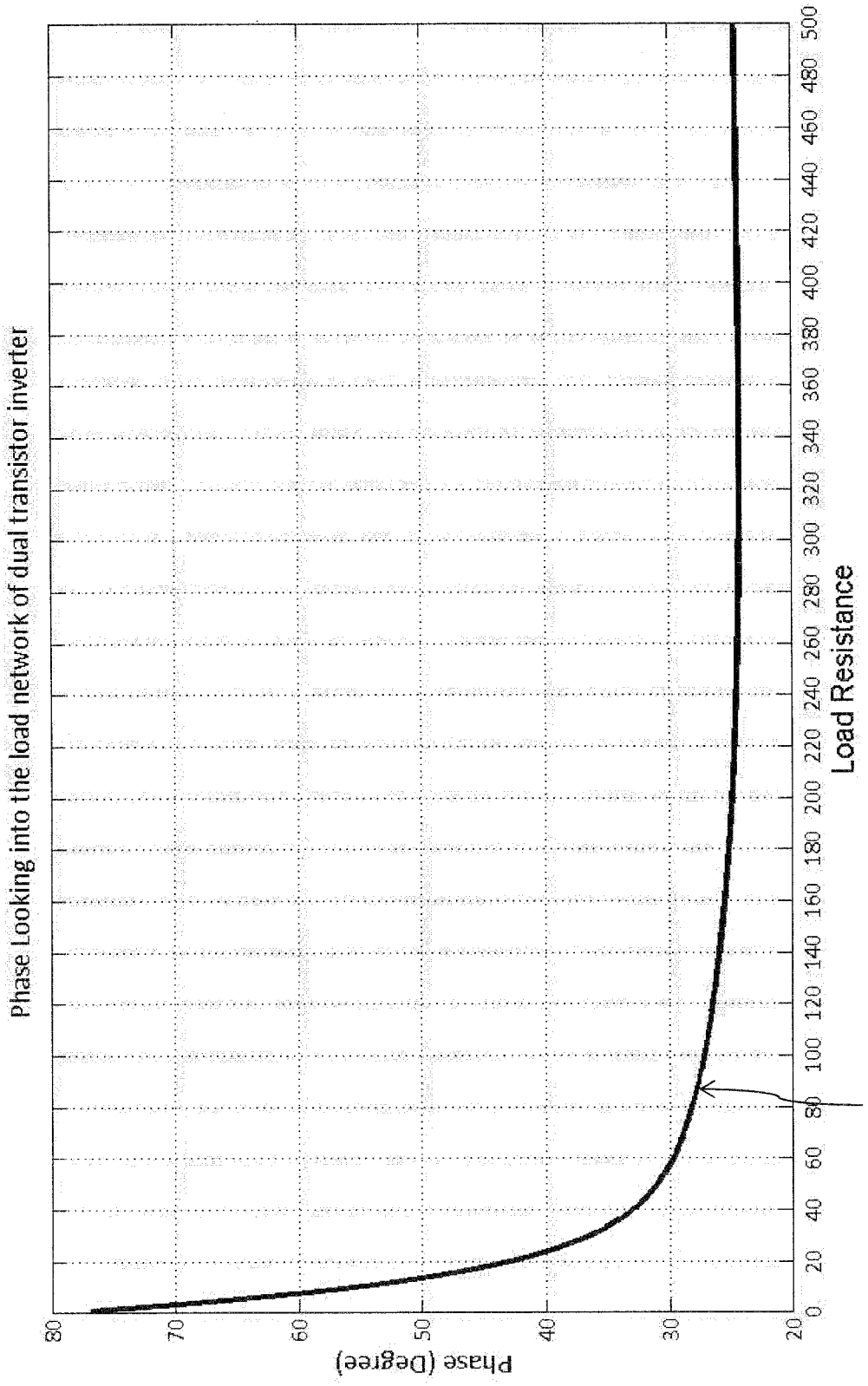

Phase Looking into the load network of dual transistor inverter
Phase (Degree)
Load Resistance
240

FIG. 24

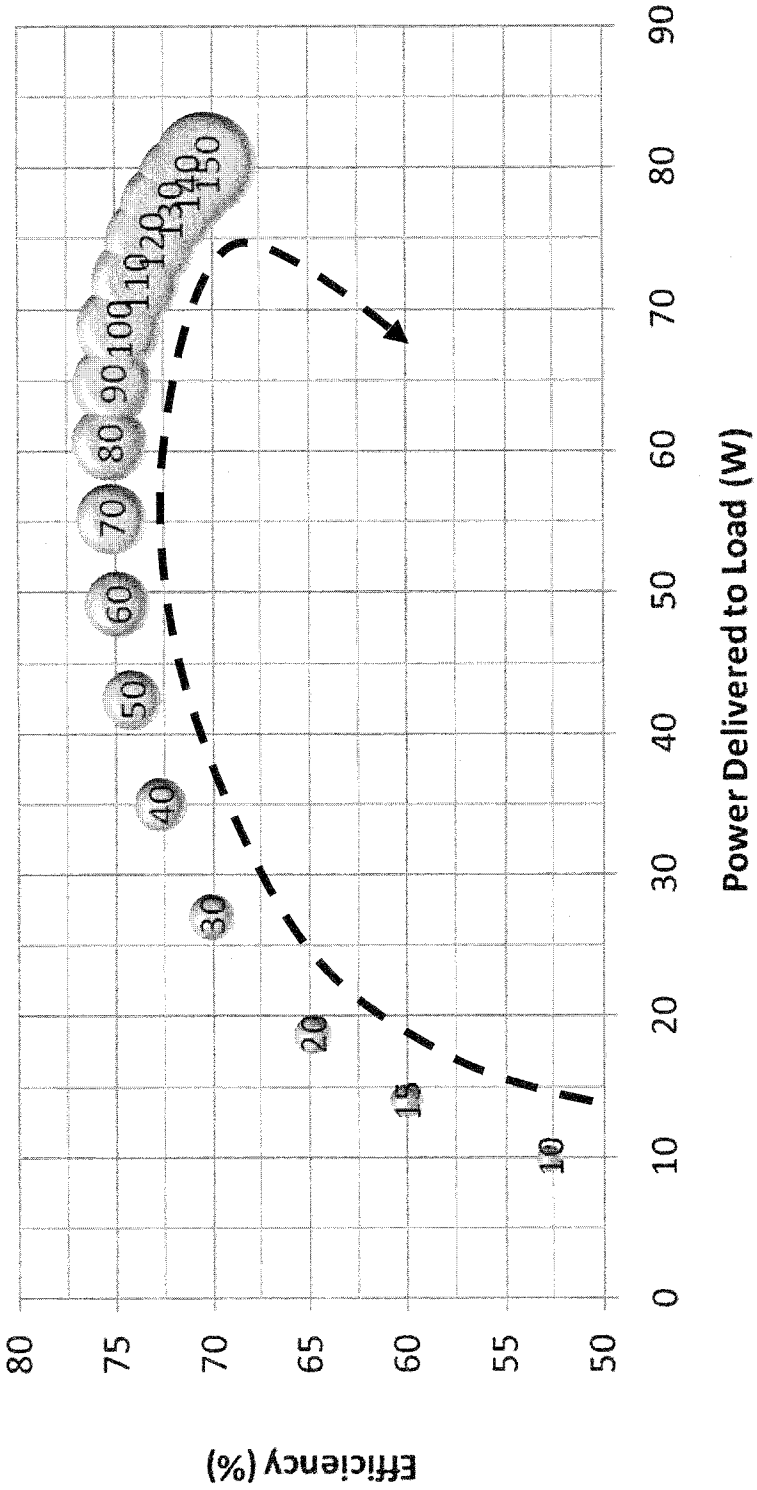

Efficiency (%)
80
75
70
65
60
55
50
Power Delivered to Load (W)
0
10
20
30
40
50
60
70
80
90
10
15
20
30
40
50
60
70
80
90
100
110
120
130
140
150

FIG. 25

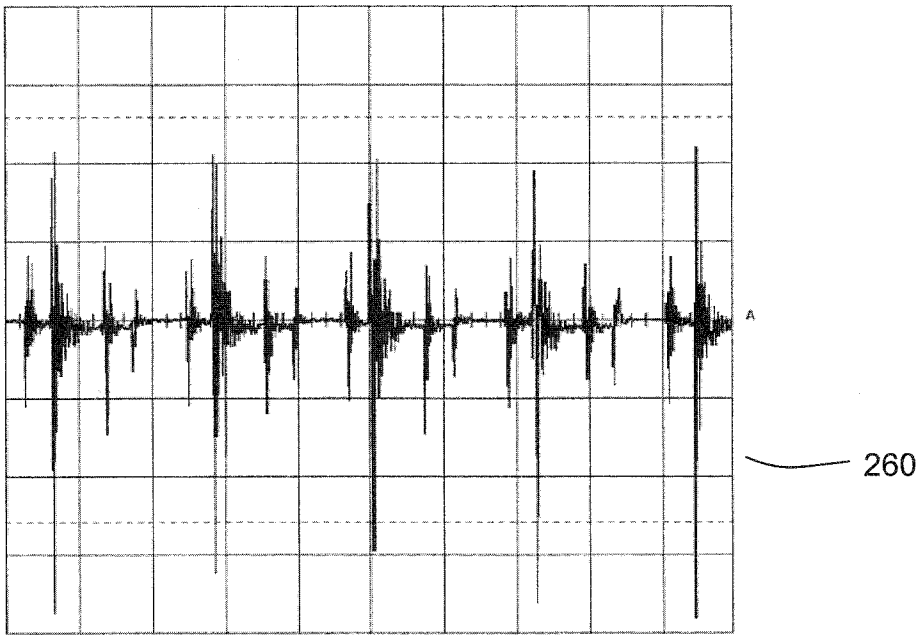


FIG. 26A

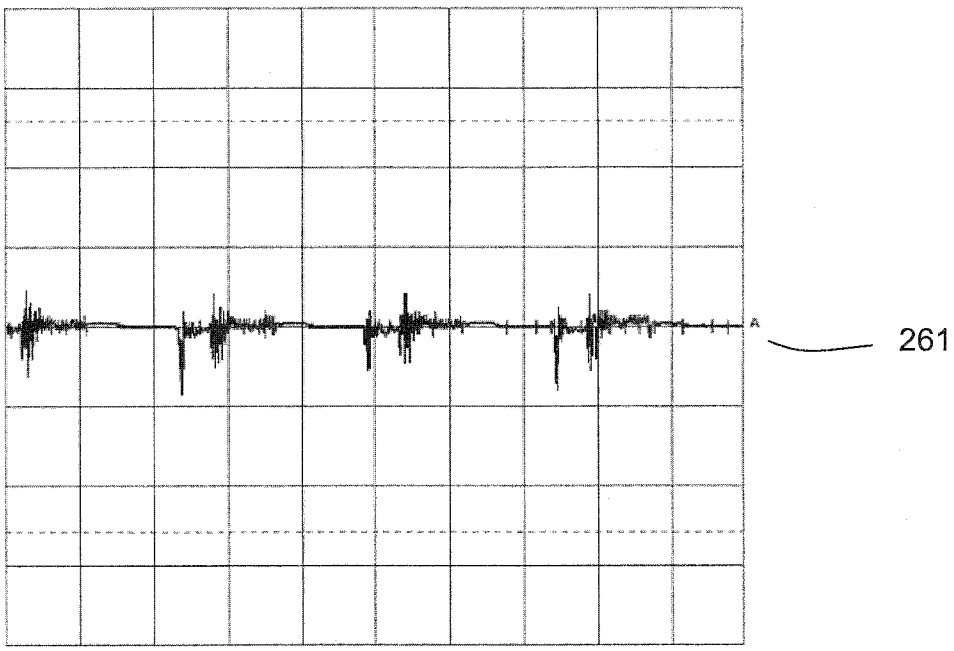


FIG. 26B

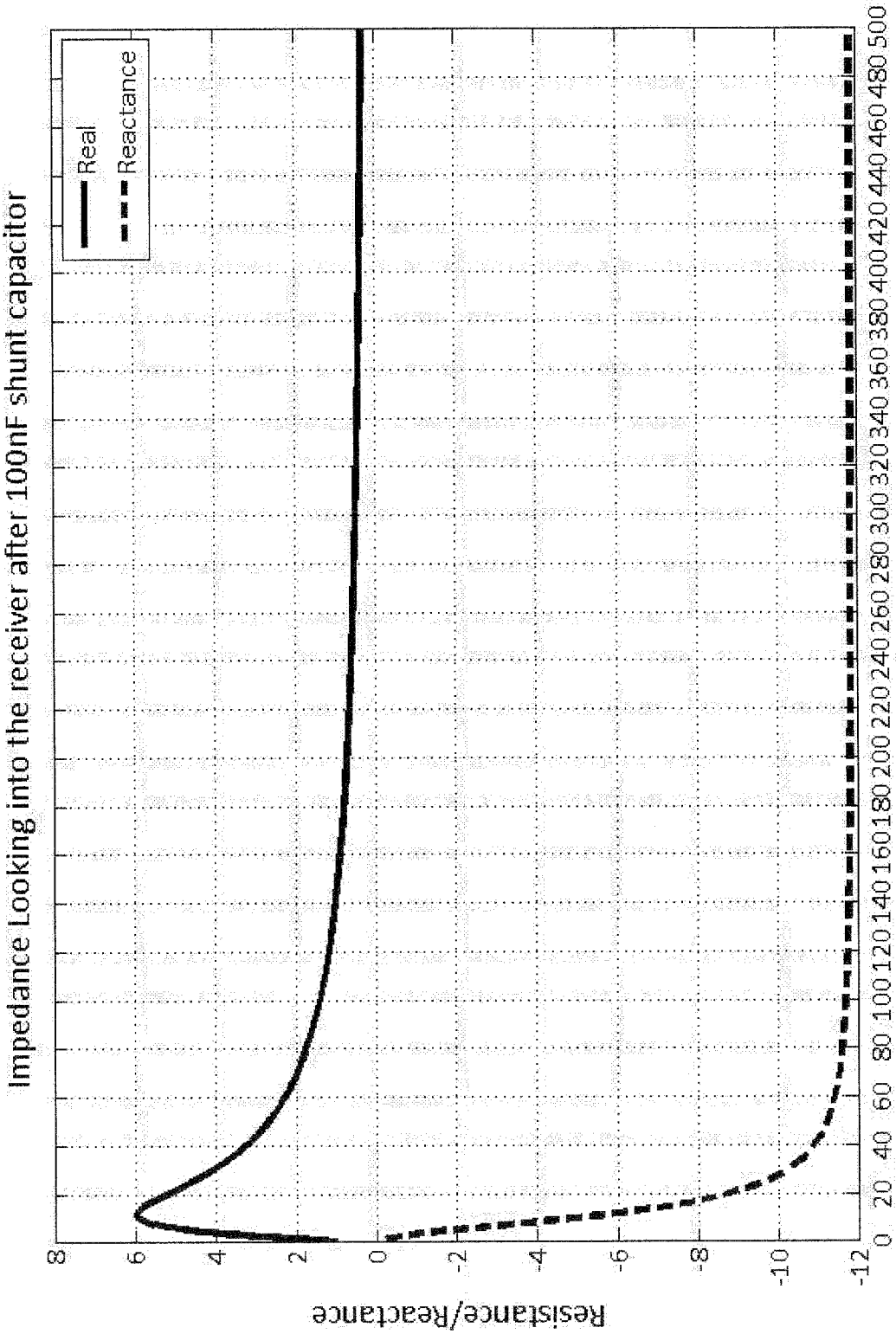

Impedance Looking into the receiver after 100nF shunt capacitor
Real
Reactance
Resistance/Reactance
Load Resistance
8
6
4
2
0
-2
-4
-6
-8
-10
-12
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500

FIG. 27

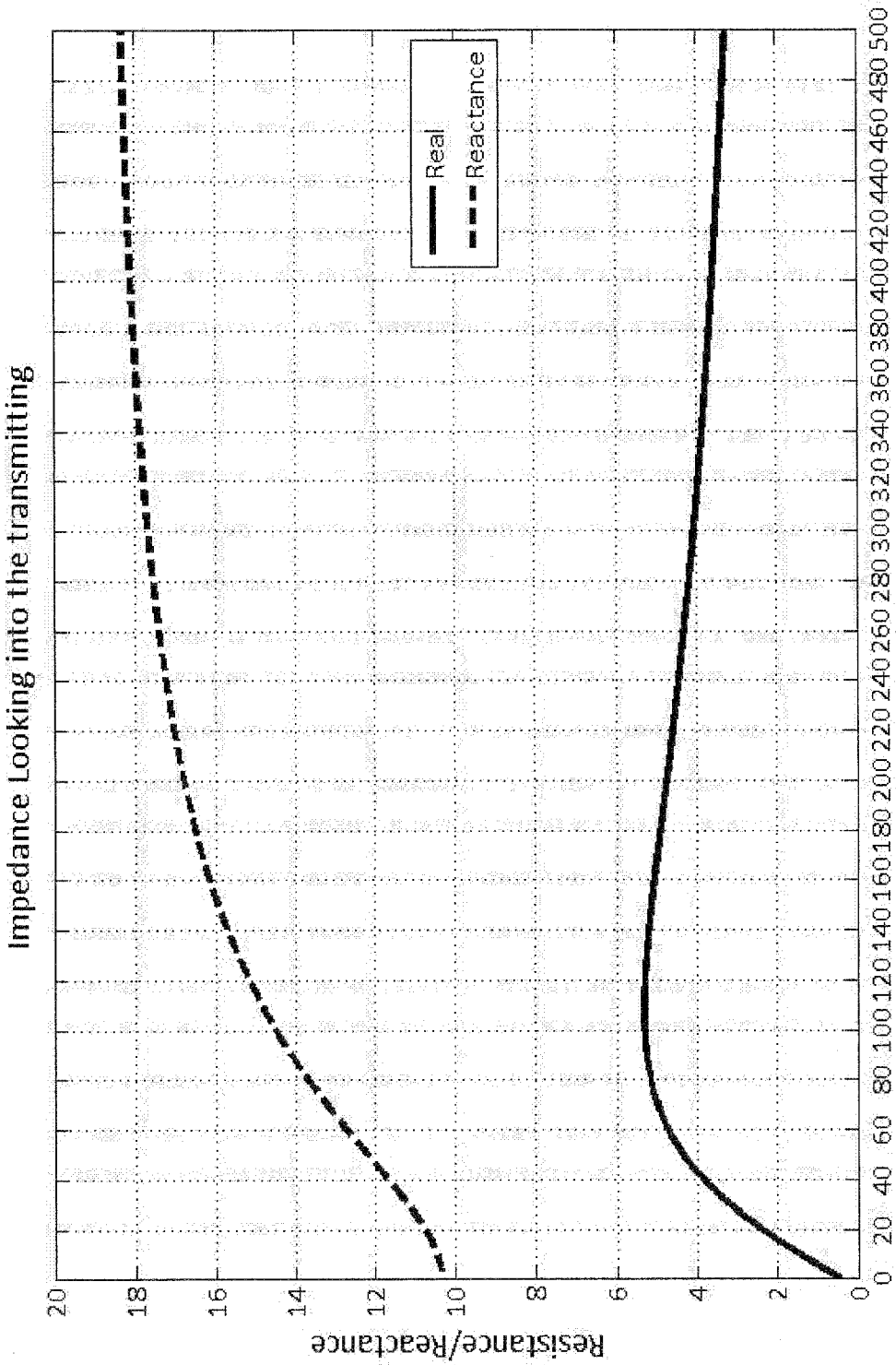

Impedance Looking into the transmitting
Resistance/Reactance
Load Resistance
Real
Reactance
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500
0 2 4 6 8 10 12 14 16 18 20

FIG. 28

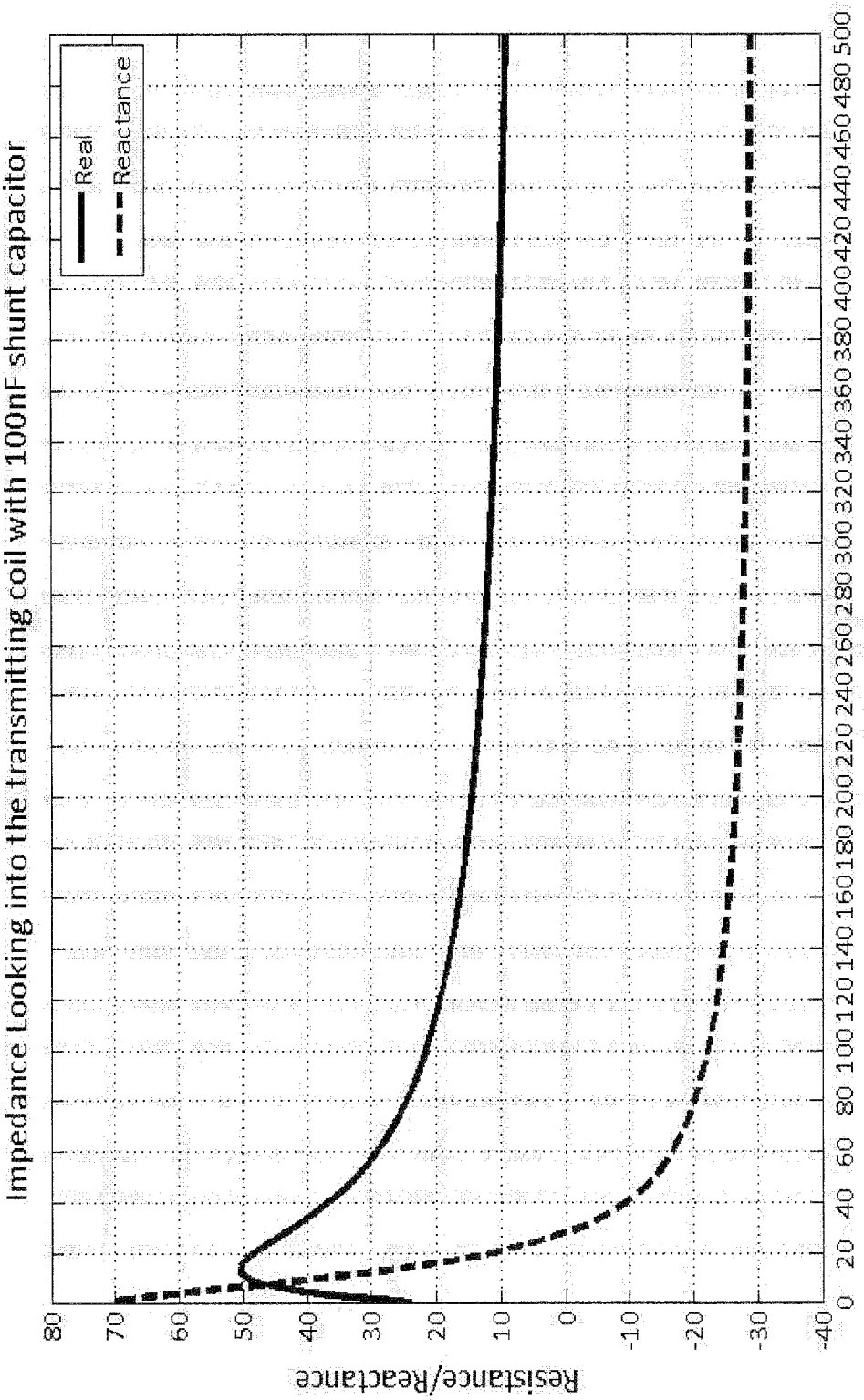

Impedance Looking into the transmitting coil with 100nF shunt capacitor
Real
Reactance
Resistance/Reactance
Load Resistance
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500

FIG. 29

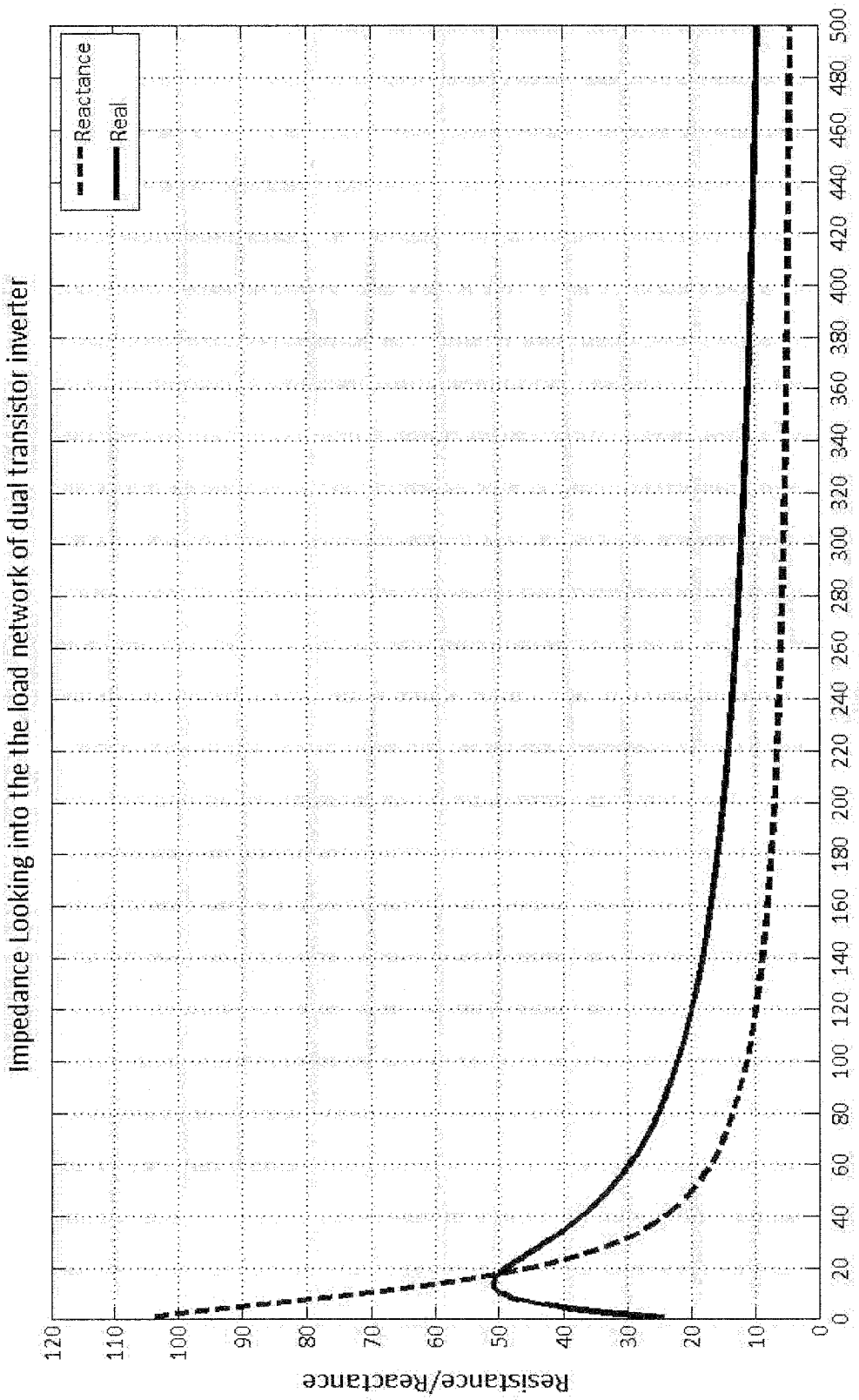

Impedance Looking into the the load network of dual transistor inverter
Reactance
Real
Resistance/Reactance
Load Resistance
0
10
20
30
40
50
60
70
80
90
100
110
120
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500

FIG. 30

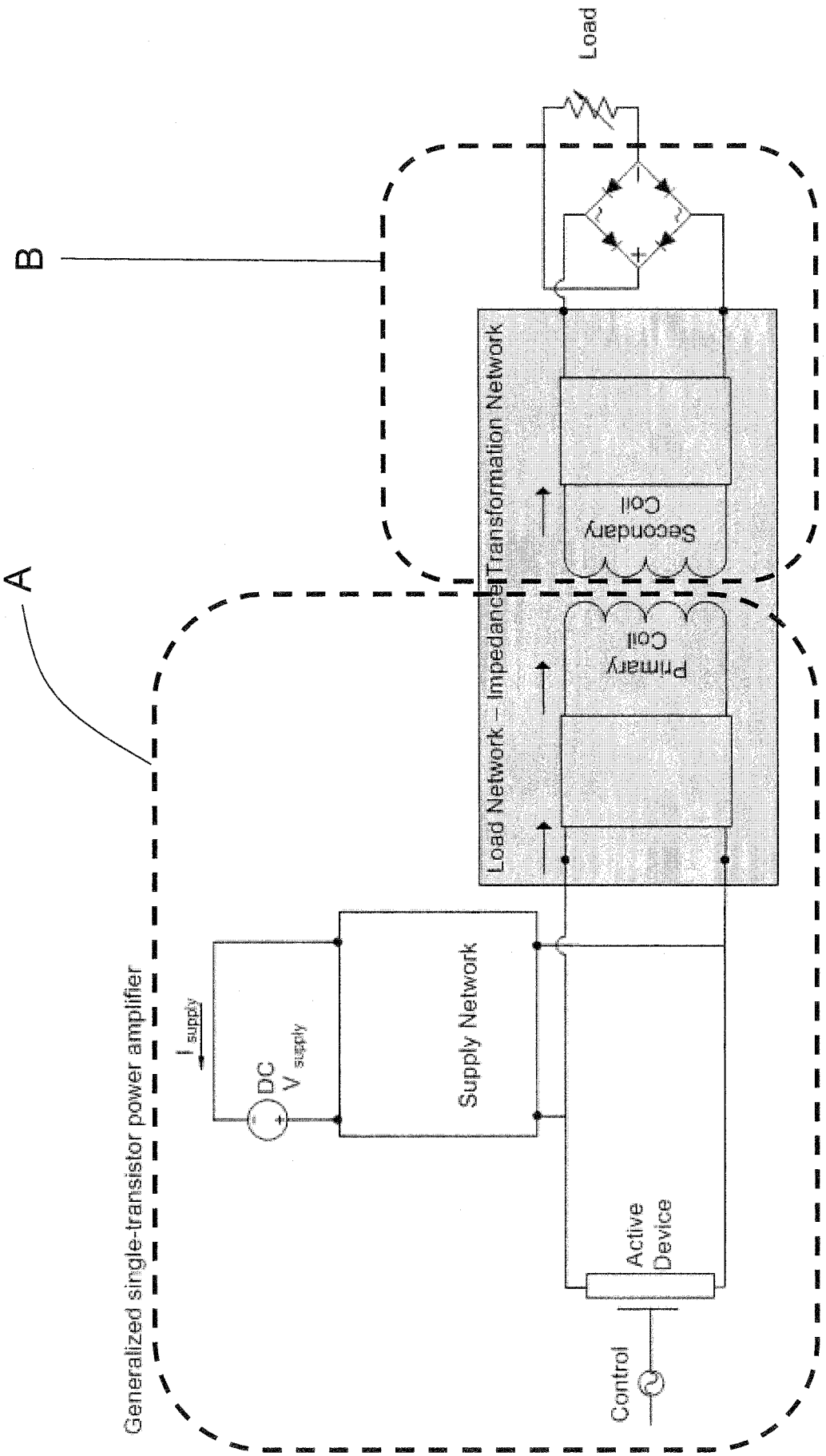

Load
B
A
Load Network – Impedance Transformation Network
Secondary Coil
Primary Coil
Generalized single-transistor power amplifier
Supply Network
DC
V supply
I supply
Active Device
Control

FIG. 31

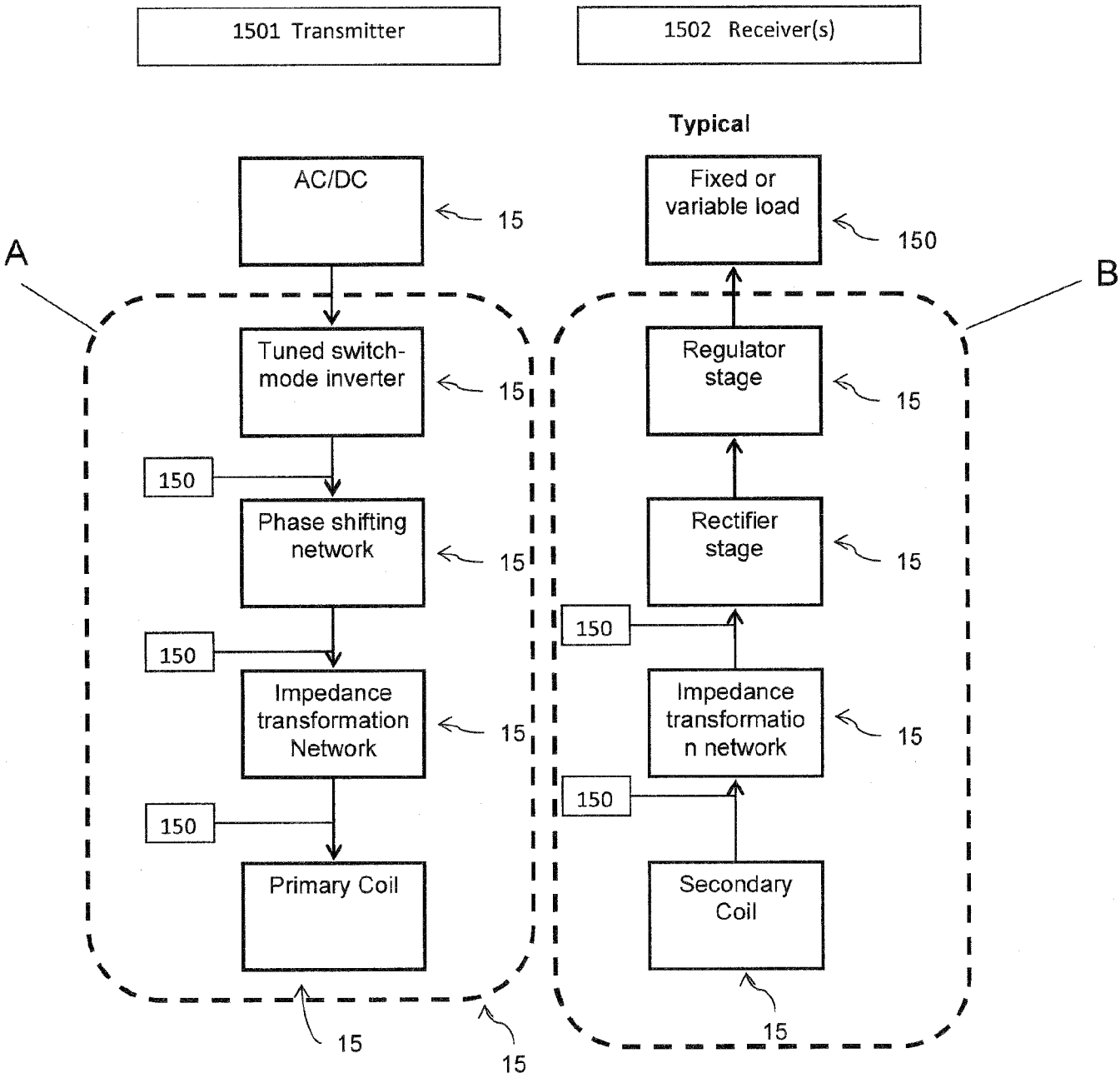

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
15
Fixed or variable load
150
A
B
Tuned switch-mode inverter
15
Regulator stage
15
150
Phase shifting network
15
Rectifier stage
15
150
150
Impedance transformation Network
15
Impedance transformatio n network
15
150
150
Primary Coil
Secondary Coil
15
15
15

FIG. 32

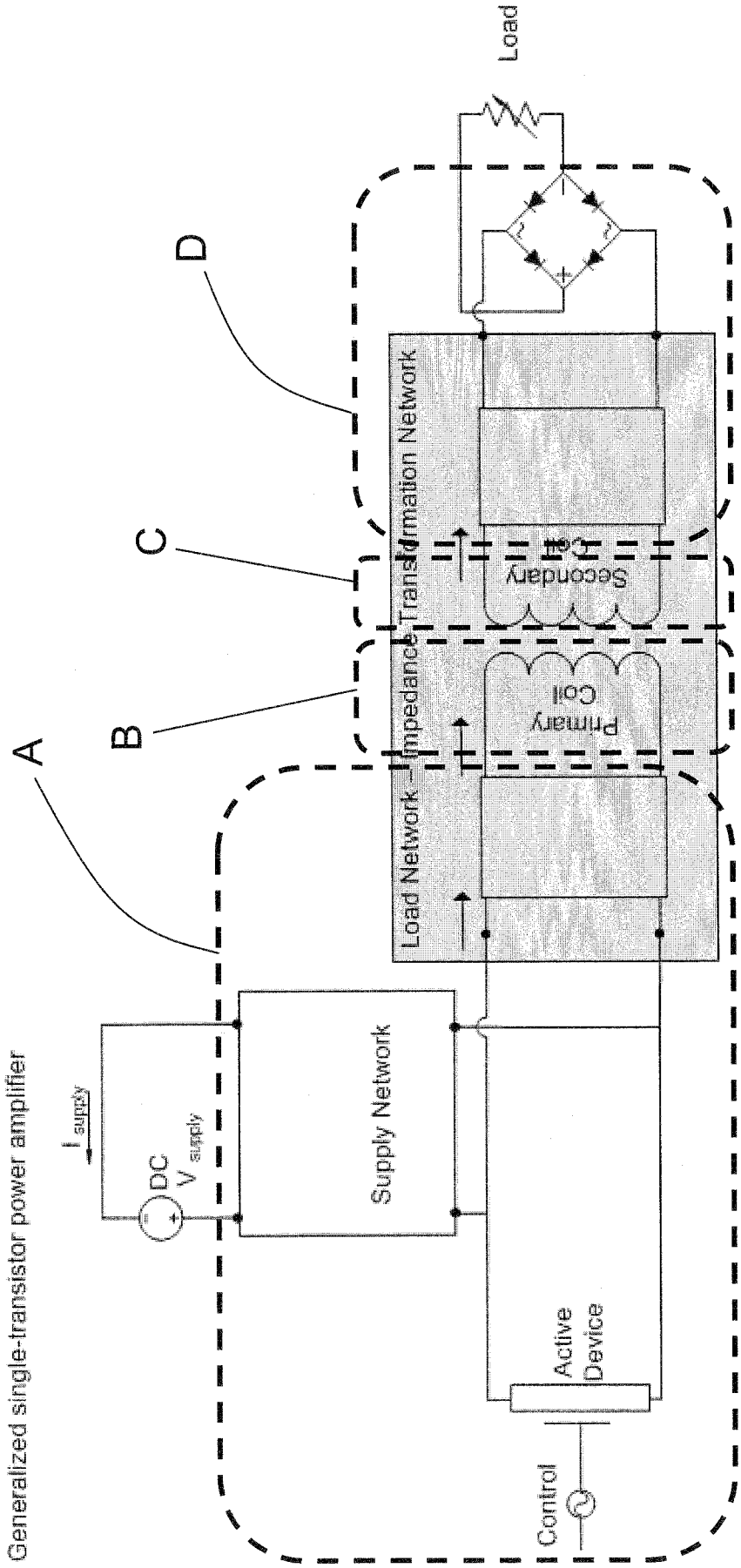

Generalized single-transistor power amplifier
A
B
C
D
Load
Load Network / Impedance Transformation Network
Secondary Coil
Primary Coil
Supply Network
DC
V supply
I supply
Active Device
Control

FIG. 33

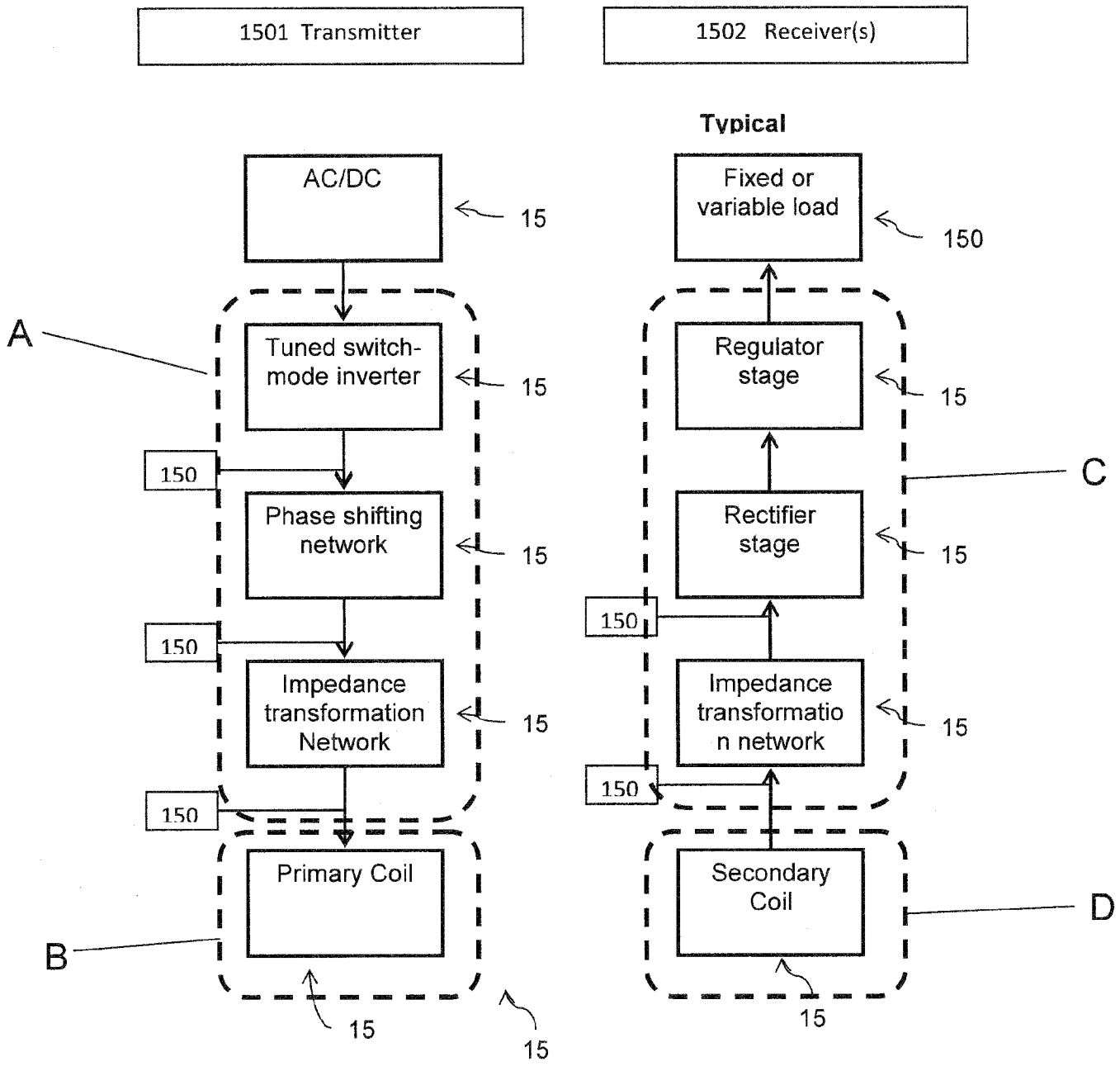

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
15
Tuned switch-mode inverter
15
150
Phase shifting network
15
150
Impedance transformation Network
15
150
Primary Coil
15
15
A
B
Fixed or variable load
150
Regulator stage
15
C
Rectifier stage
15
150
Impedance transformatio n network
15
150
Secondary Coil
15
D

FIG. 34

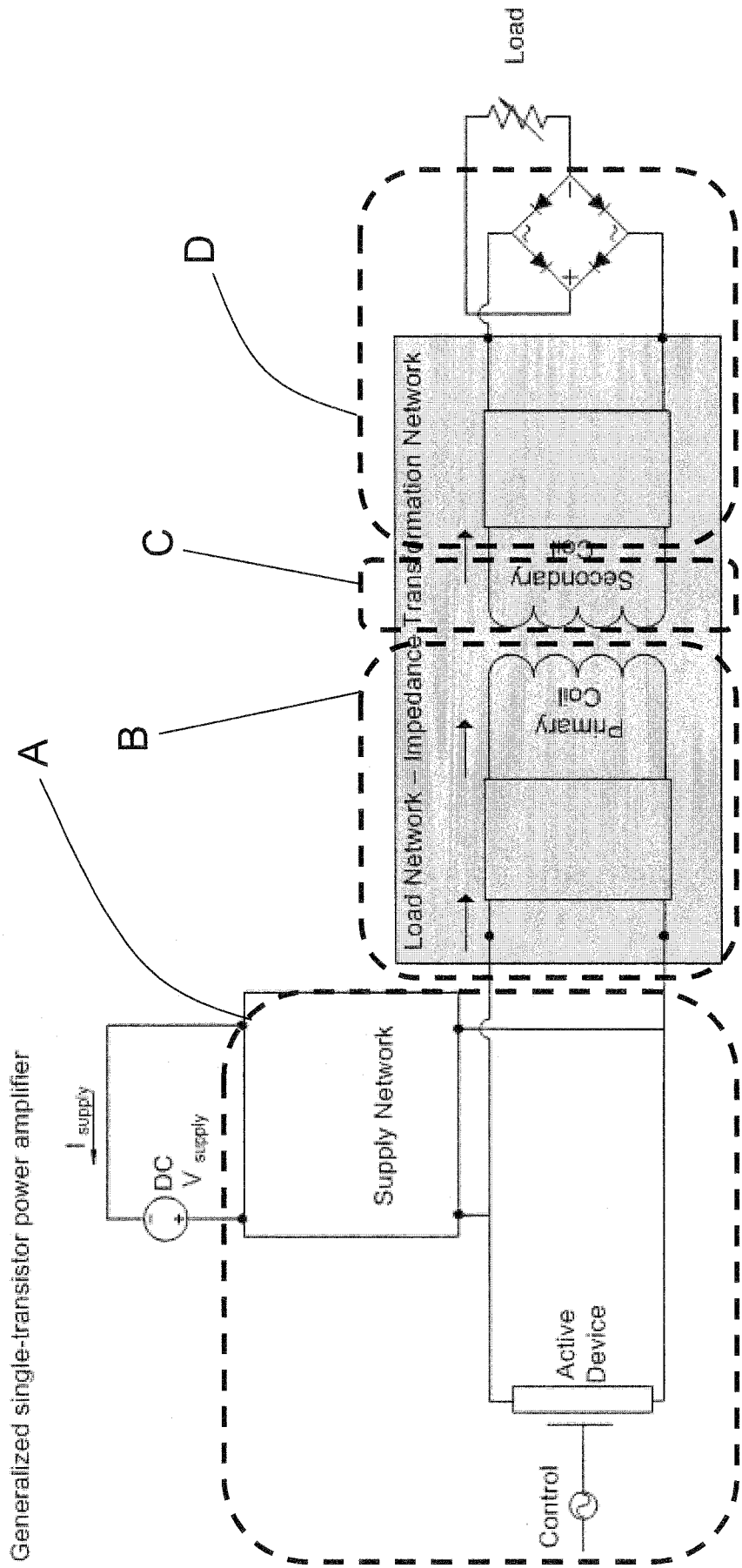

Load
D
C
B
A
Load Network – Impedance Transformation Network
Secondary Coil
Primary Coil
Supply Network
DC
V_{supply}
I_{supply}
Active Device
Control
Generalized single-transistor power amplifier

FIG. 35

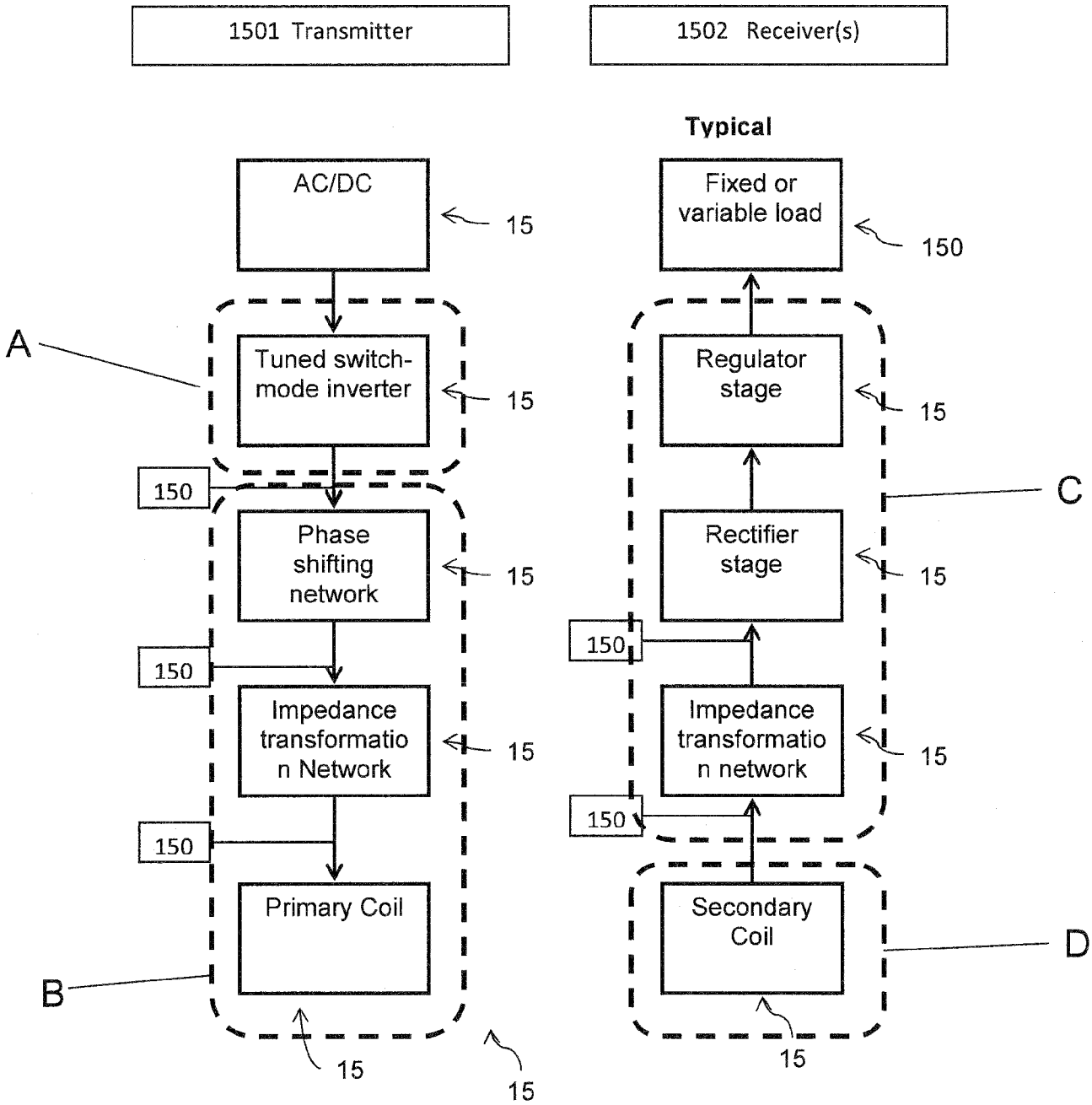

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
15
Tuned switch-mode inverter
15
A
150
Phase shifting network
15
150
Impedance transformatio n Network
15
150
Primary Coil
B
15
15
Fixed or variable load
150
Regulator stage
15
C
Rectifier stage
15
150
Impedance transformatio n network
15
150
Secondary Coil
D
15

FIG. 36

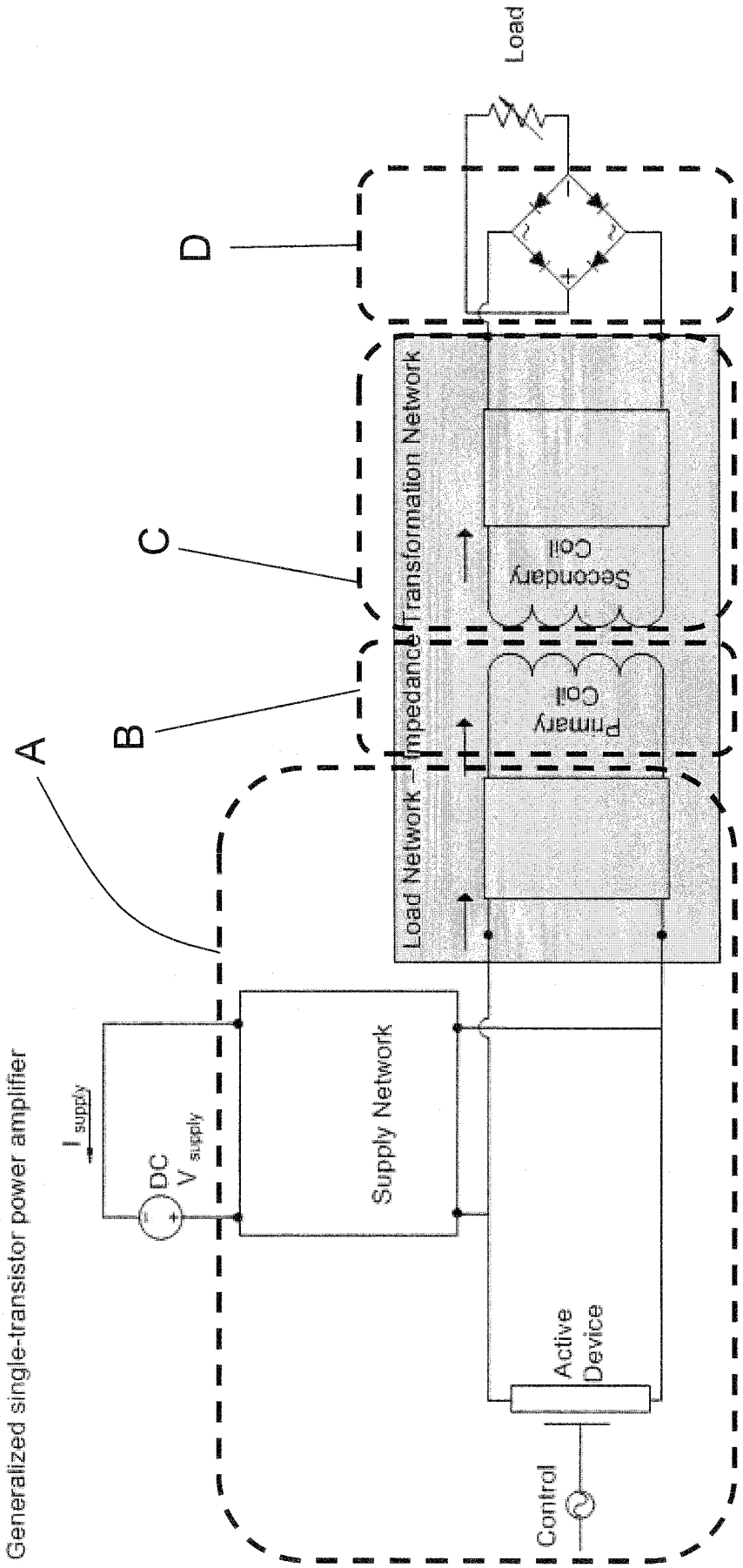

Load
D
C
B
A
Load Network – Impedance Transformation Network
Secondary Coil
Primary Coil
Generalized single-transistor power amplifier
DC
V_{supply}
I_{supply}
Supply Network
Active Device
Control

FIG. 37

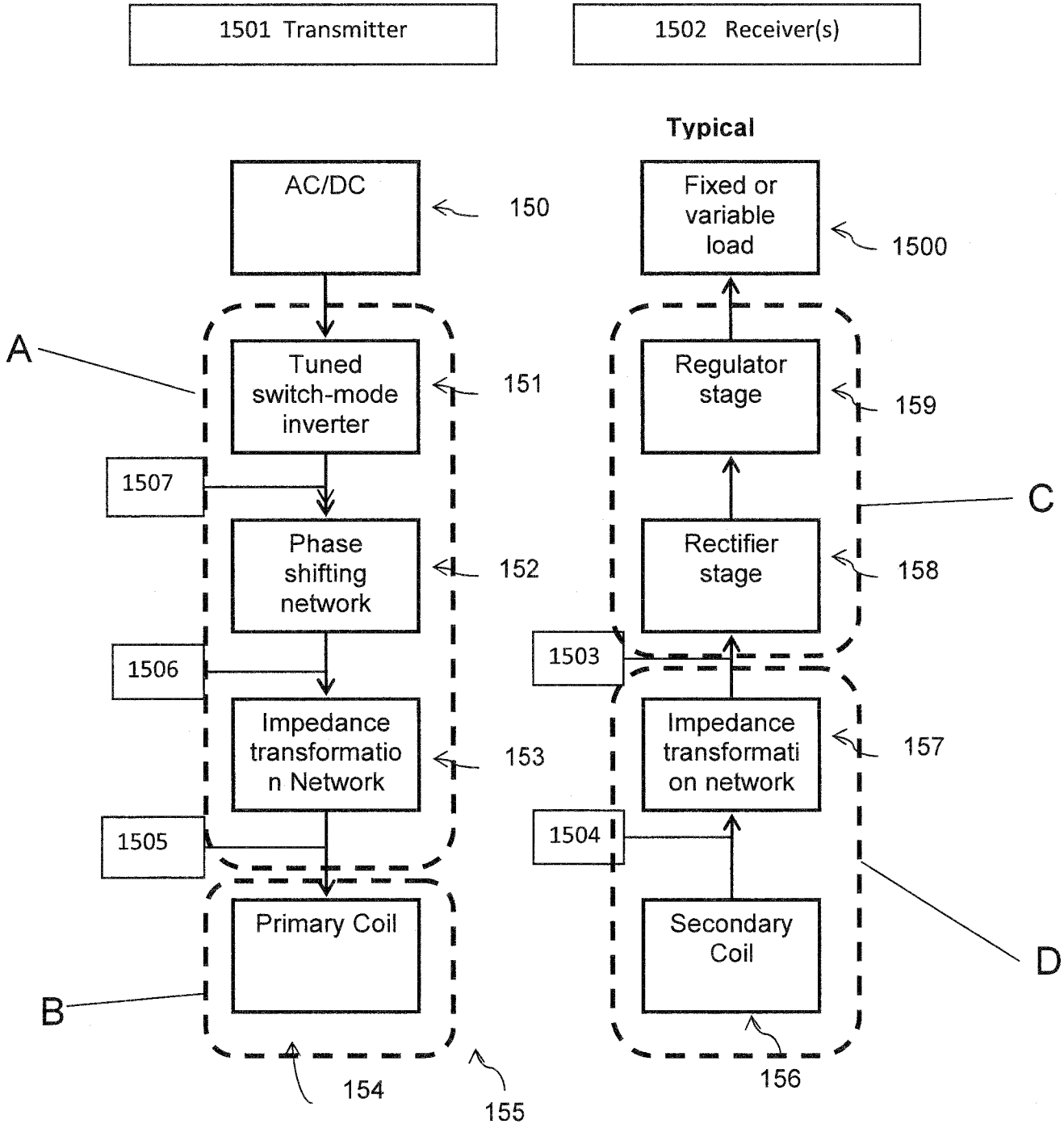

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
150
Fixed or variable load
1500
A
Tuned switch-mode inverter
151
Regulator stage
159
1507
C
Phase shifting network
152
Rectifier stage
158
1506
1503
Impedance transformatio n Network
153
Impedance transformati on network
157
1505
1504
Primary Coil
Secondary Coil
B
D
154
155
156

FIG. 38

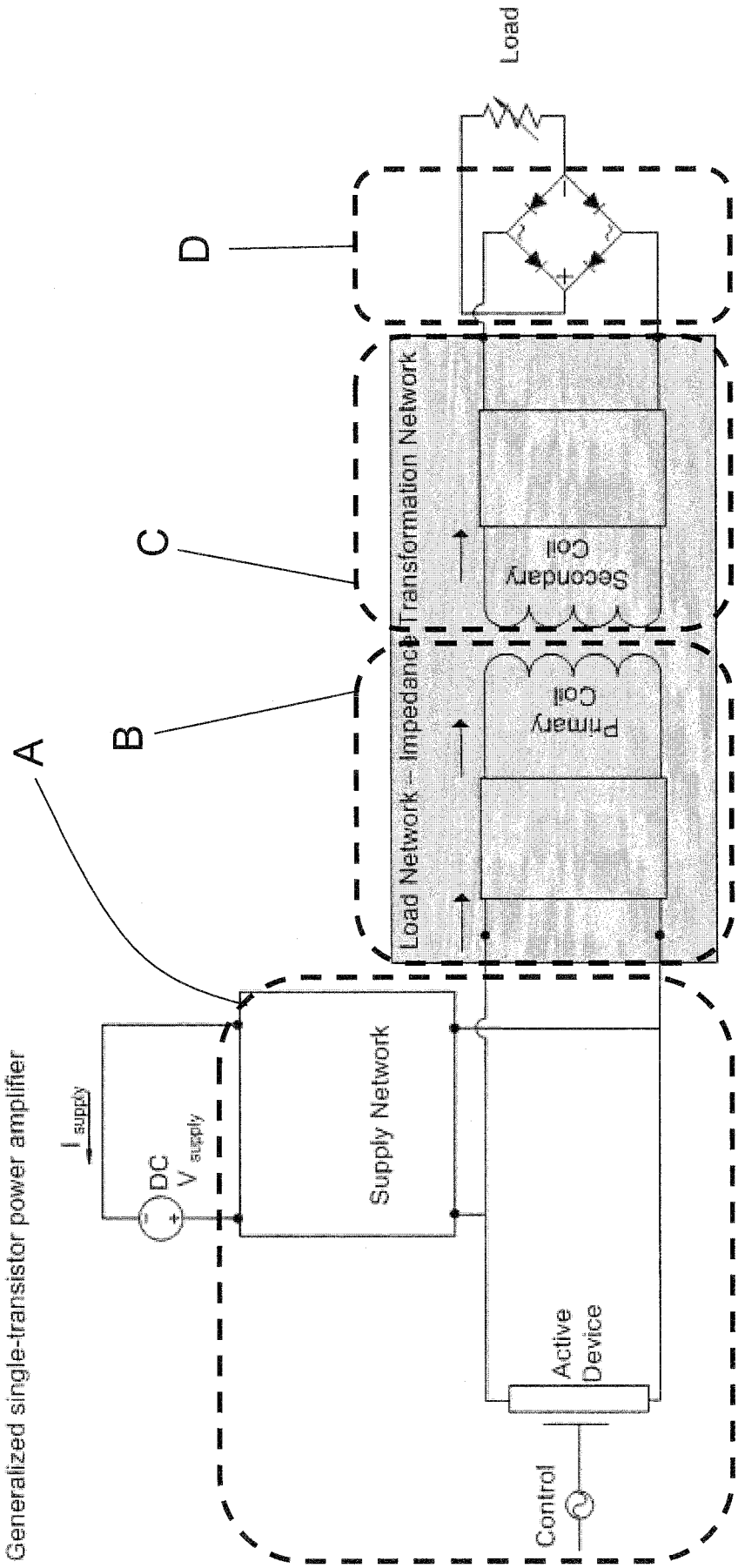

Load
D
C
Secondary Coil
Transformation Network
B
Primary Coil
Load Network – Impedance
A
Supply Network
DC
V supply
I supply
Active Device
Control
Generalized single-transistor power amplifier

FIG. 39

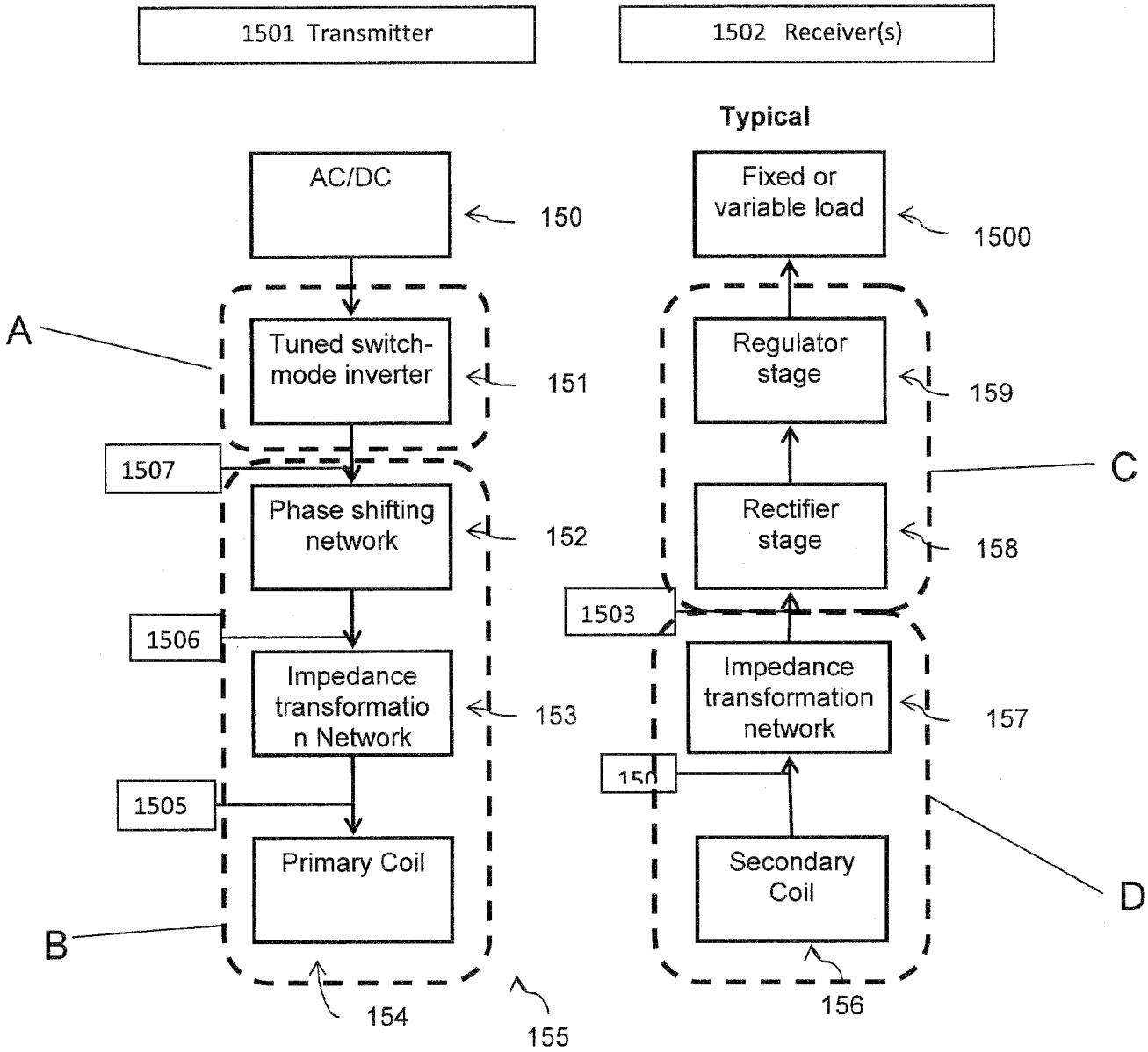

1501 Transmitter
1502 Receiver(s)
Typical
AC/DC
150
Fixed or variable load
1500
A
Tuned switch-mode inverter
151
Regulator stage
159
1507
C
Phase shifting network
152
Rectifier stage
158
1506
1503
Impedance transformatio n Network
153
Impedance transformation network
157
1505
150
Primary Coil
Secondary Coil
B
D
154
155
156

FIG. 40

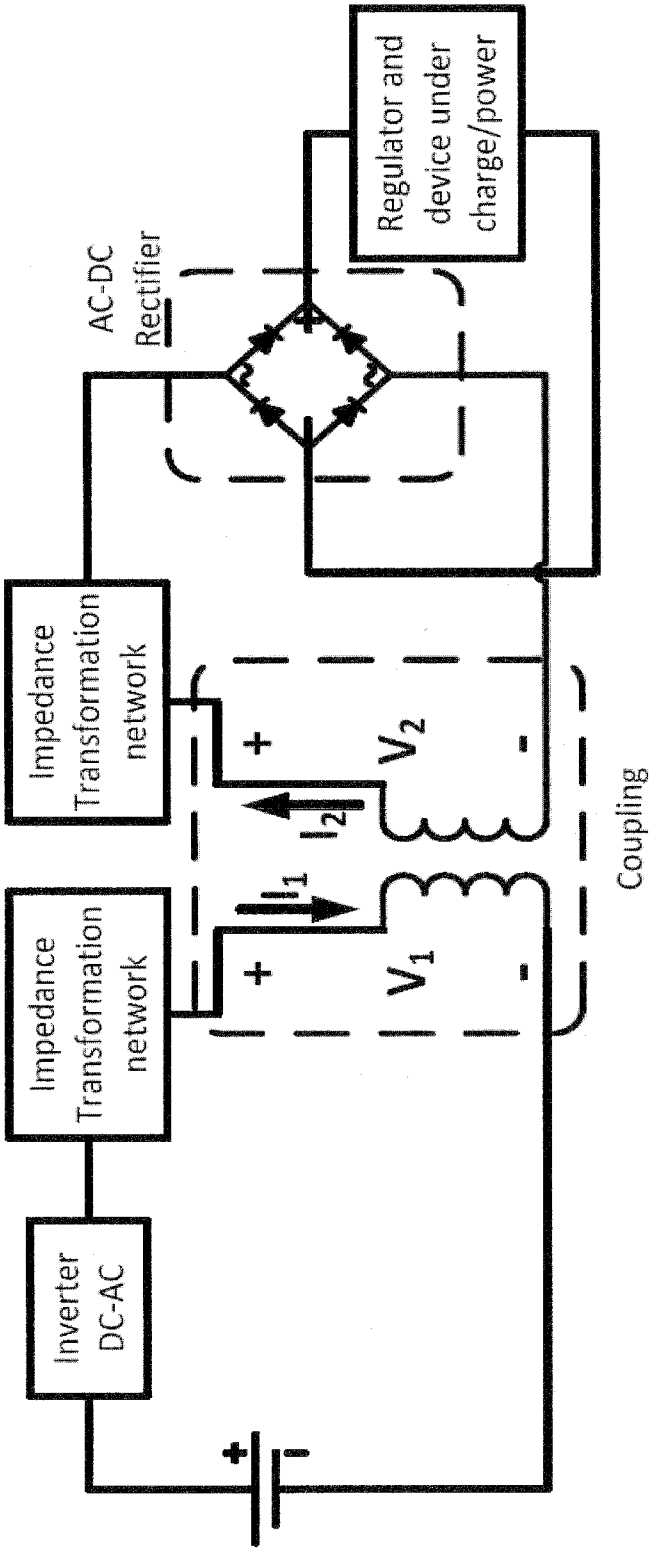

Regulator and device under charge/power
AC-DC Rectifier
Impedance Transformation network
Impedance Transformation network
Inverter DC-AC
+
-
V_2
I_2
I_1
V_1
Coupling

FIG. 41

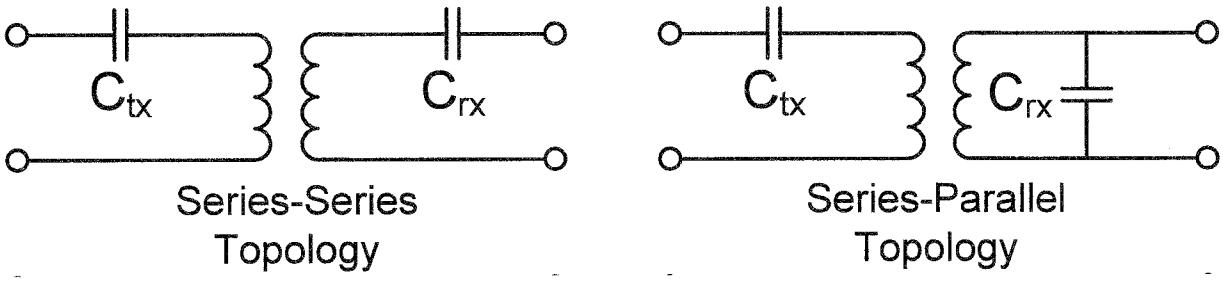

Ctx
Crx
Series-Series
Topology
Ctx
Crx
Series-Parallel
Topology

FIG. 42

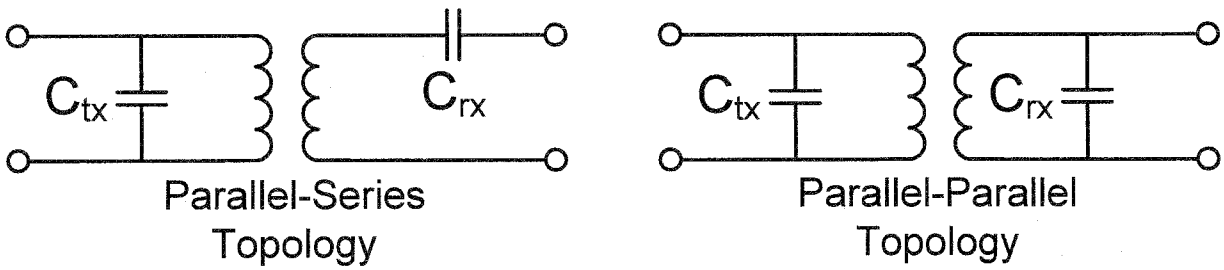

Ctx
Crx
Parallel-Series
Topology
Ctx
Crx
Parallel-Parallel
Topology

FIG. 43

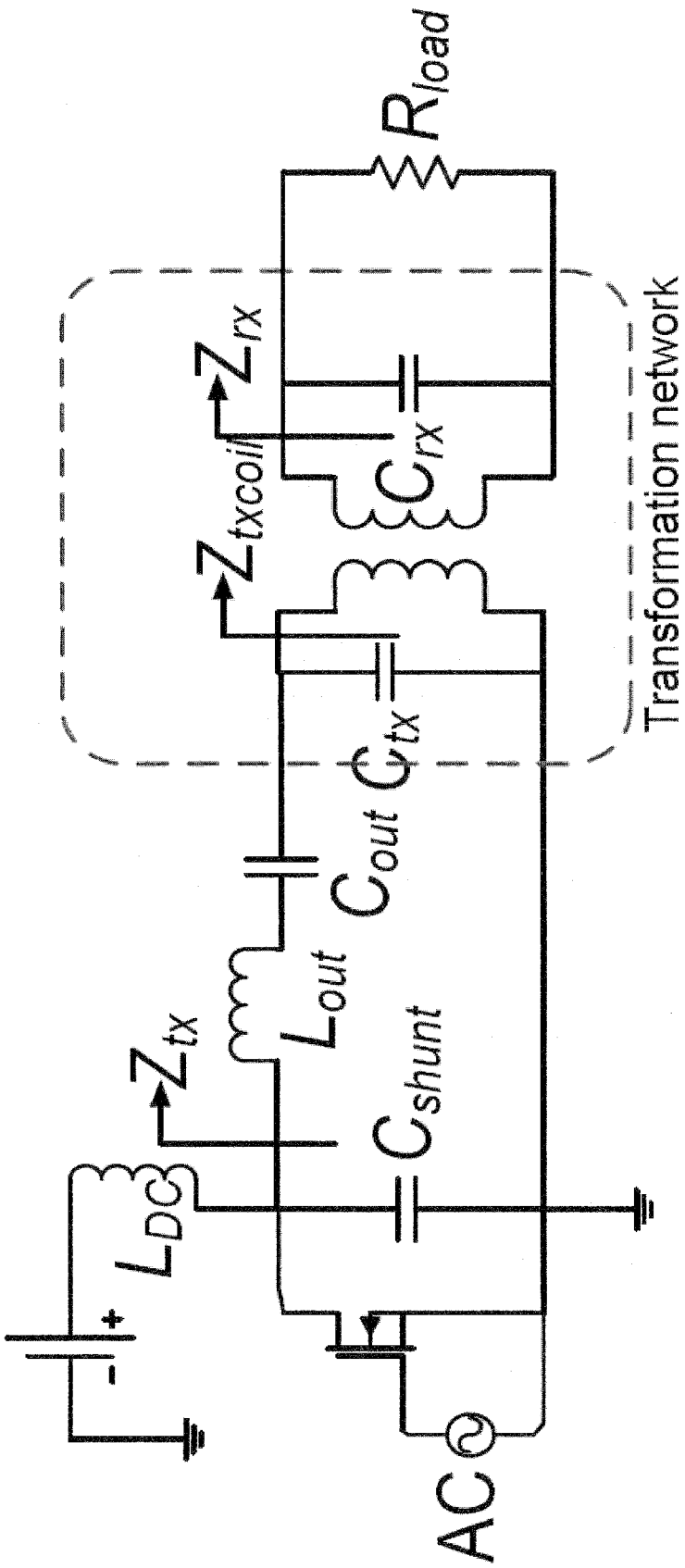

R_{load}
Z_{rx}
C_{rx}
Z_{txcoil}
Transformation network
C_{tx}
C_{out}
L_{out}
Z_{tx}
C_{shunt}
L_{DC}
+
-
AC

FIG. 44

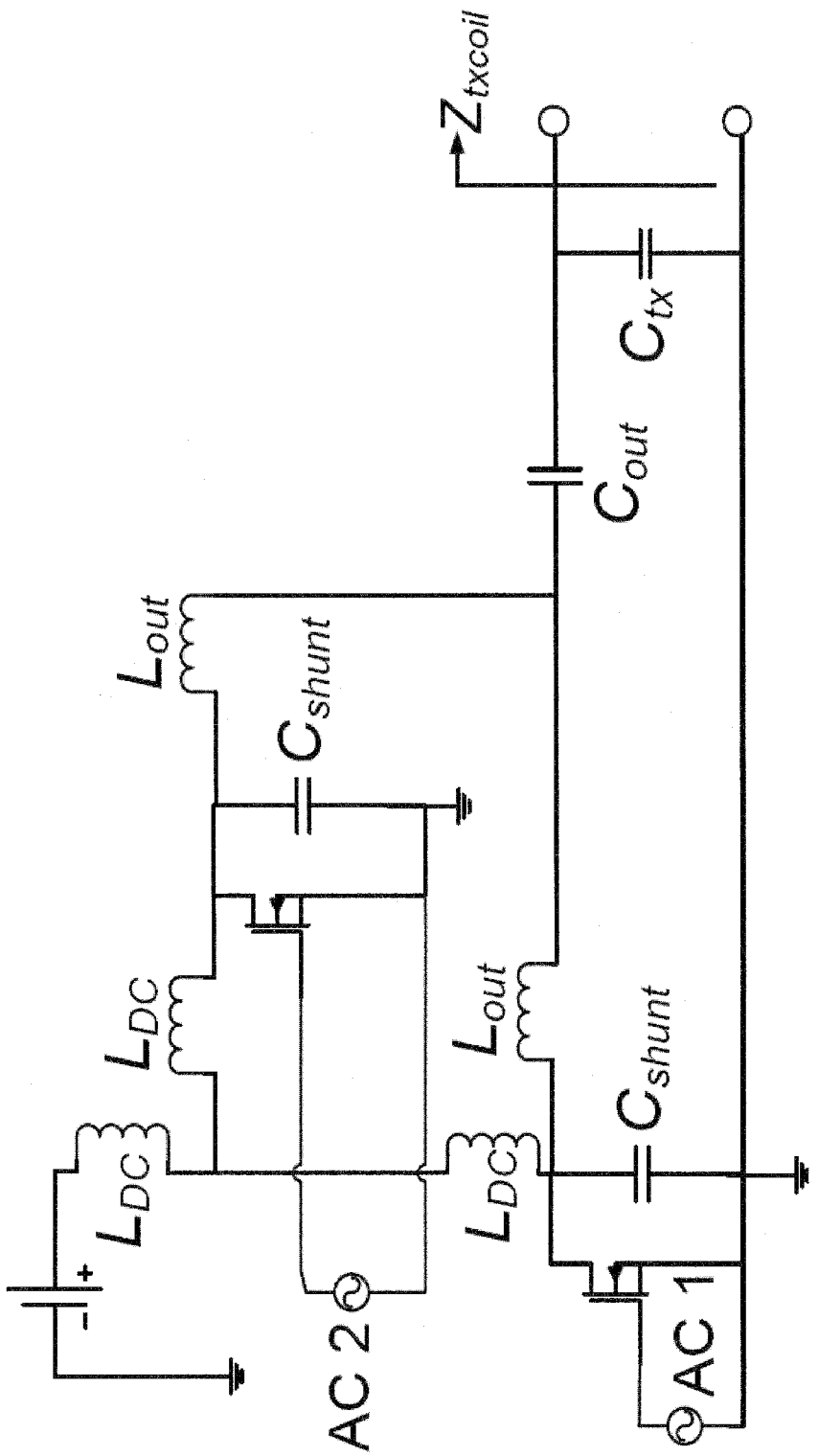


FIG. 45

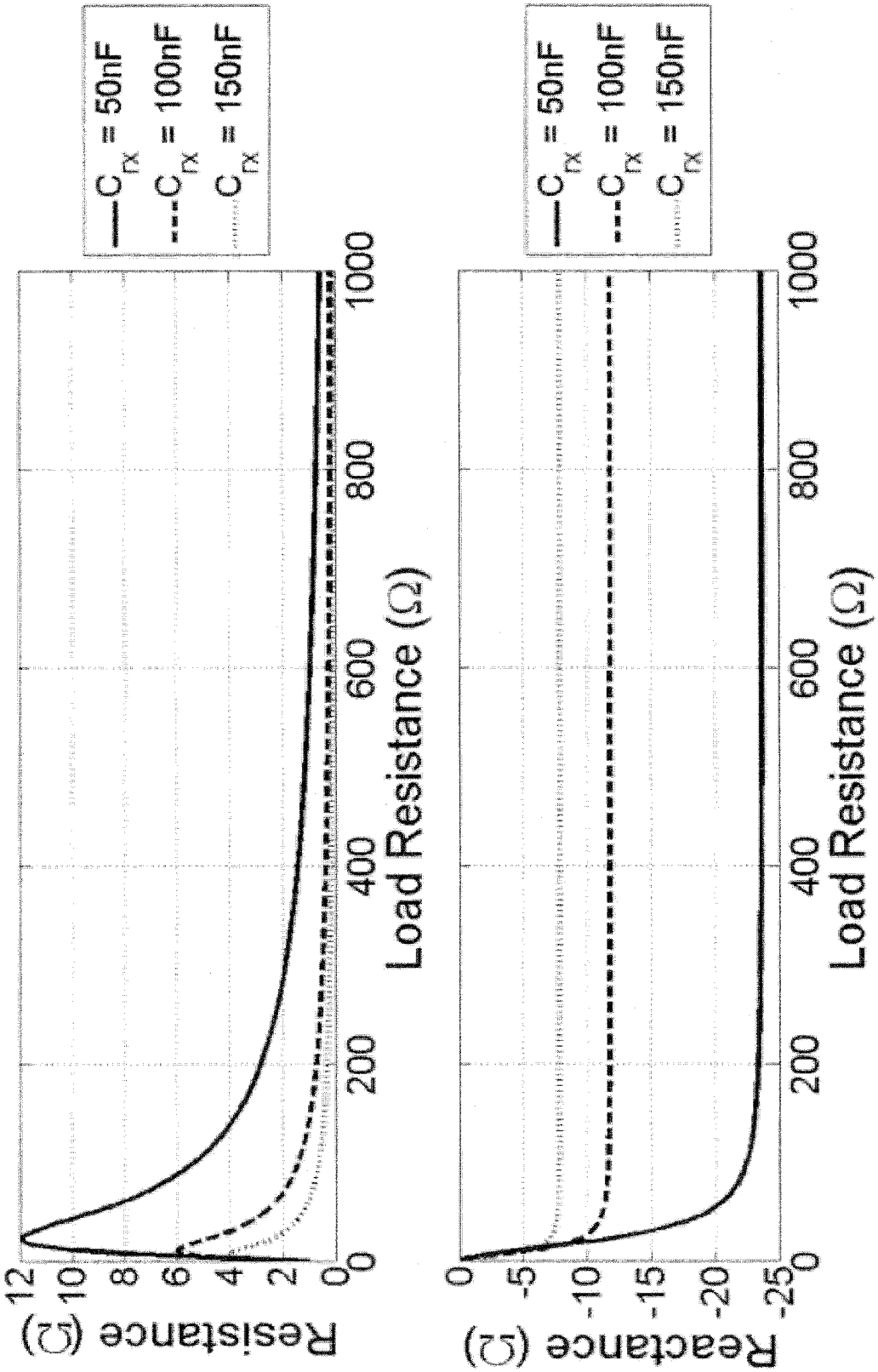

Resistance (Ω)
Load Resistance (Ω)
Reactance (Ω)
Load Resistance (Ω)
C_{rx} = 50nF
C_{rx} = 100nF
C_{rx} = 150nF

FIG. 46

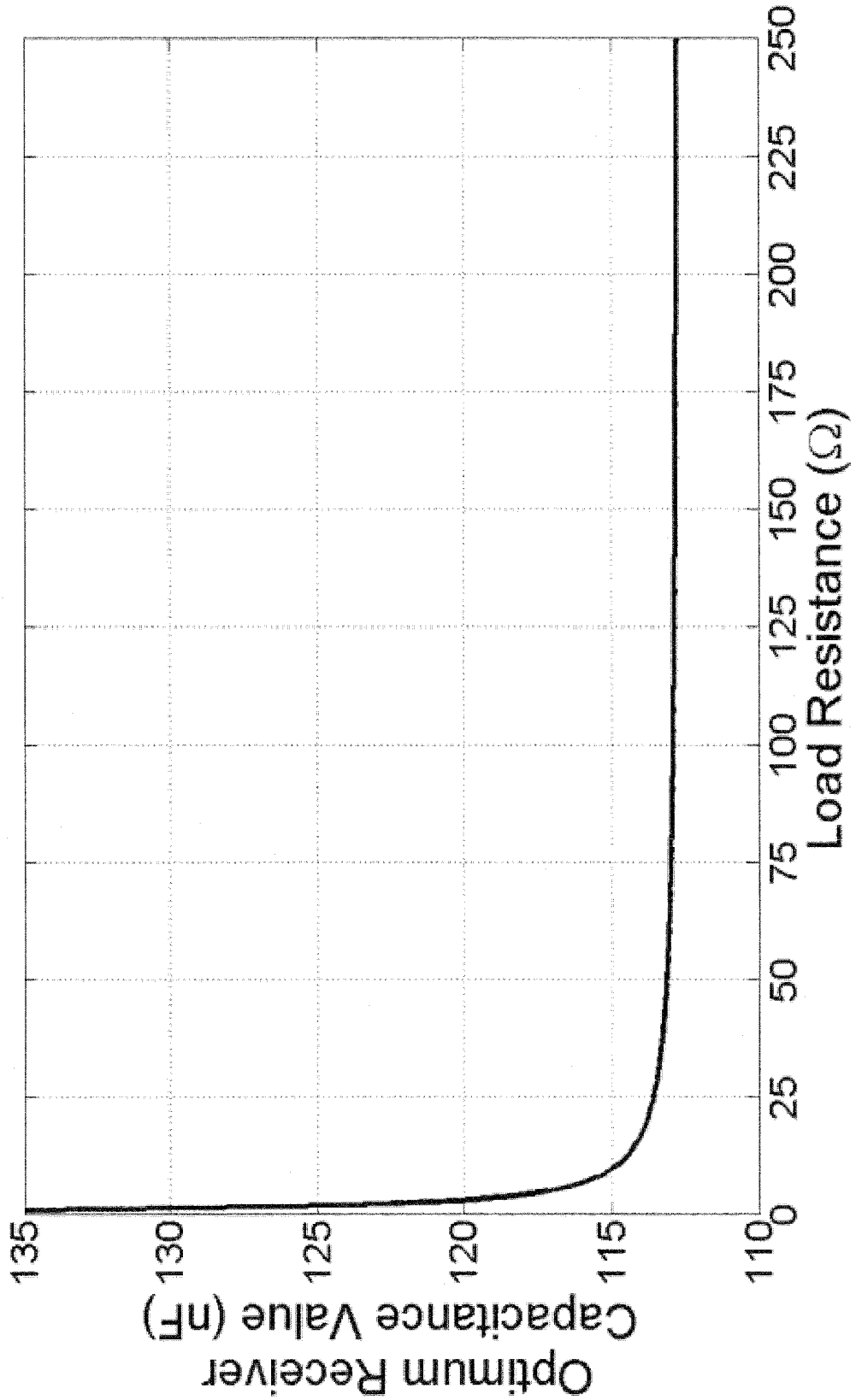

Optimum Receiver
Capacitance Value (nF)
135
130
125
120
115
110
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)

FIG. 47

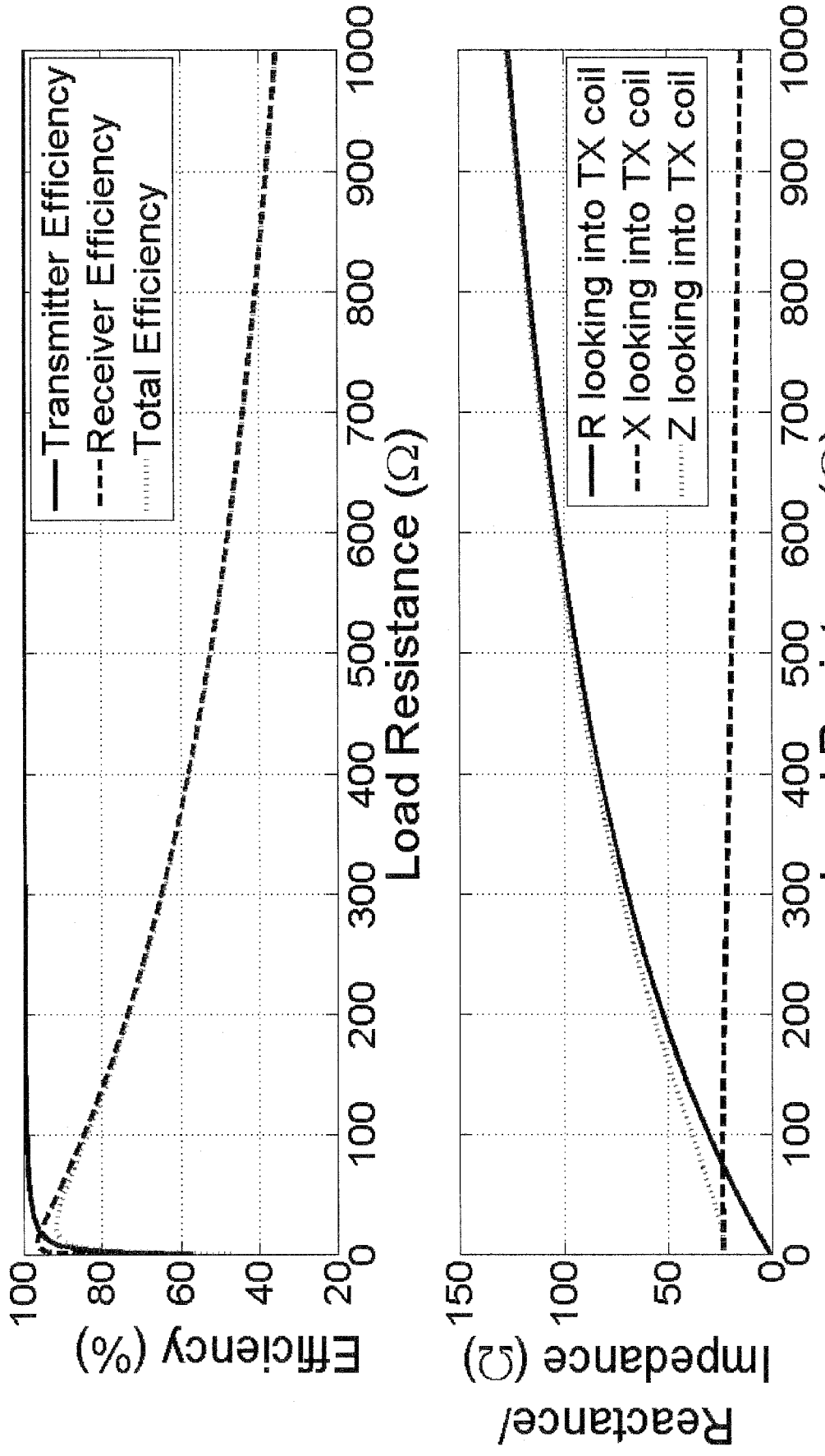

Transmitter Efficiency
Receiver Efficiency
Total Efficiency
Efficiency (%)
Load Resistance (Ω)
R looking into TX coil
X looking into TX coil
Z looking into TX coil
Reactance/
Impedance (Ω)
Load Resistance (Ω)

FIG. 48A

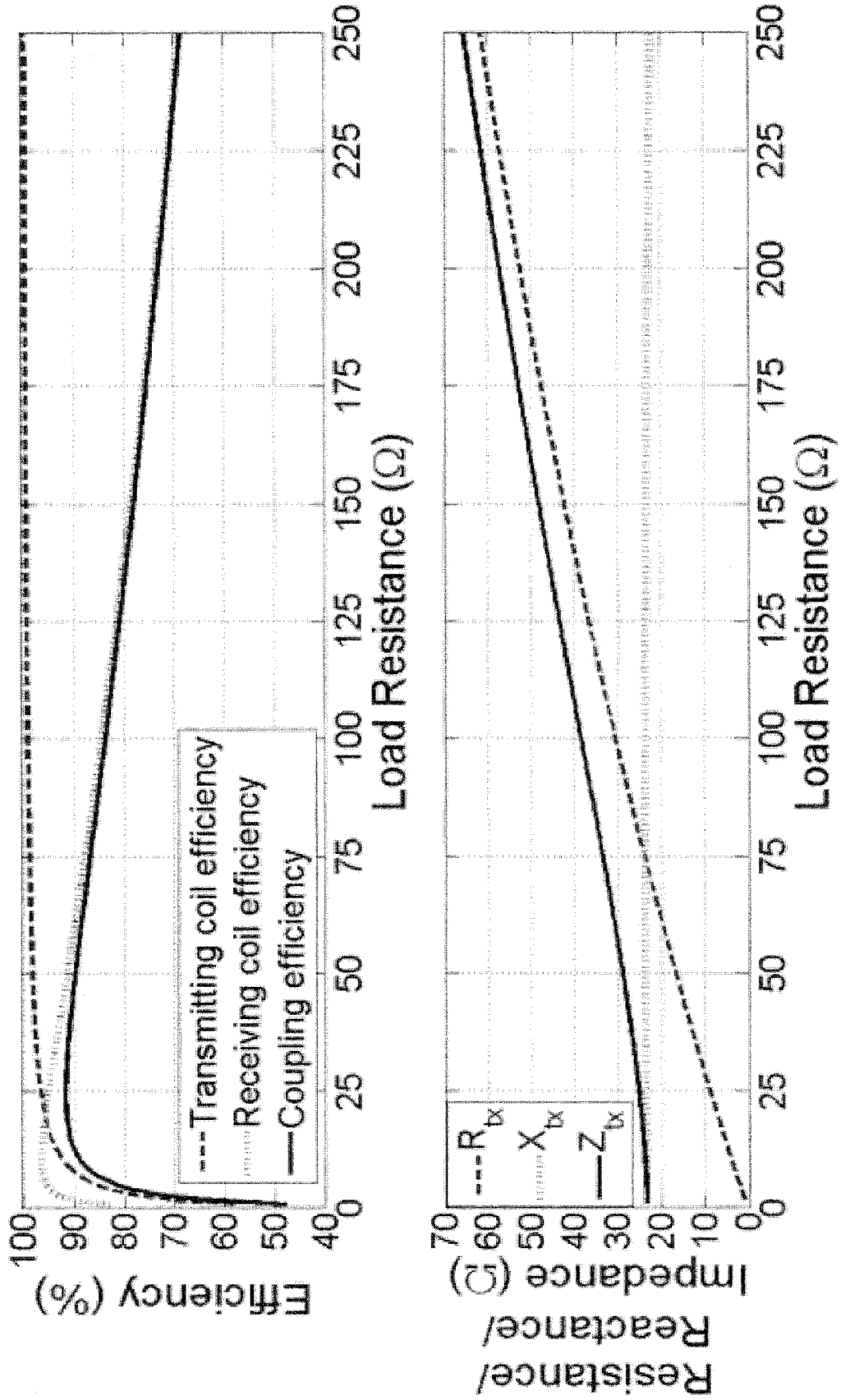

Efficiency (%)
Load Resistance (Ω)
Transmitting coil efficiency
Receiving coil efficiency
Coupling efficiency
Resistance/
Reactance/
Impedance (Ω)
Load Resistance (Ω)
R_{tx}
X_{tx}
Z_{tx}

FIG. 48B

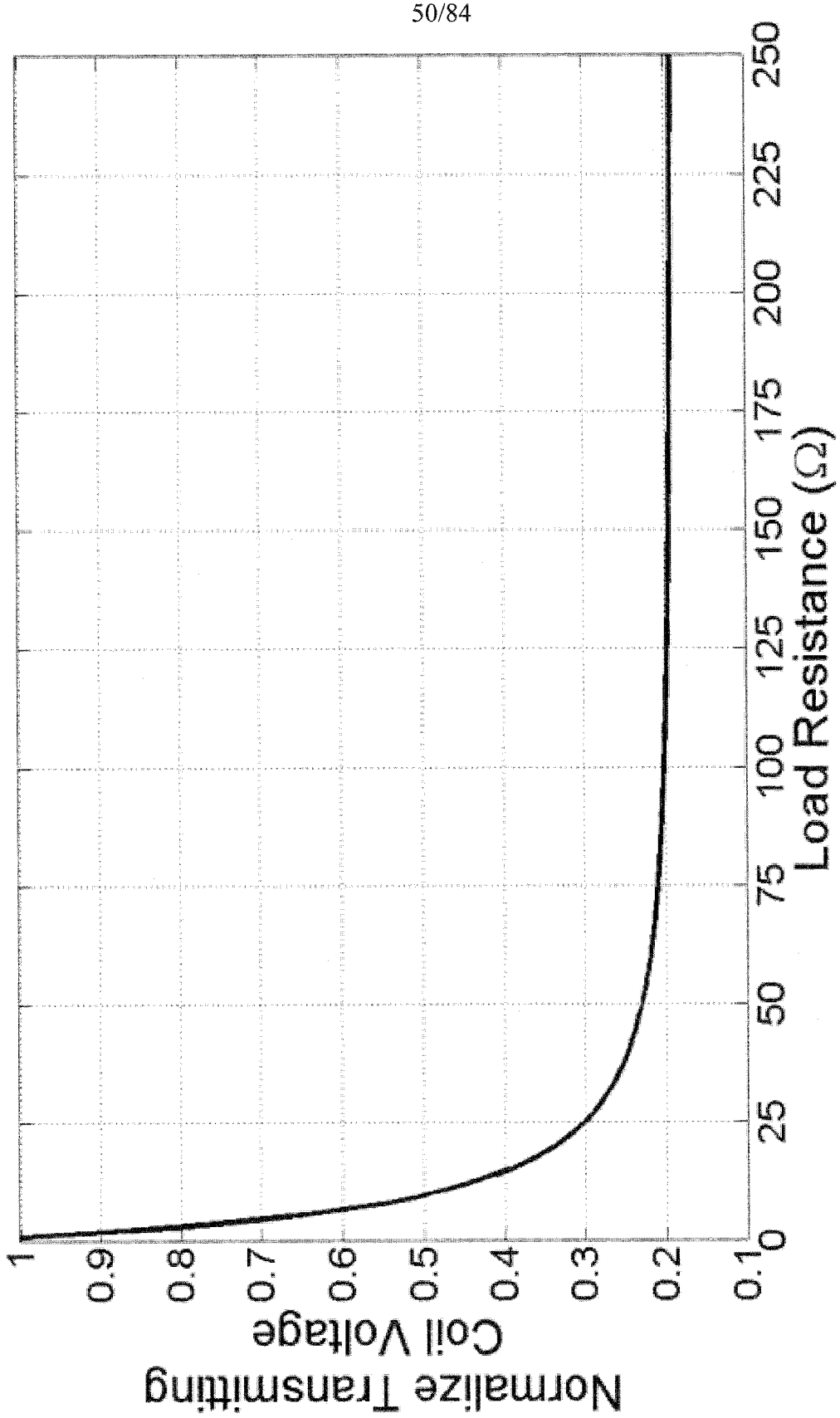

Normalize Transmitting Coil Voltage
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)

FIG. 49

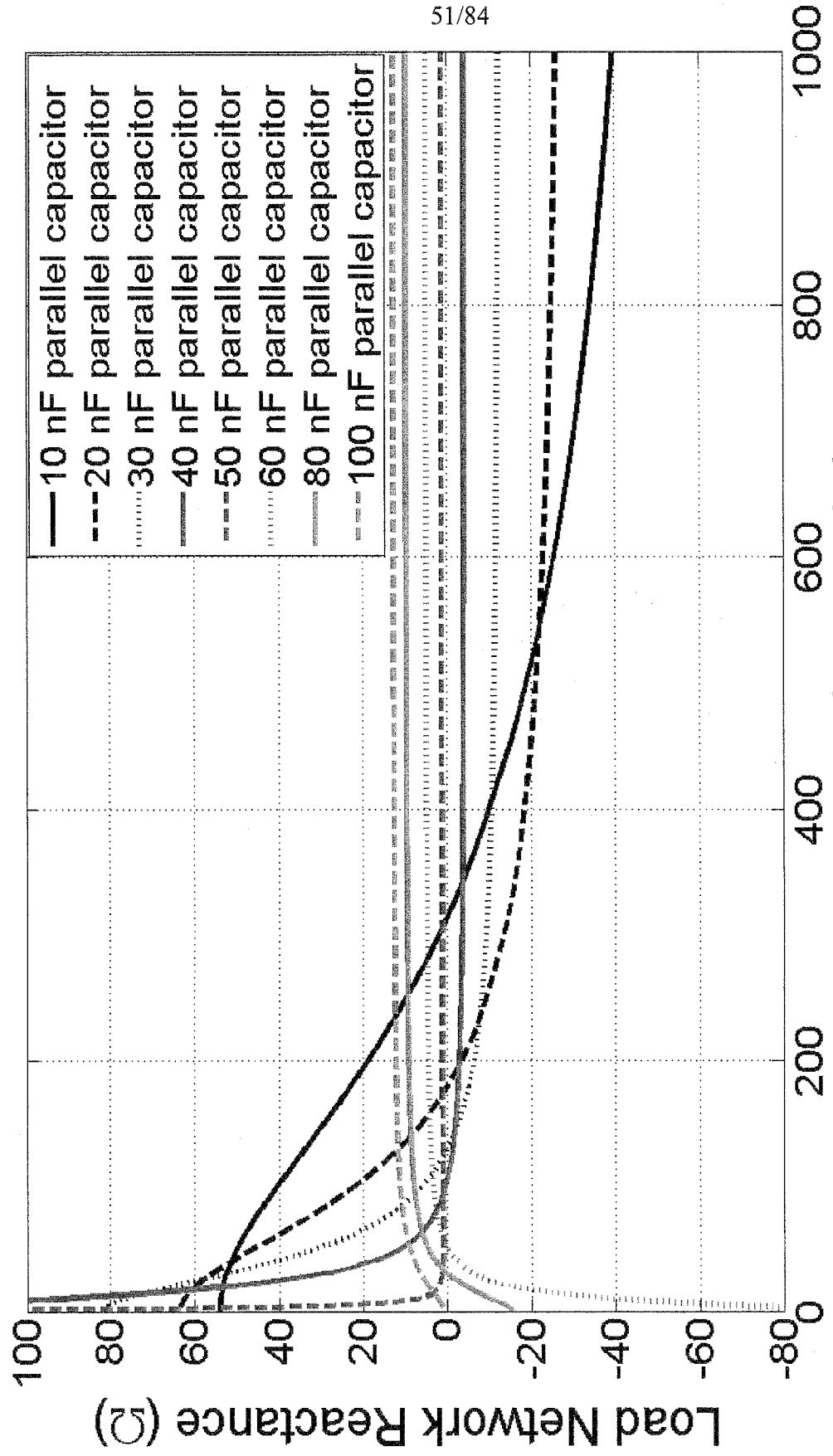

10 nF parallel capacitor
20 nF parallel capacitor
30 nF parallel capacitor
40 nF parallel capacitor
50 nF parallel capacitor
60 nF parallel capacitor
80 nF parallel capacitor
100 nF parallel capacitor
Load Network Reactance (Ω)
Load Resistance (Ω)
100
80
60
40
20
0
-20
-40
-60
-80
0
200
400
600
800
1000

FIG. 50

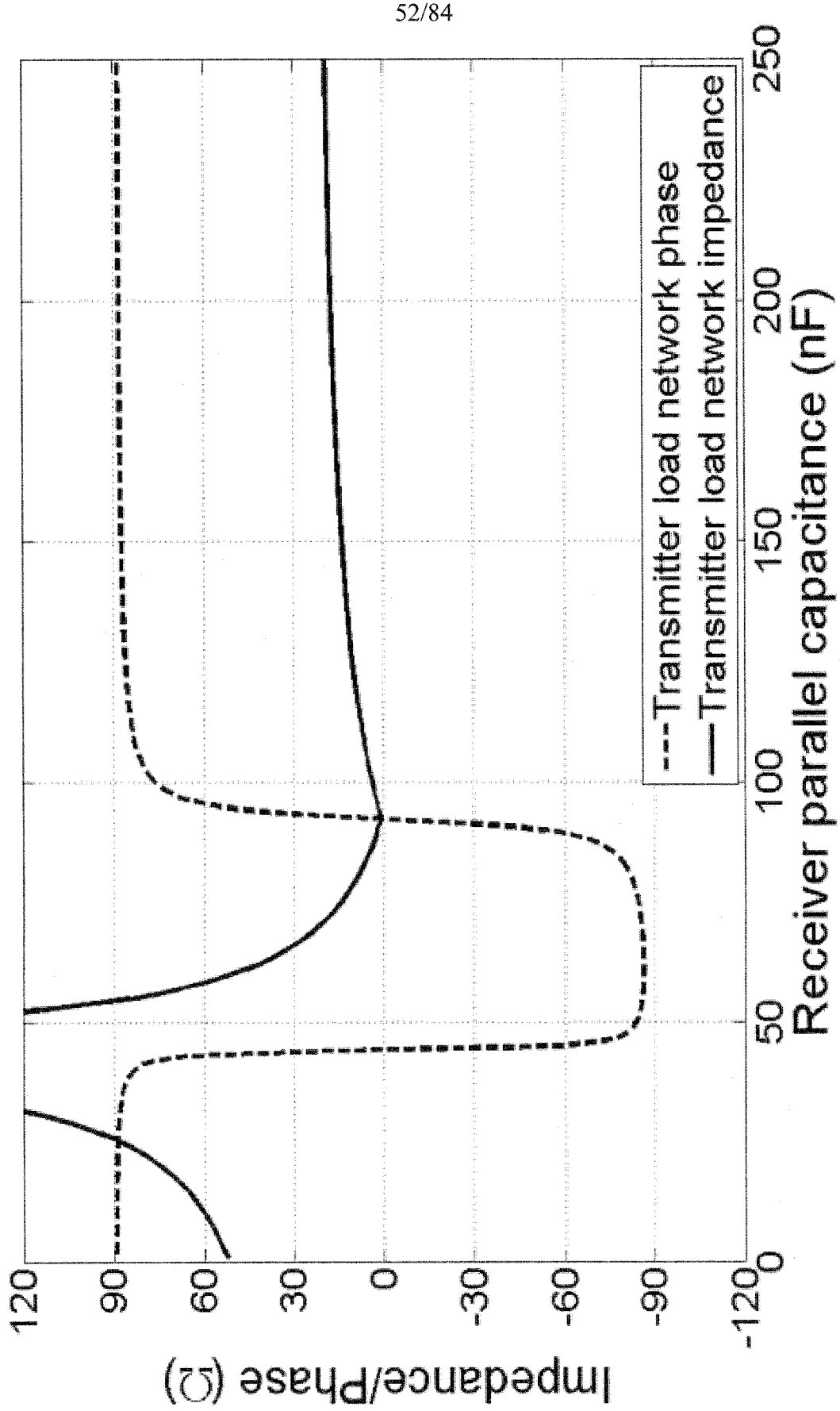

Impedance/Phase (Ω)
120
90
60
30
0
-30
-60
-90
-120
0
50
100
150
200
250
Receiver parallel capacitance (nF)
Transmitter load network phase
Transmitter load network impedance

FIG. 51

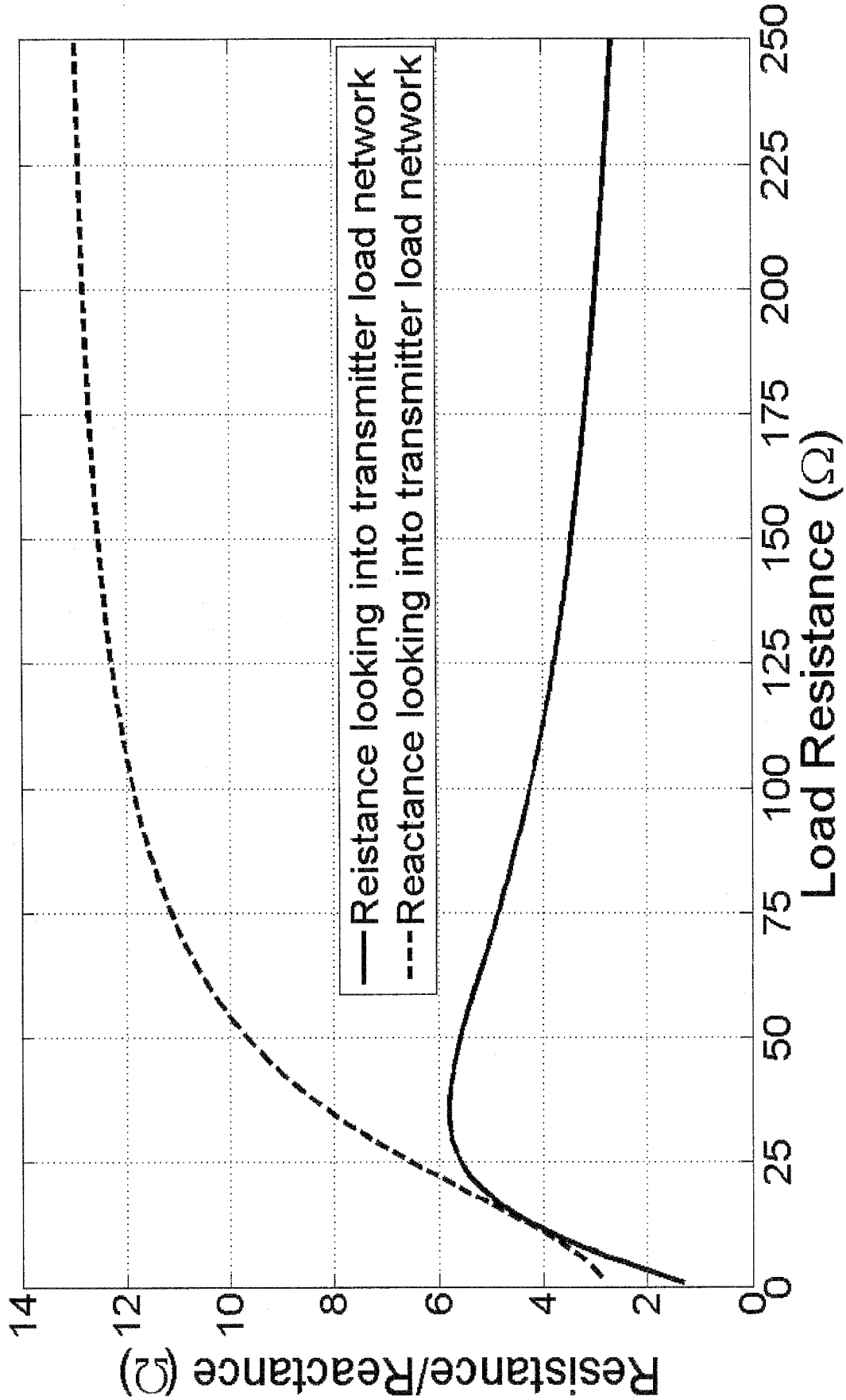

Resistance/Reactance (Ω)
Load Resistance (Ω)
Reistance looking into transmitter load network
Reactance looking into transmitter load network
0
2
4
6
8
10
12
14
0
25
50
75
100
125
150
175
200
225
250

FIG. 52

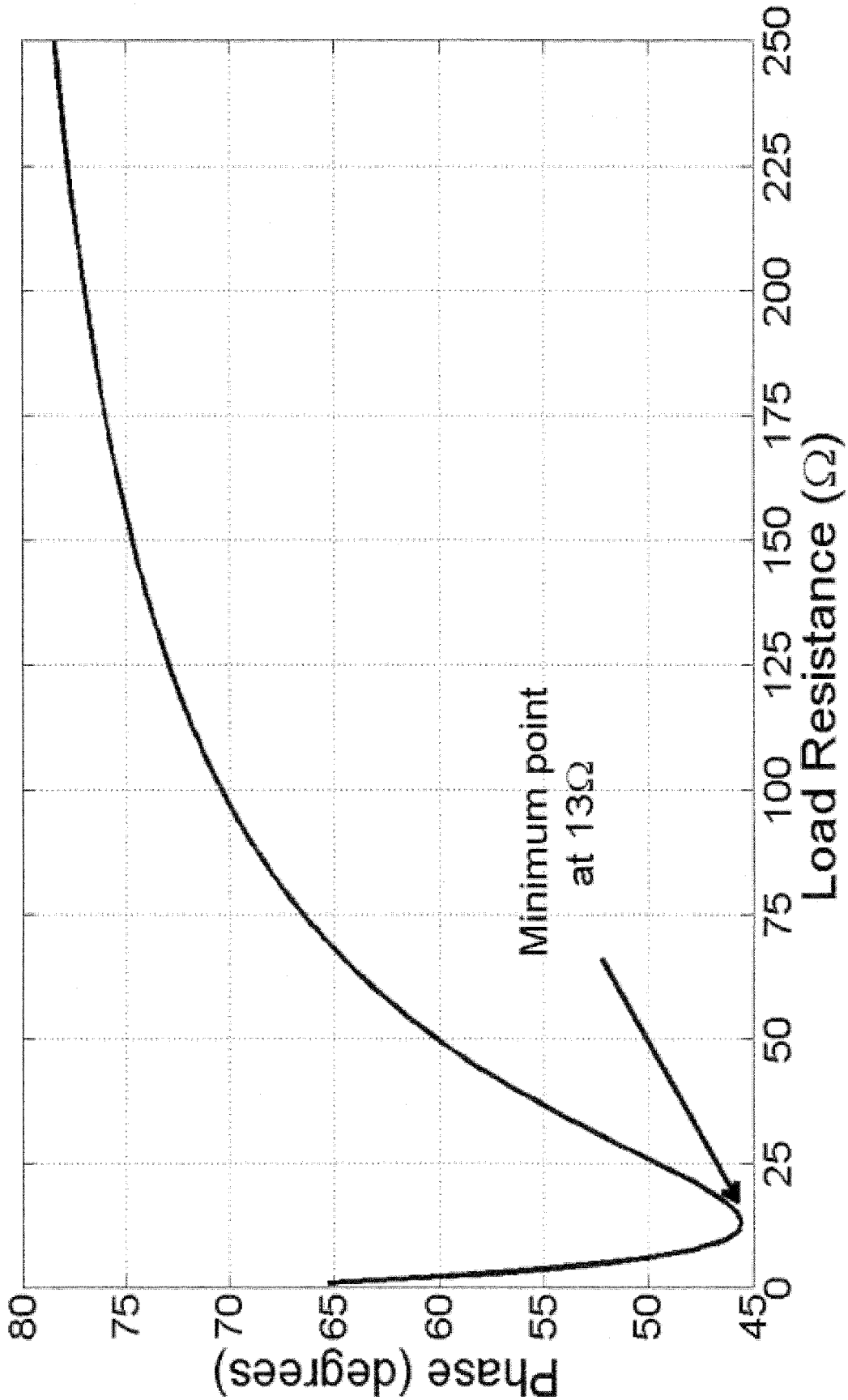

Phase (degrees)
80
75
70
65
60
55
50
45
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)
Minimum point
at 13Ω

FIG. 53

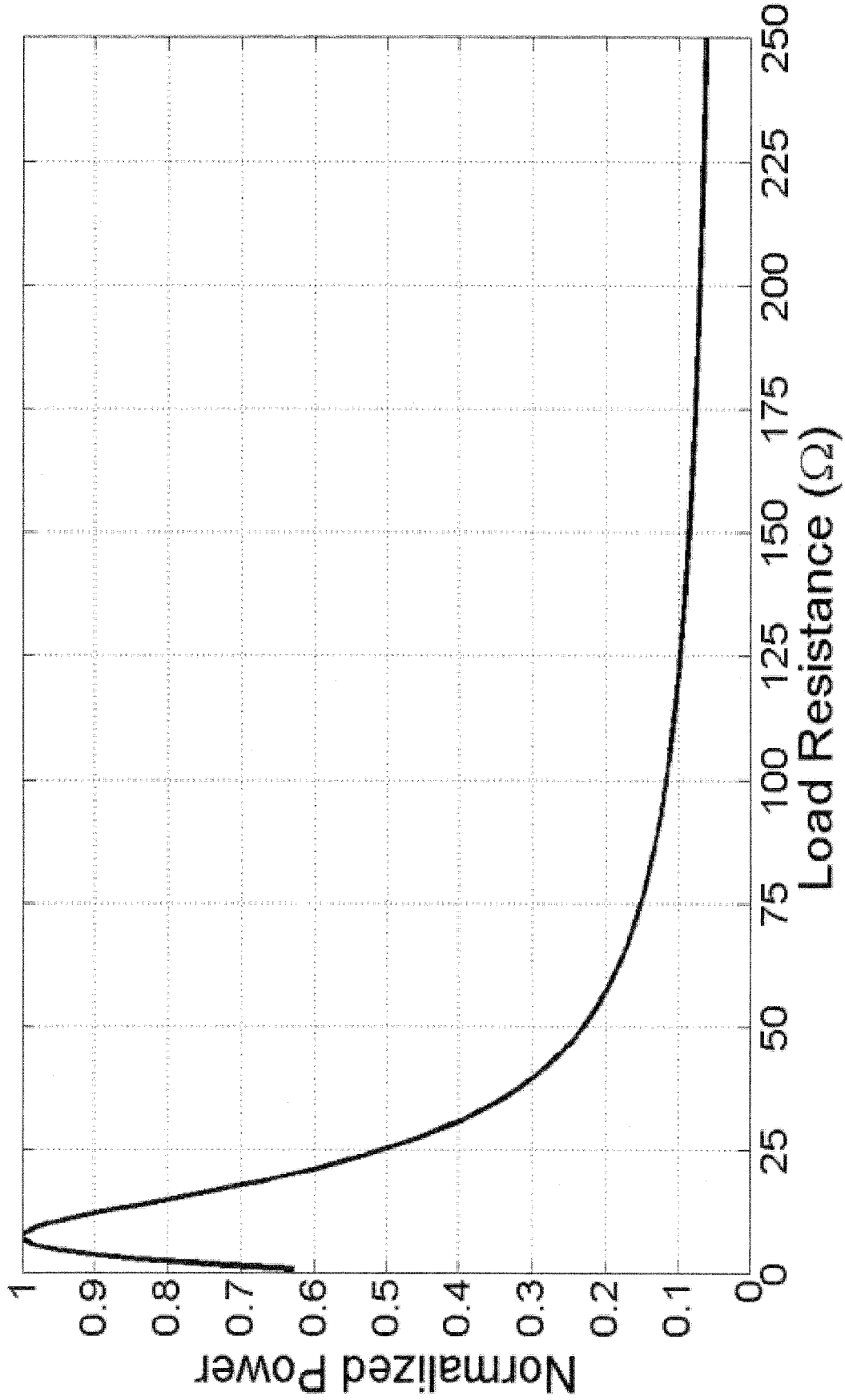

Normalized Power
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
25
50
75
100
125
150
175
200
225
250
Load Resistance (Ω)

FIG. 54

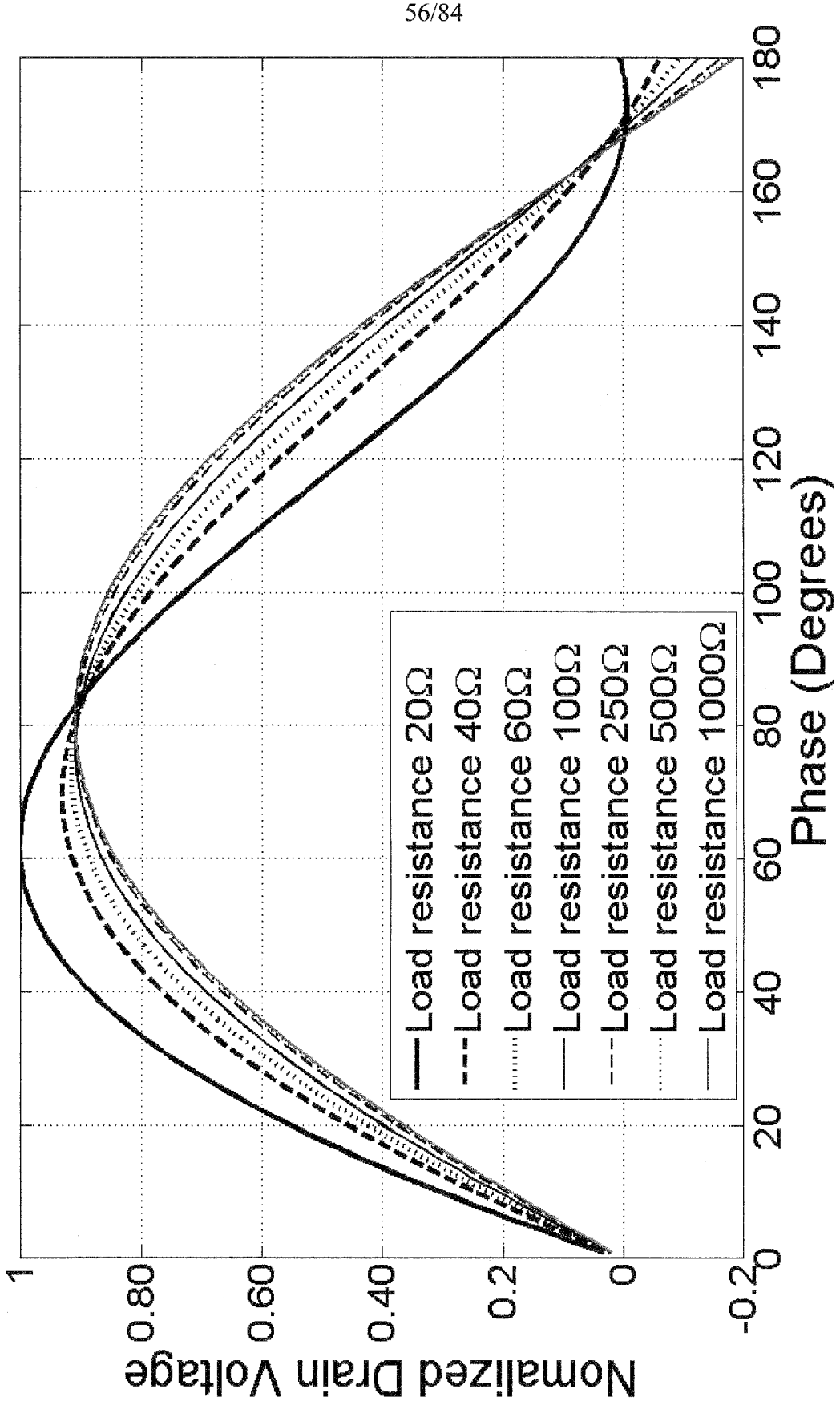
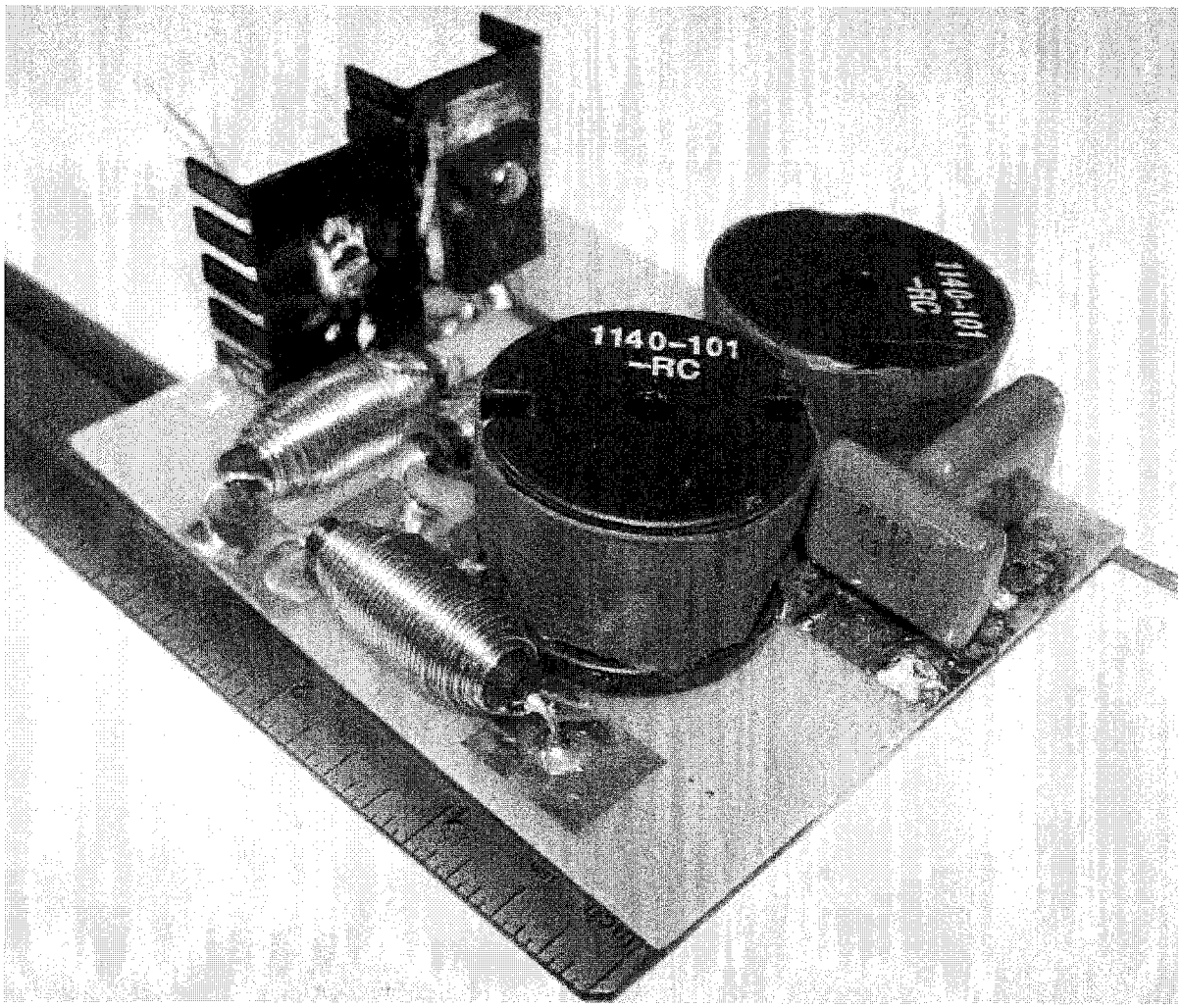

Normalized Drain Voltage
1
0.80
0.60
0.40
0.2
0
-0.2
0
20
40
60
80
100
120
140
160
180
Phase (Degrees)
Load resistance 20Ω
Load resistance 40Ω
Load resistance 60Ω
Load resistance 100Ω
Load resistance 250Ω
Load resistance 500Ω
Load resistance 1000Ω

FIG. 55


1140-101
-RC

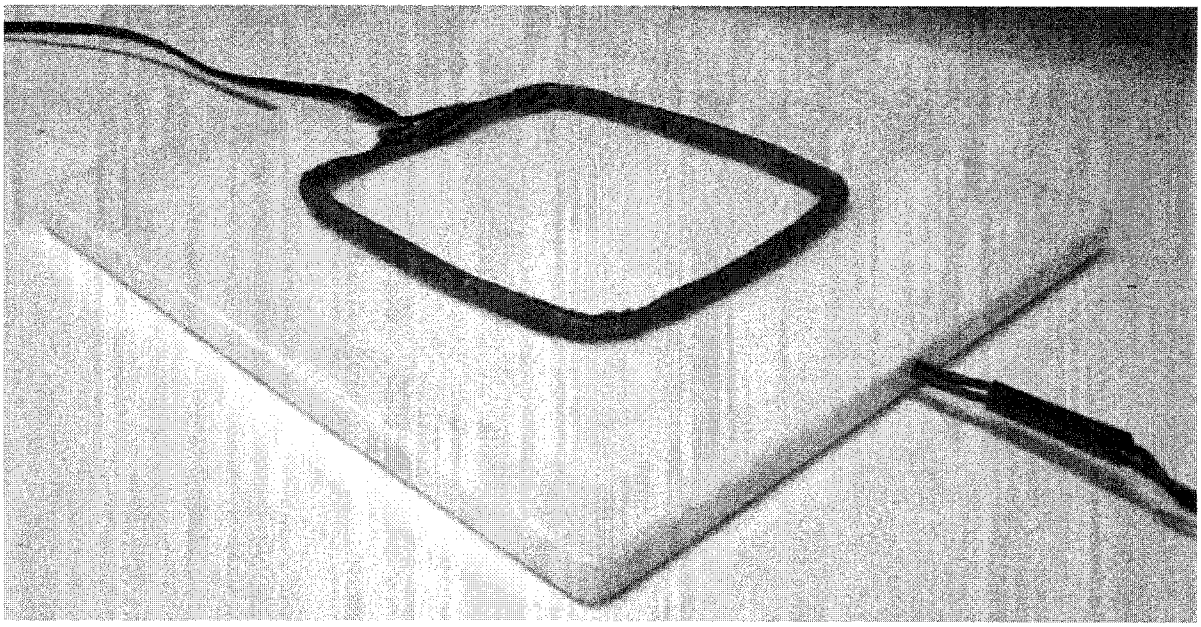


FIG. 57

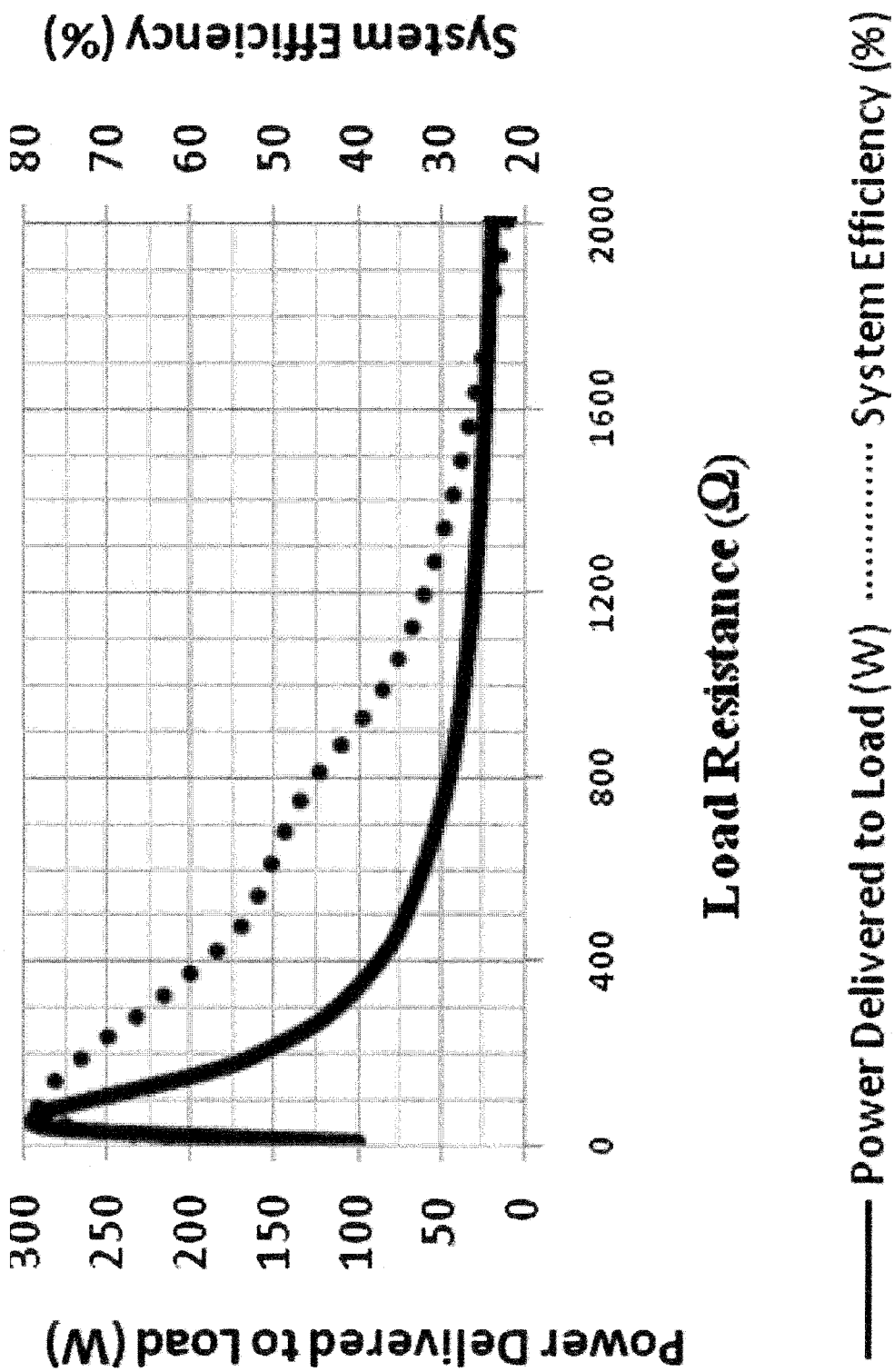
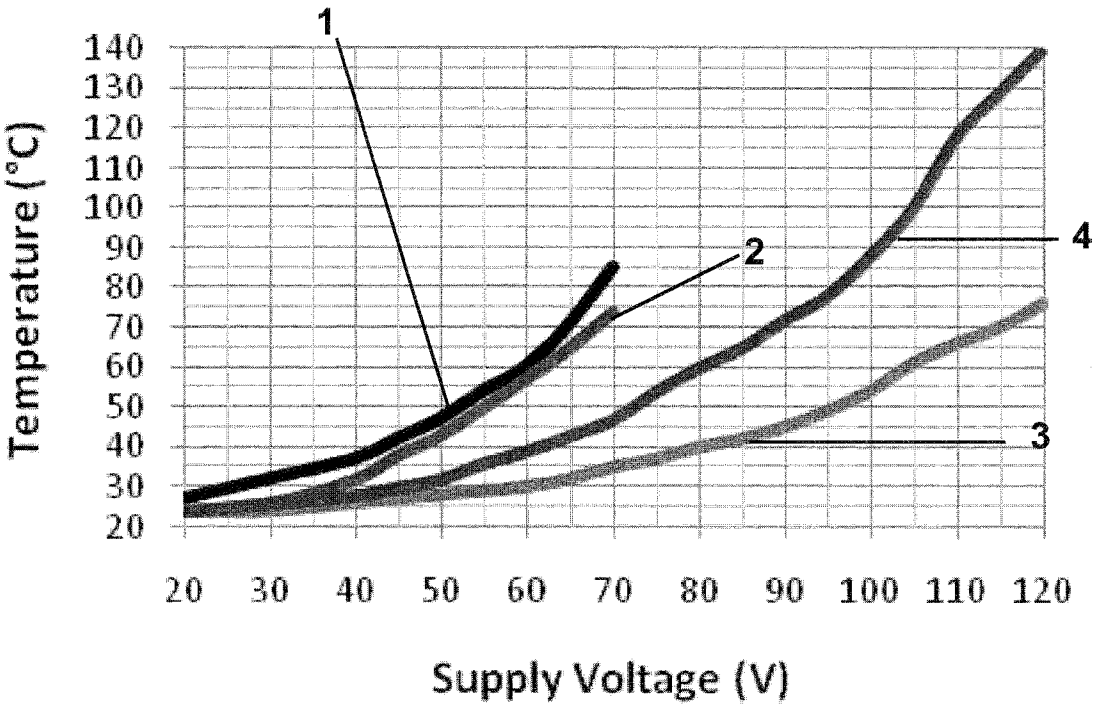

Power Delivered to load (W)
300
250
200
150
100
50
0
System Efficiency (%)
80
70
60
50
40
30
20
0
400
800
1200
1600
2000
Load Resistance (Ω)
Power Delivered to Load (W)
System Efficiency (%)

FIG. 58



1 —— Transistor Temperature (natural convection cooling)

2 —— Inductor Temperature (natural convection cooling)

3 —— Transistor Temperature (forced cooling)

4 —— Inductor Temperature (forced cooling)

FIG. 59

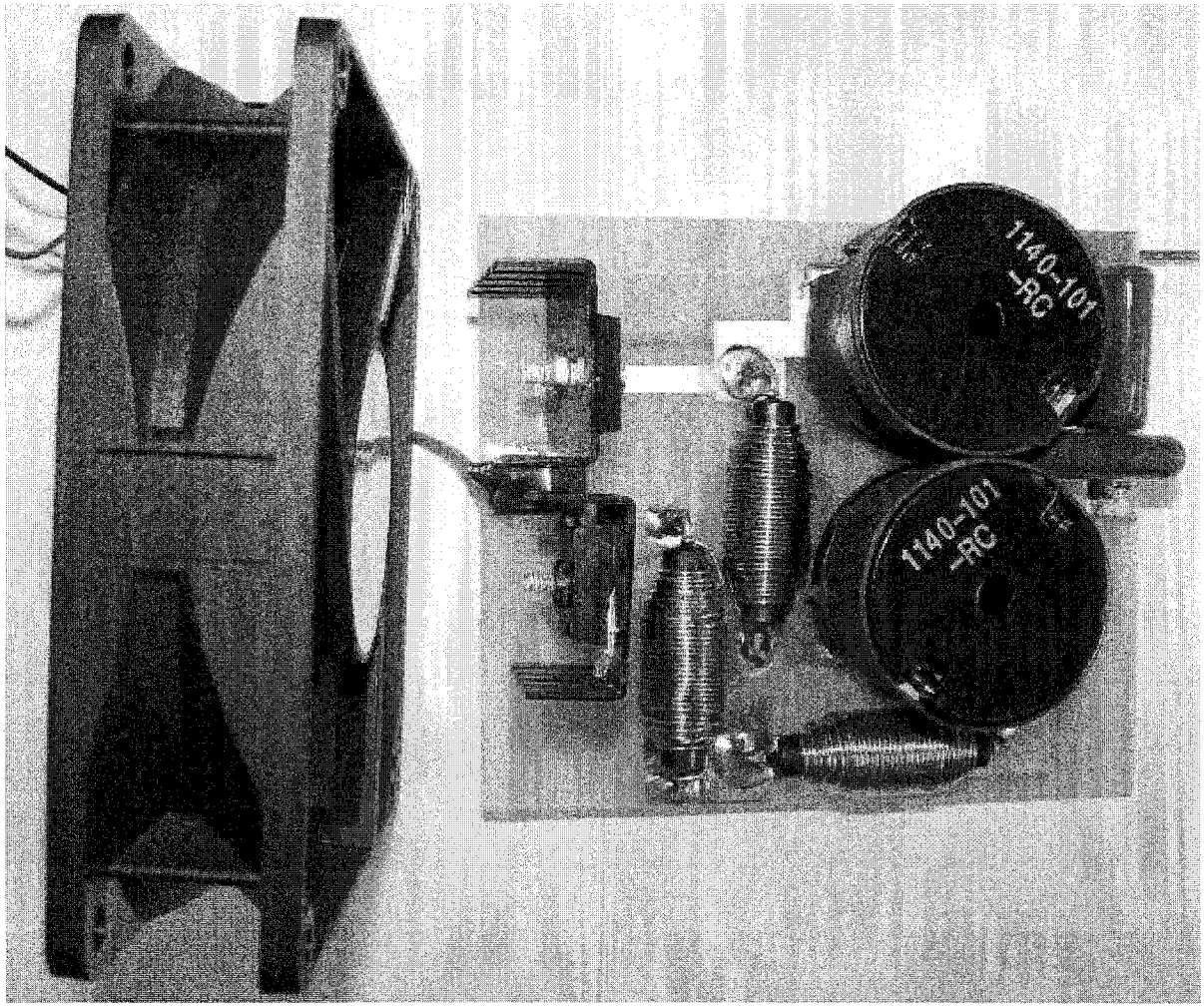


FIG. 60

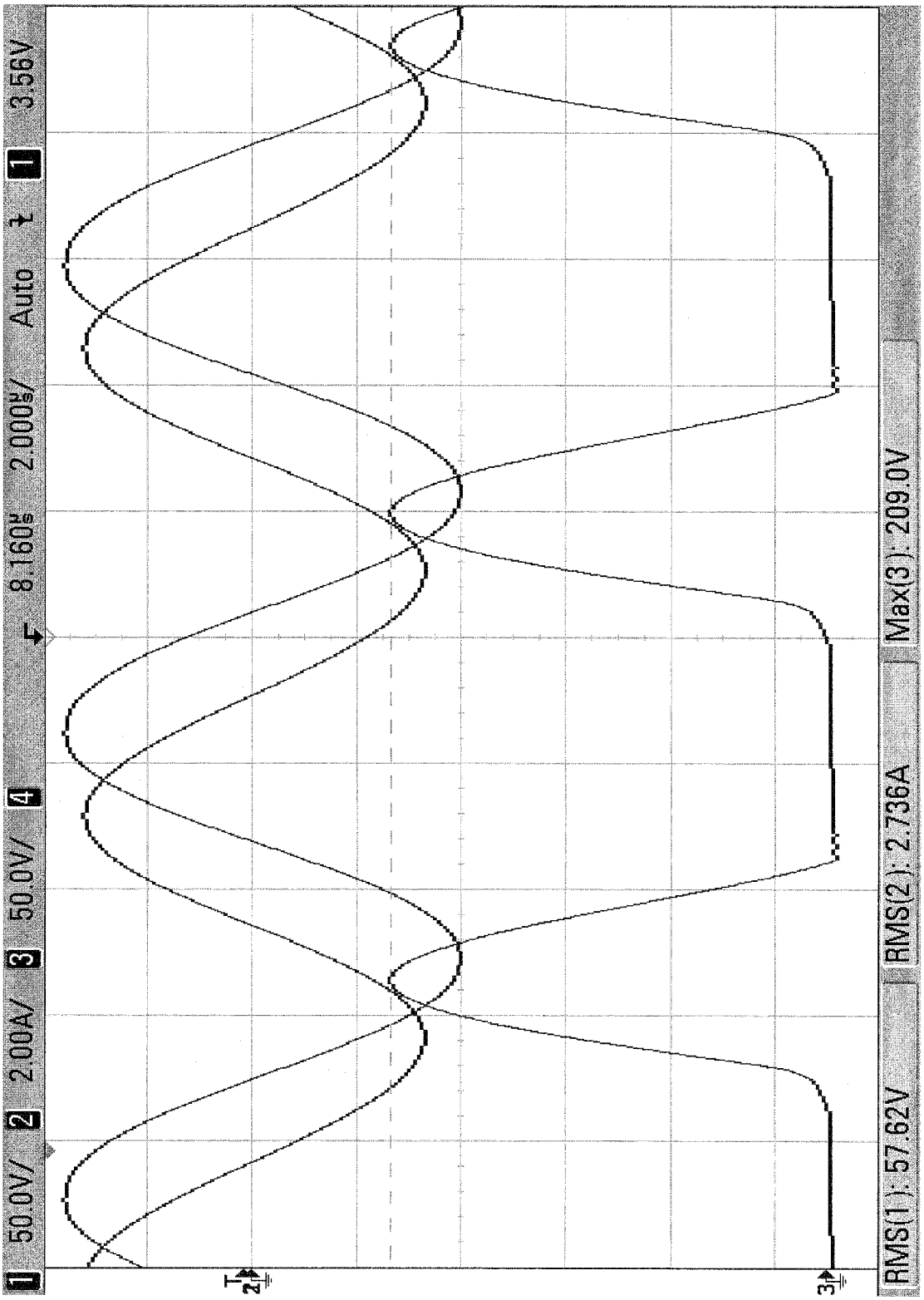

1 50.0V/ 2 2.00A/ 3 50.0V/ 4
8.160µs 2.000µs/ Auto 1 3.56V
RMS(1): 57.62V
RMS(2): 2.736A
Max(3): 209.0V

FIG. 61

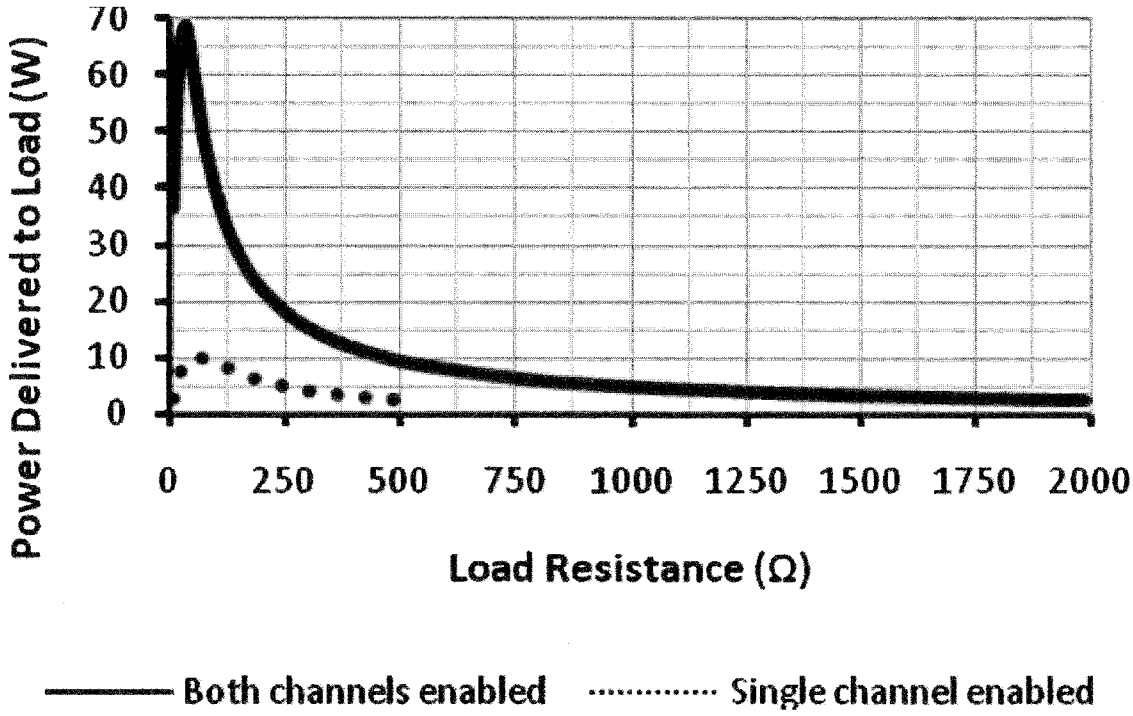


FIG. 62A

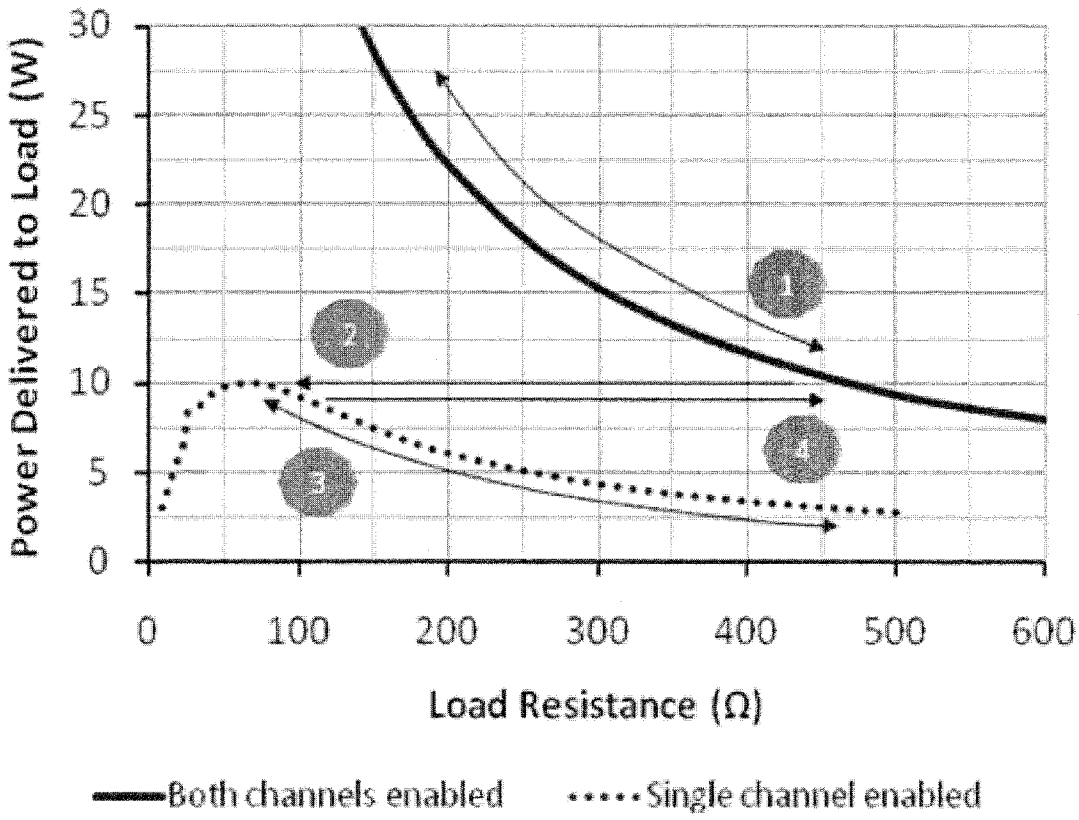


FIG. 62B

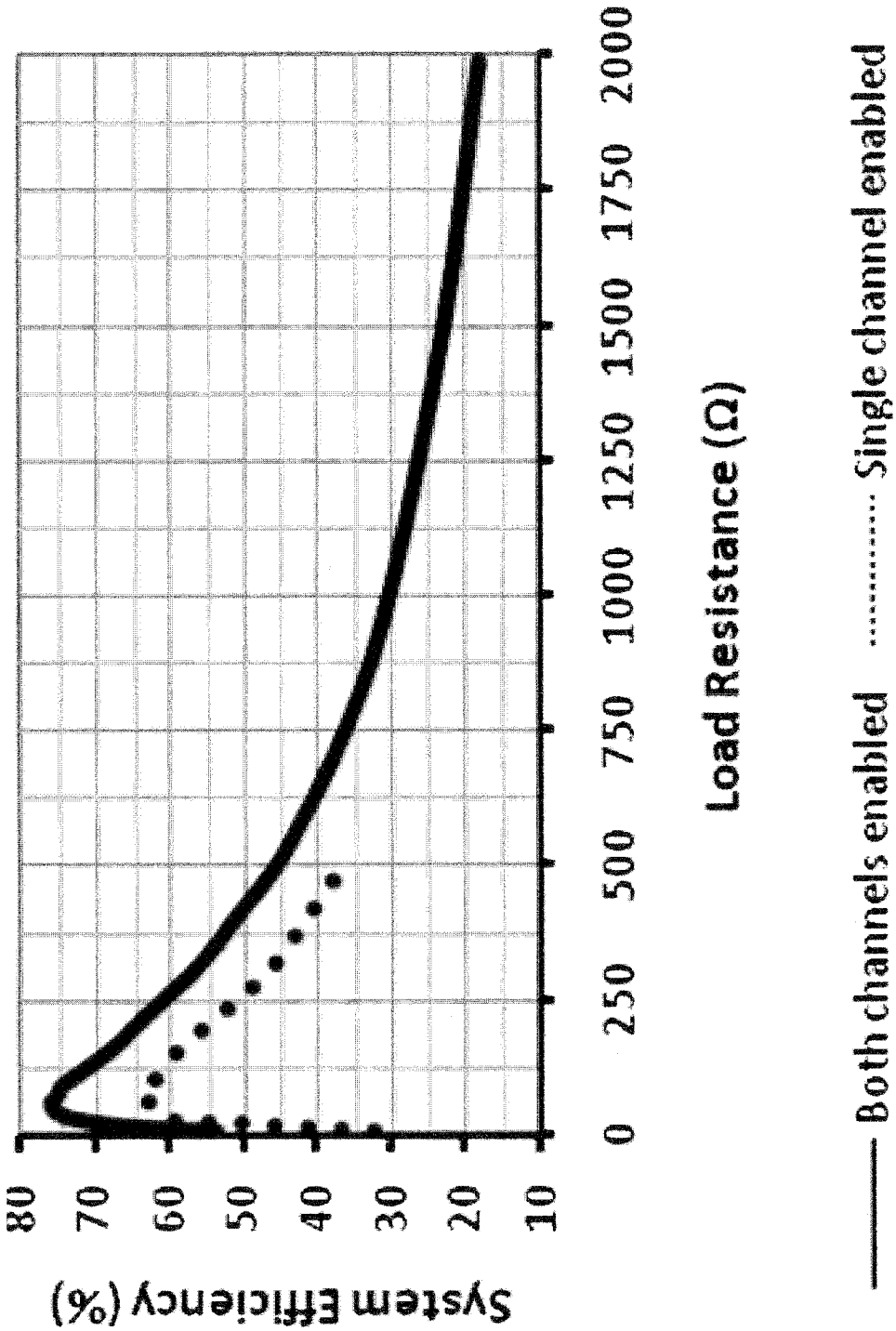

System Efficiency (%)
80
70
60
50
40
30
20
10
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 63

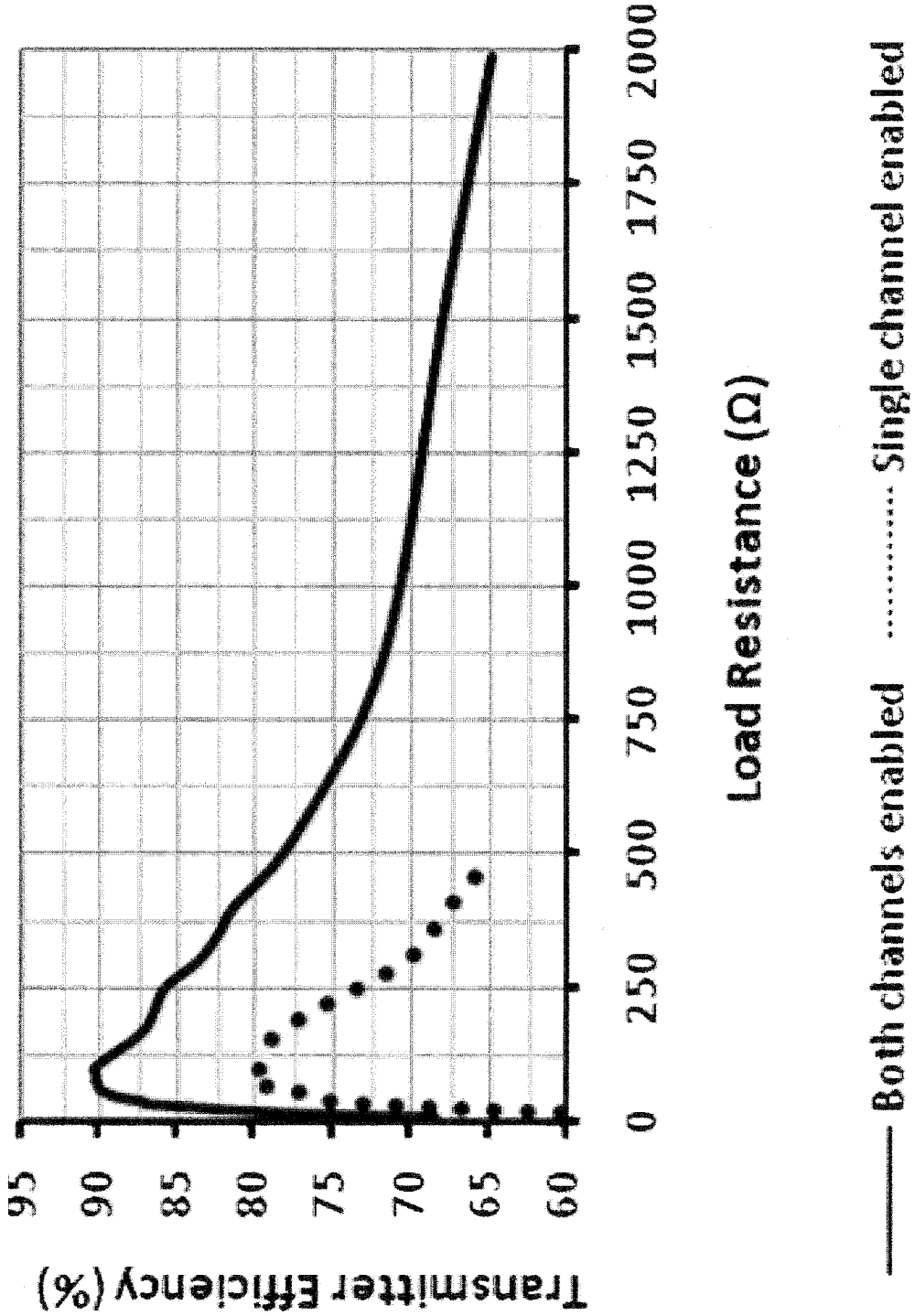

Transmitter Efficiency (%)
95
90
85
80
75
70
65
60
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
——— Both channels enabled ..... Single channel enabled

FIG. 64

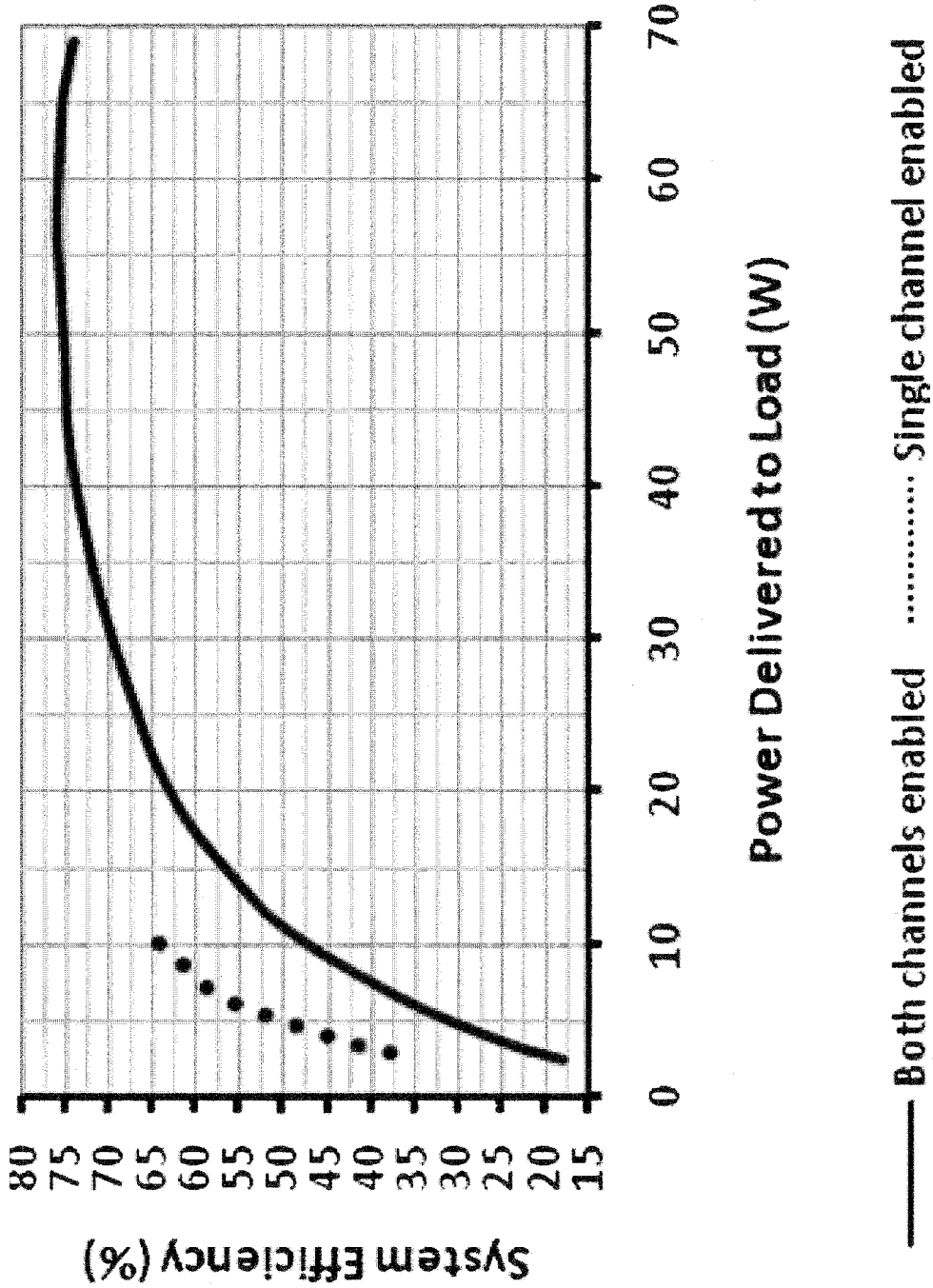

System Efficiency (%)
80
75
70
65
60
55
50
45
40
35
30
25
20
15
0
10
20
30
40
50
60
70
Power Delivered to Load (W)
Both channels enabled
Single channel enabled

FIG. 65

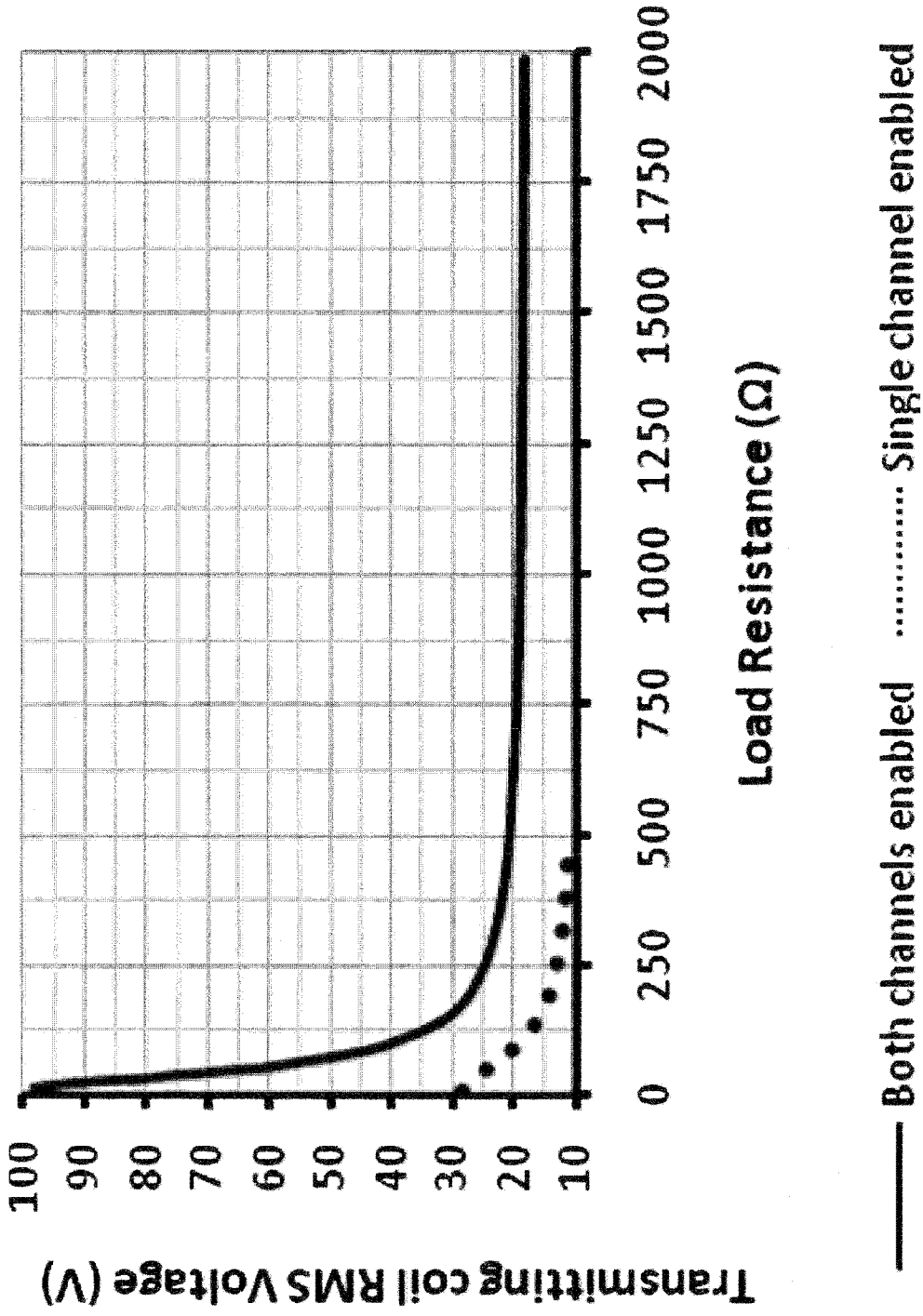

Transmitting coil RMS Voltage (V)
100
90
80
70
60
50
40
30
20
10
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 66

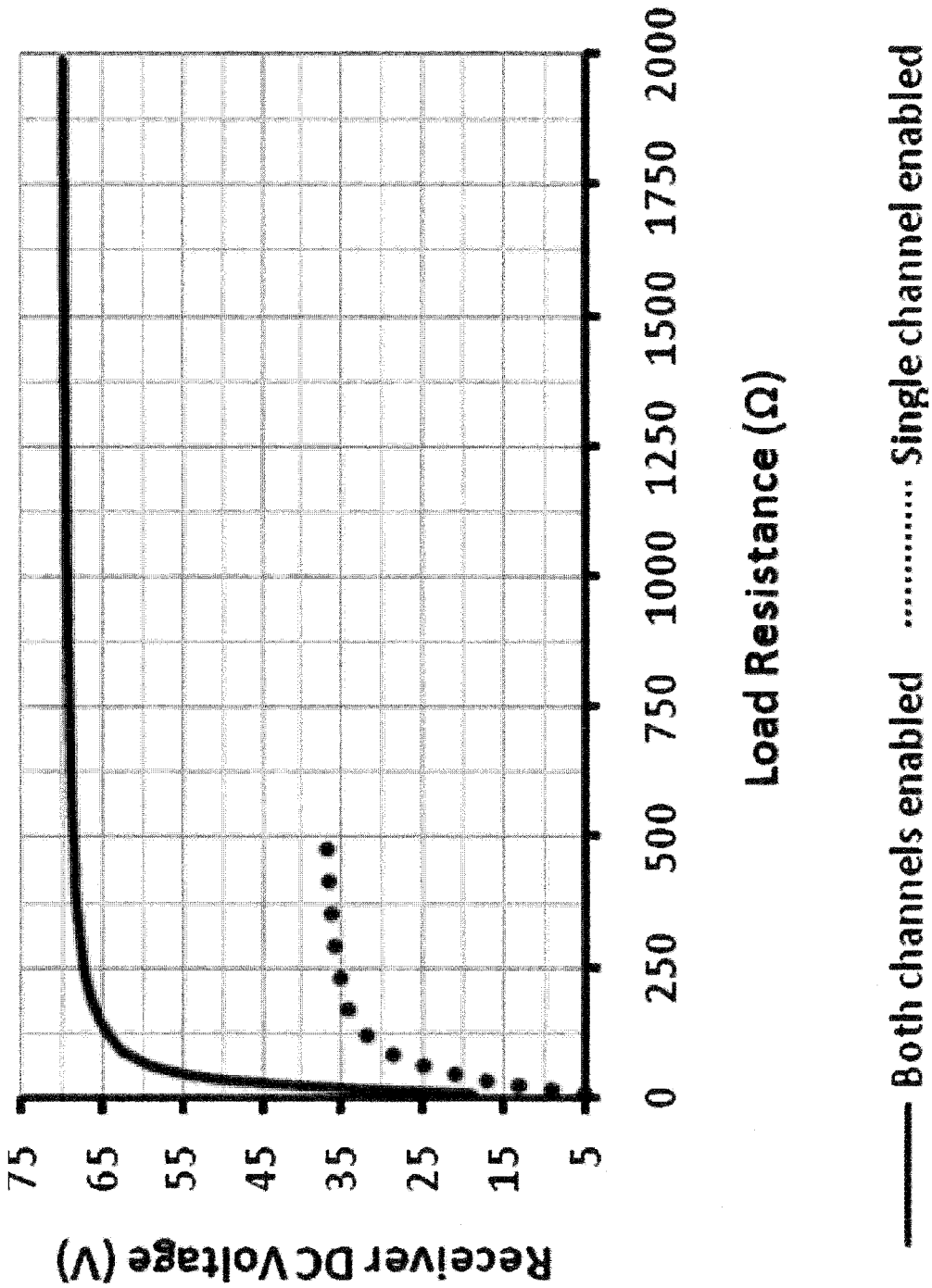

Receiver DC Voltage (V)
75
65
55
45
35
25
15
5
0
250
500
750
1000
1250
1500
1750
2000
Load Resistance (Ω)
Both channels enabled
Single channel enabled

FIG. 67

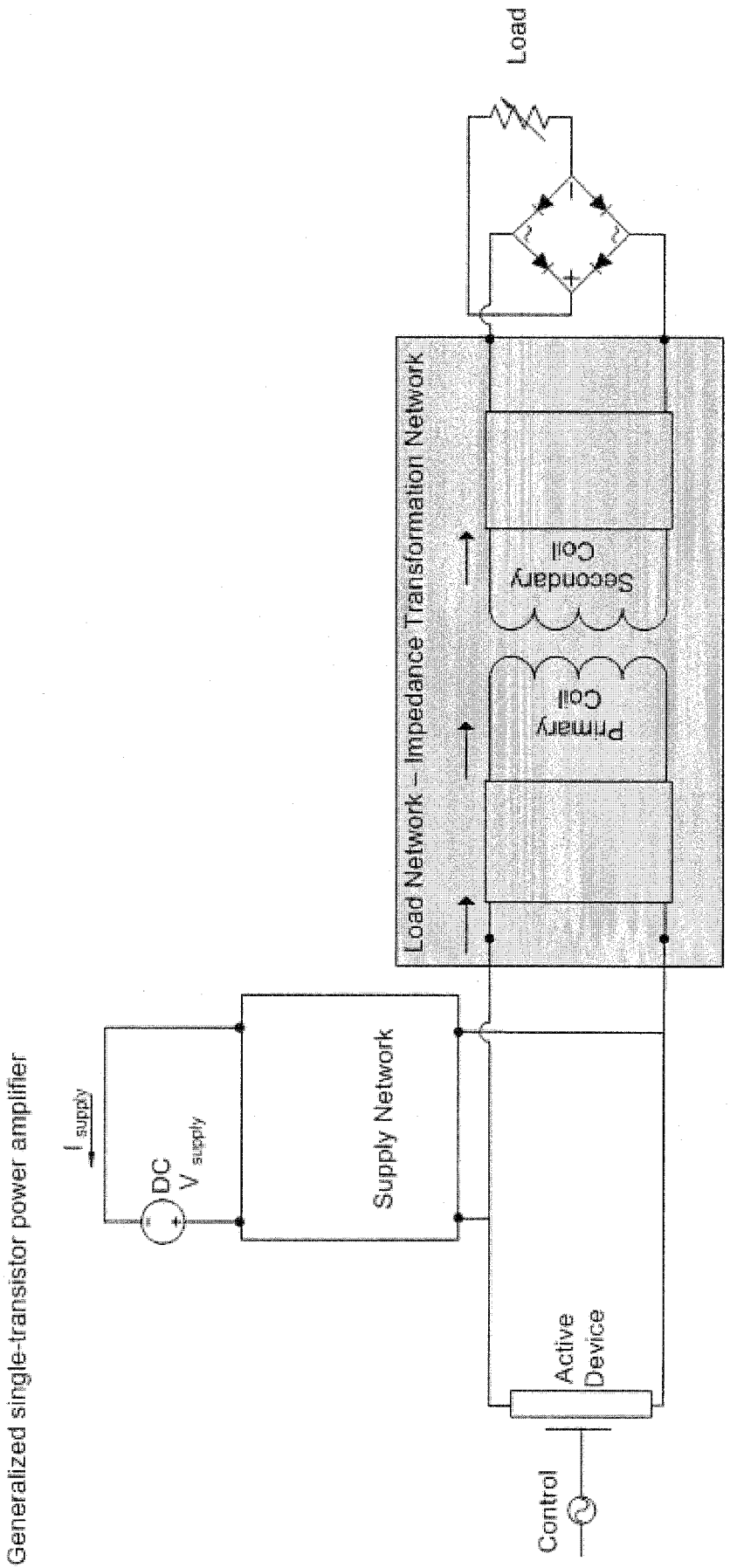

Generalized single-transistor power amplifier
I supply
DC
V supply
Supply Network
Load Network – Impedance Transformation Network
Primary Coil
Secondary Coil
Load
Active Device
Control

FIG. 68

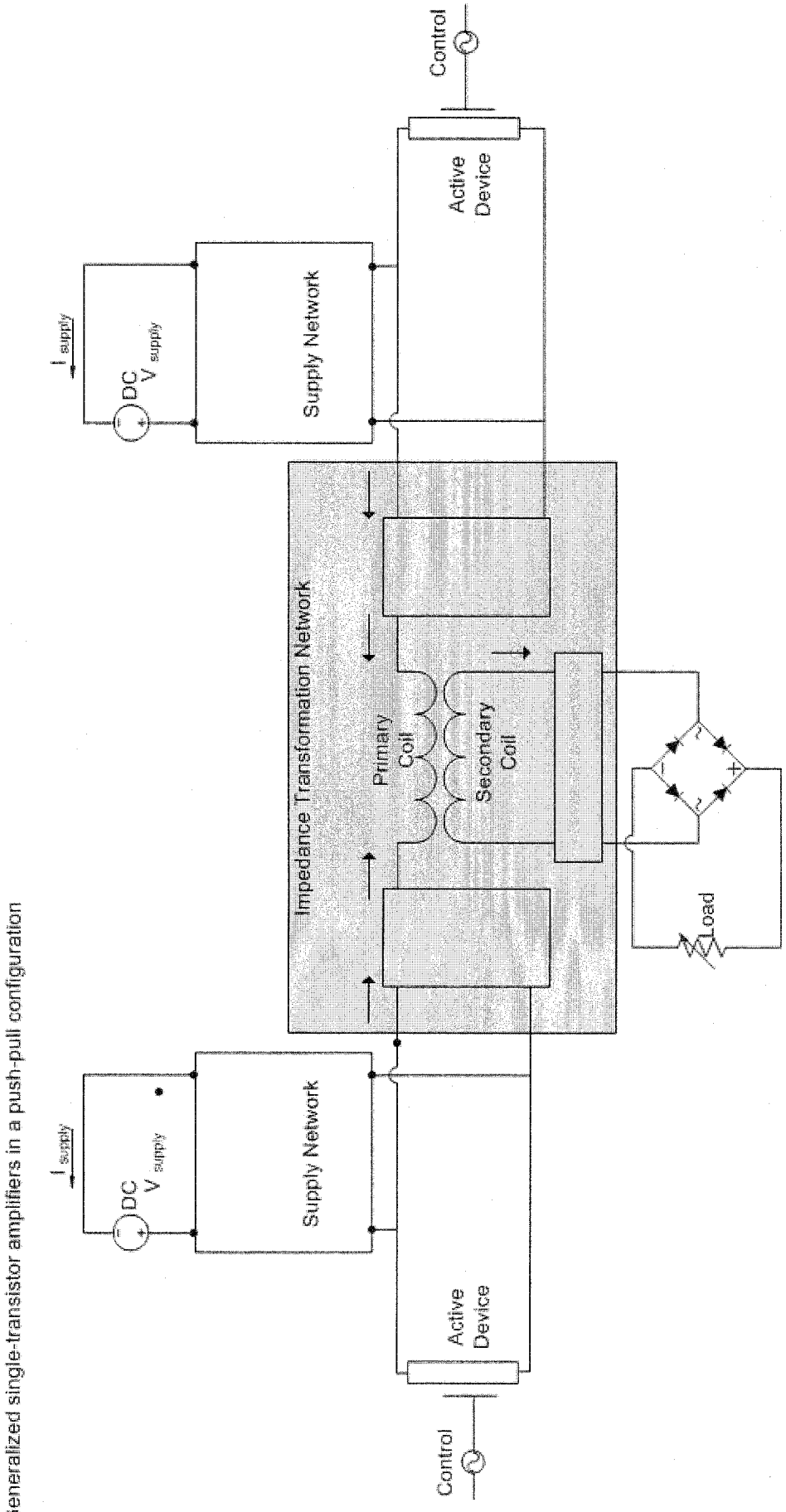

Generalized single-transistor amplifiers in a push-pull configuration
Control
Active Device
Supply Network
DC
V supply
I supply
Impedance Transformation Network
Primary Coil
Secondary Coil
Load
Supply Network
DC
V supply
I supply
Active Device
Control

FIG. 69

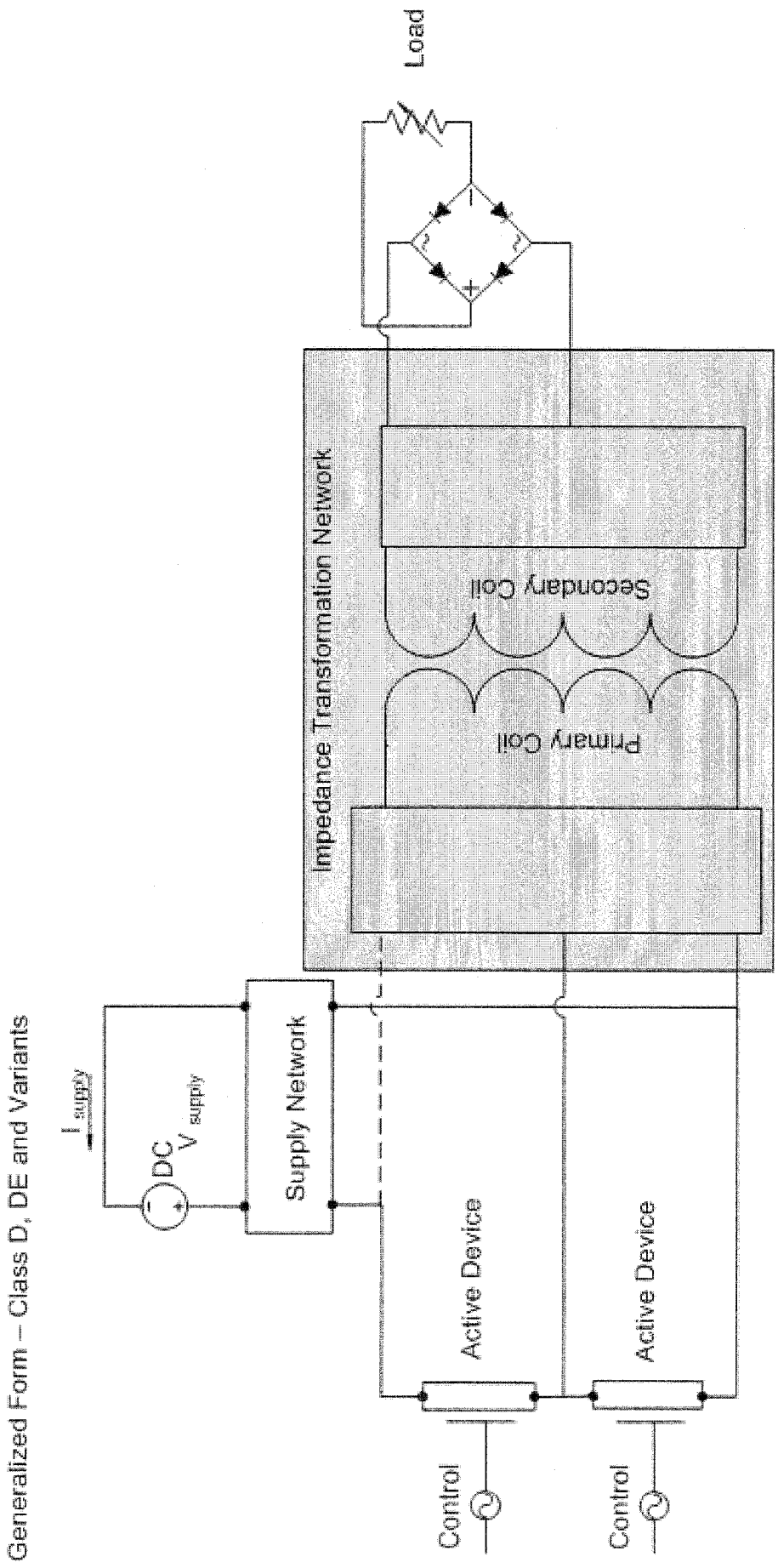

Generalized Form – Class D, DE and Variants
I supply
DC
V supply
Supply Network
Impedance Transformation Network
Secondary Coil
Primary Coil
Load
Active Device
Active Device
Control
Control

FIG. 70

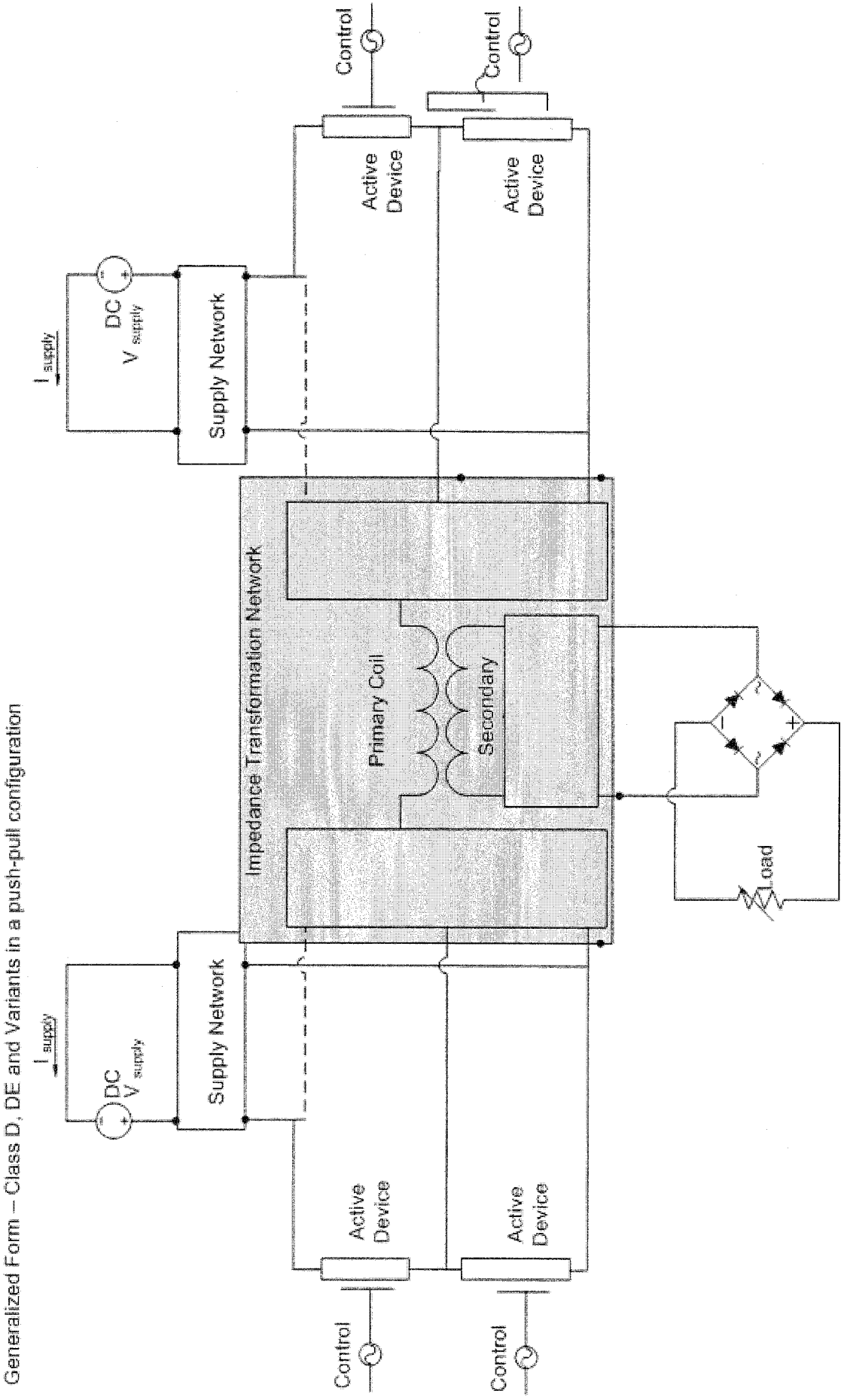

Generalized Form – Class D, DE and Variants in a push-pull configuration
I supply
DC
V supply
Supply Network
Active Device
Control
Impedance Transformation Network
Primary Coil
Secondary
Load

FIG. 71

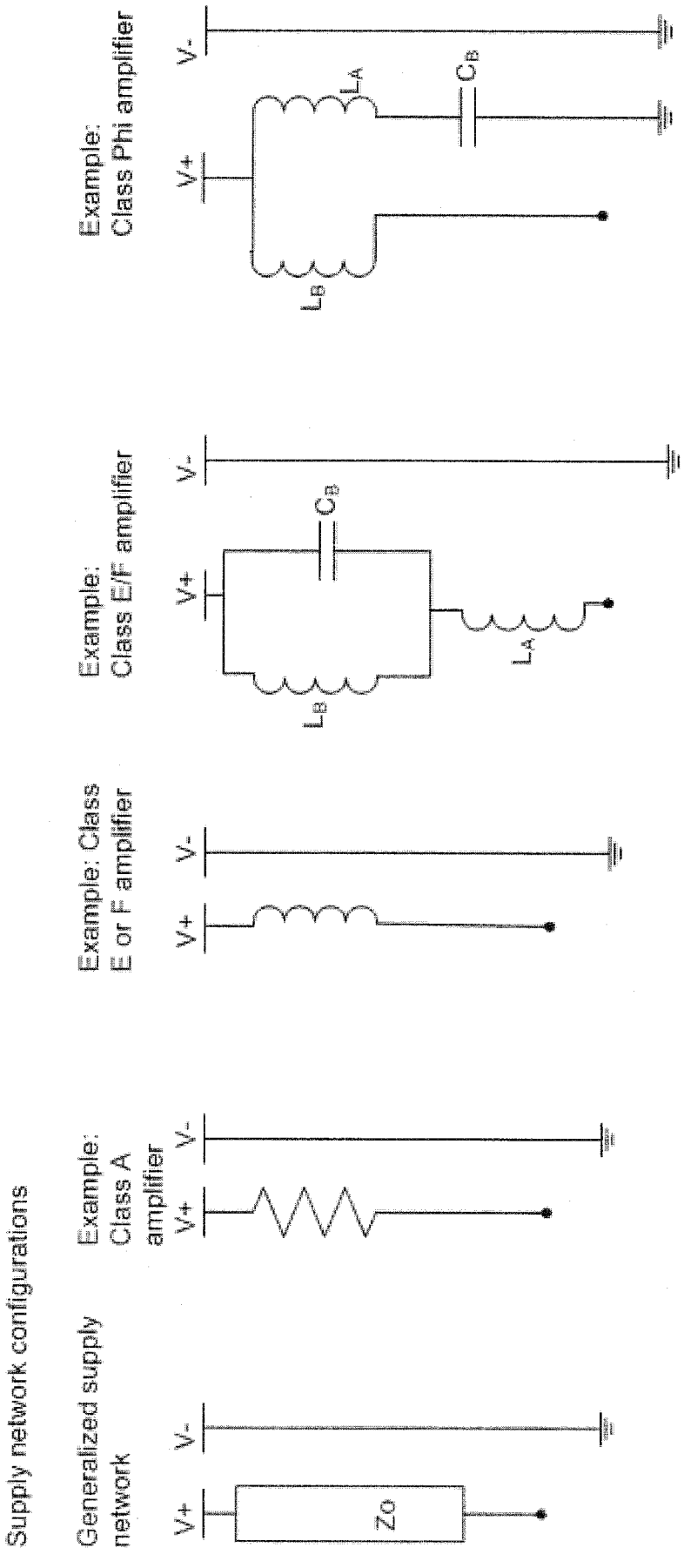

Supply network configurations
Generalized supply network
V+
V-
Zo
Example: Class A amplifier
V+
V-
Example: Class E or F amplifier
V+
V-
Example: Class E/F amplifier
V+
V-
C_B
L_B
L_A
Example: Class Phi amplifier
V+
V-
L_A
C_B
L_B

FIG. 72

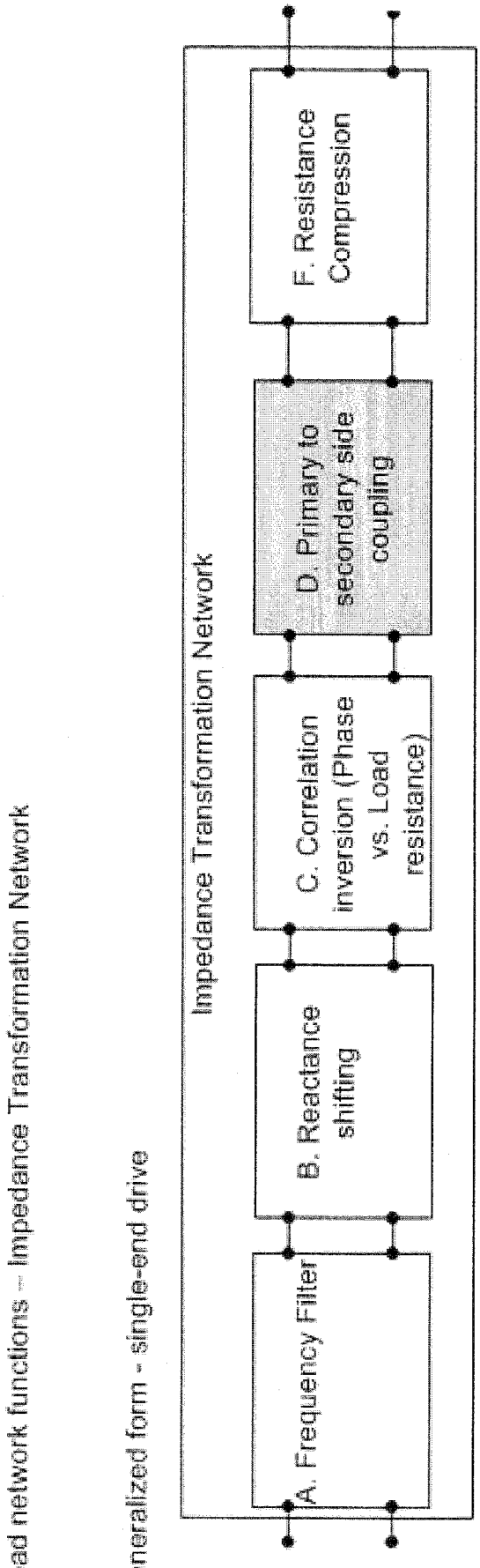

Load network functions -- Impedance Transformation Network
Generalized form - single-end drive
Impedance Transformation Network
A. Frequency Filter
B. Reactance shifting
C. Correlation inversion (Phase vs. Load resistance)
D. Primary to secondary side coupling
F. Resistance Compression

FIG. 73

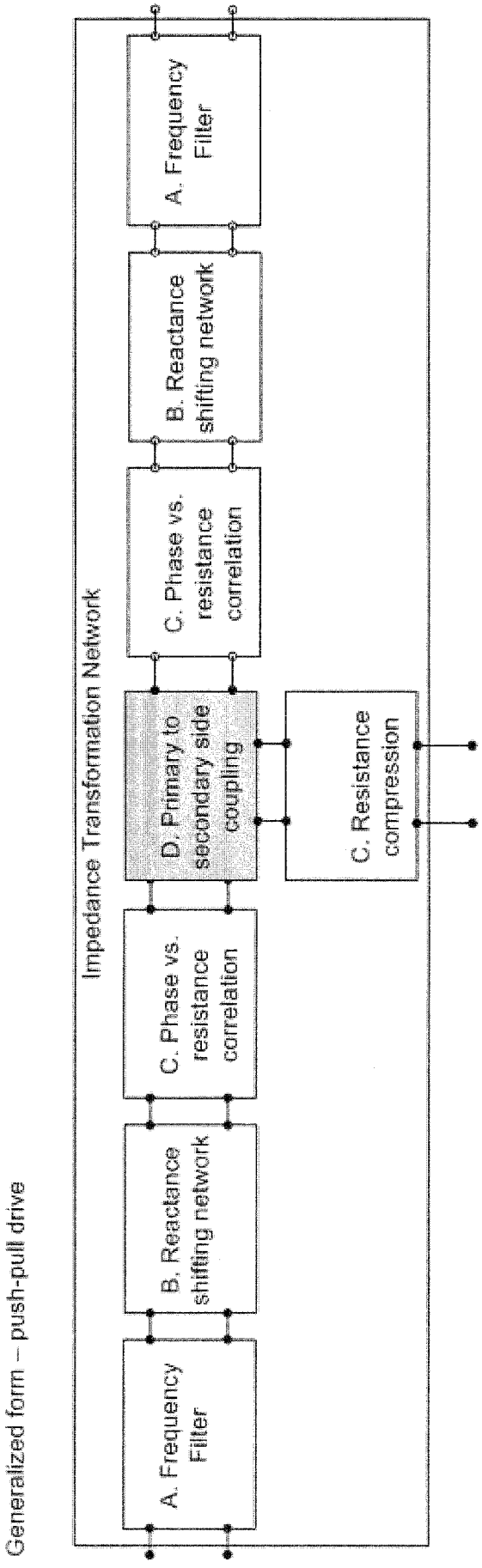

Generalized form – push-pull drive
Impedance Transformation Network
A. Frequency Filter
B. Reactance shifting network
C. Phase vs. resistance correlation
D. Primary to secondary side coupling
C. Resistance compression
C. Phase vs. resistance correlation
B. Reactance shifting network
A. Frequency Filter

FIG. 74

A. Reactance shifting network
Reactance shift – positive shift
Reactance shift – positive shift
Reactance shift – negative shift
Reactance shift – negative shift

FIG. 75

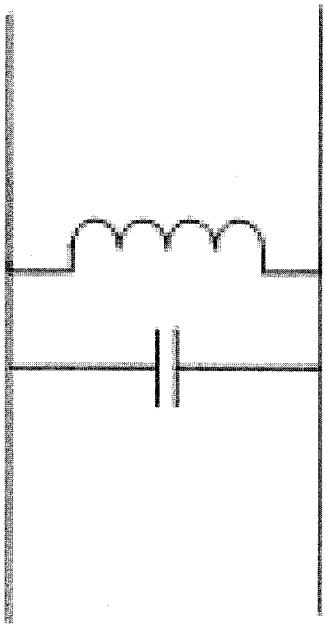
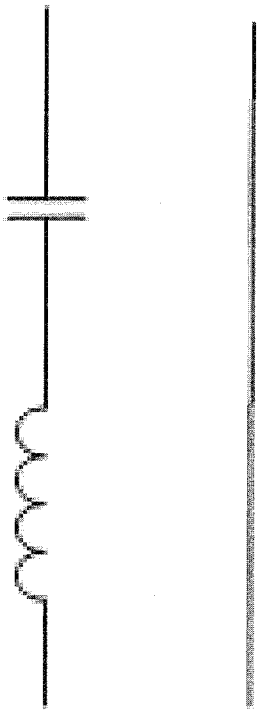


FIG. 76

B. Notch Filter



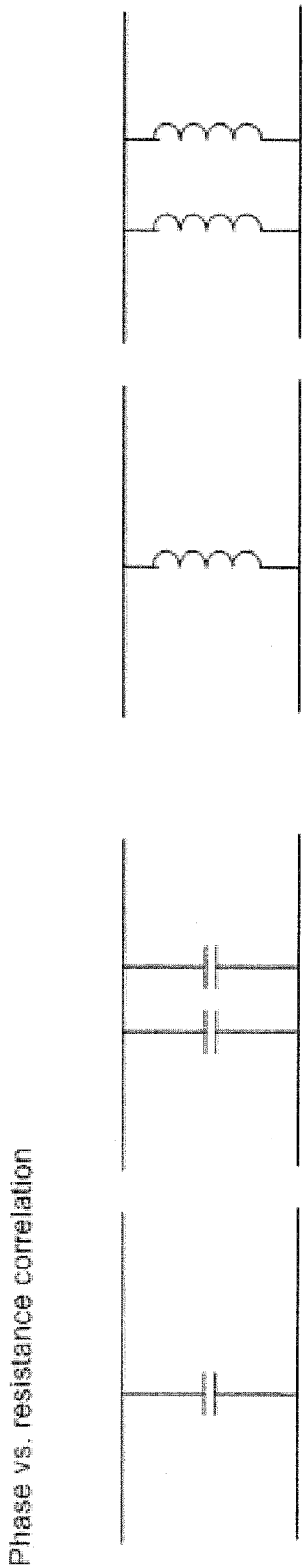


FIG. 77

D. Primary to Secondary Side Coupling
One primary:
One secondary
One primary:
Multiple secondary
Multiple primary:
One secondary
Multiple primary:
Multiple secondary

FIG. 78

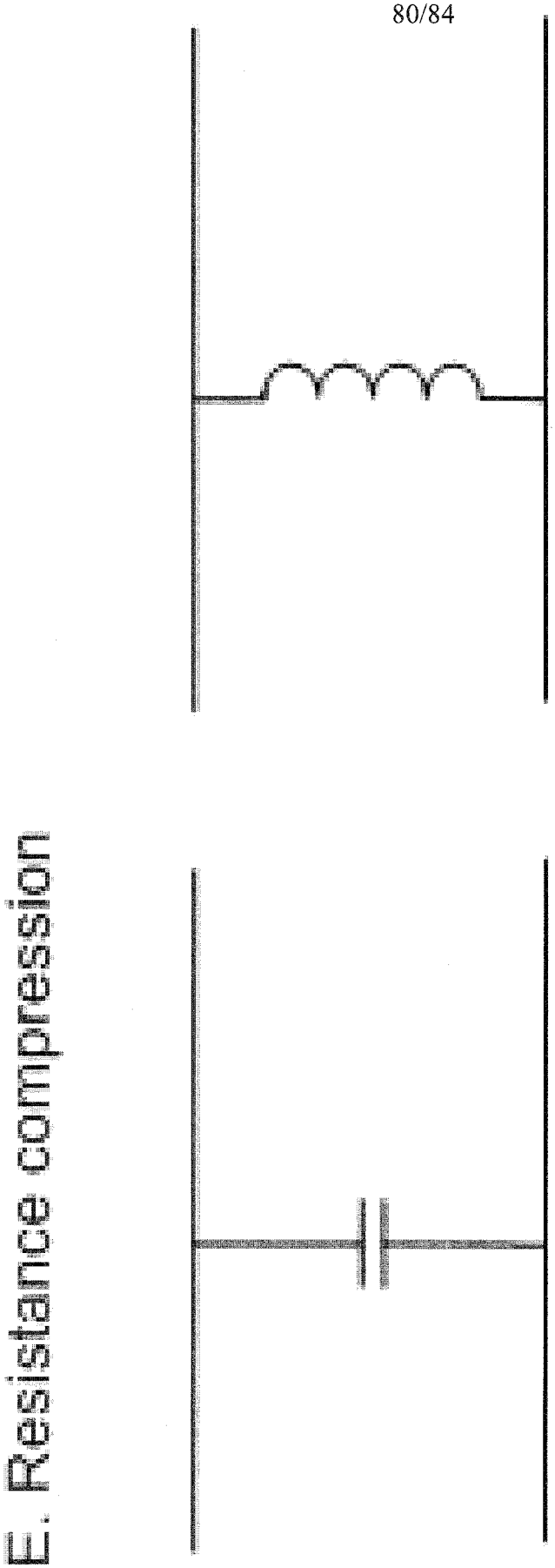


FIG. 79

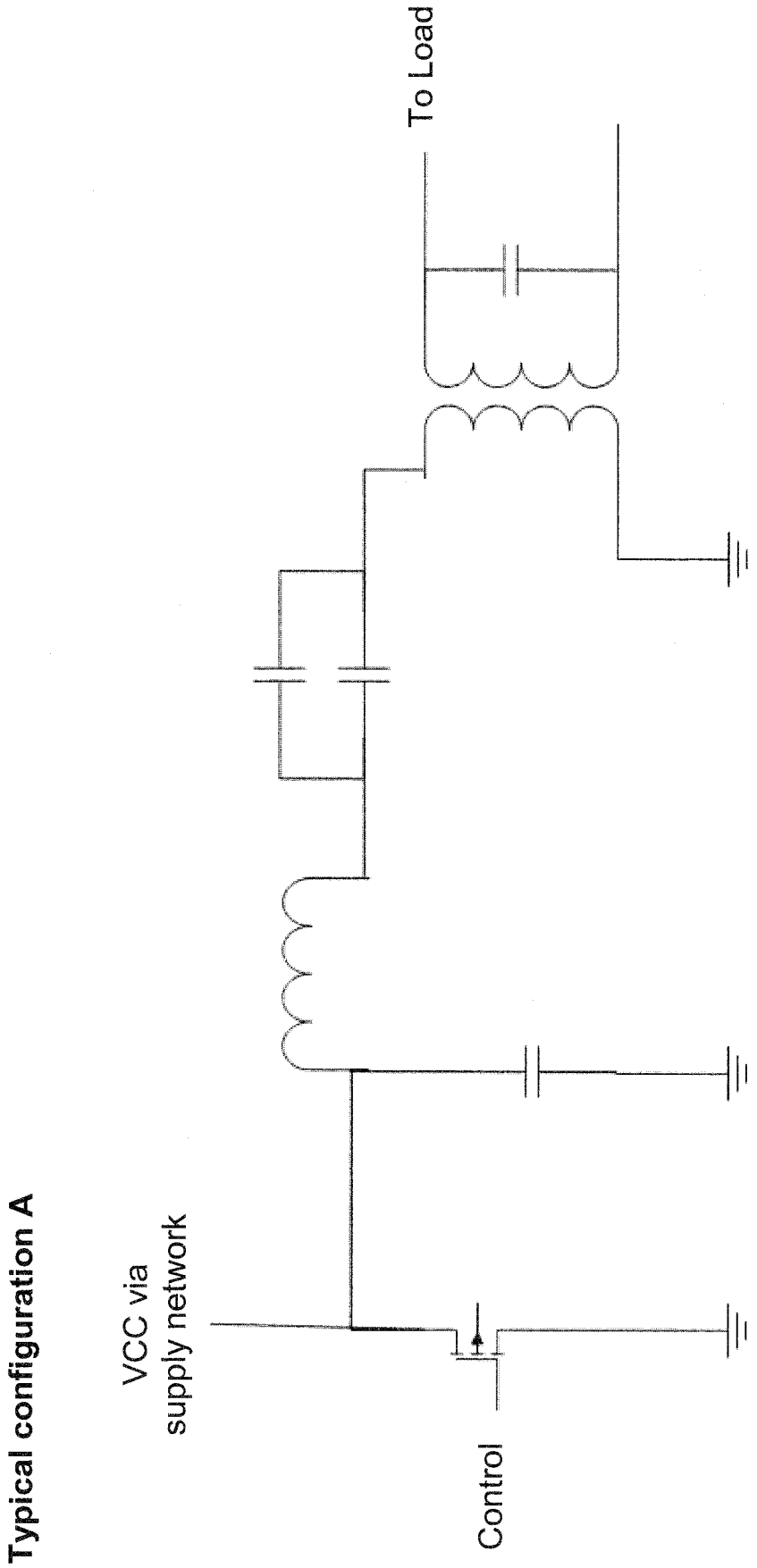

Typical configuration A
VCC via
supply network
Control
To Load

FIG. 80

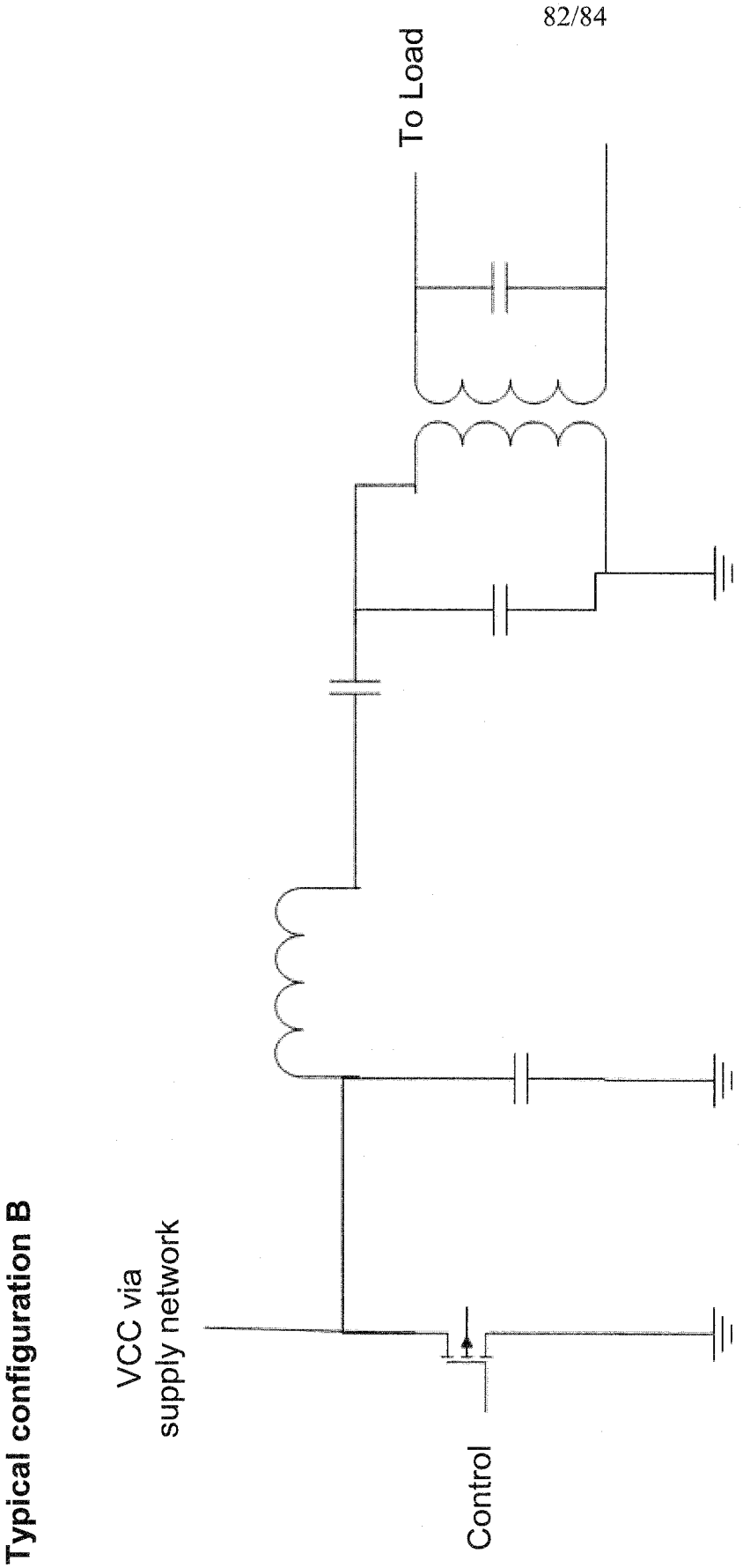

Typical configuration B
VCC via
supply network
Control
To Load

FIG. 81

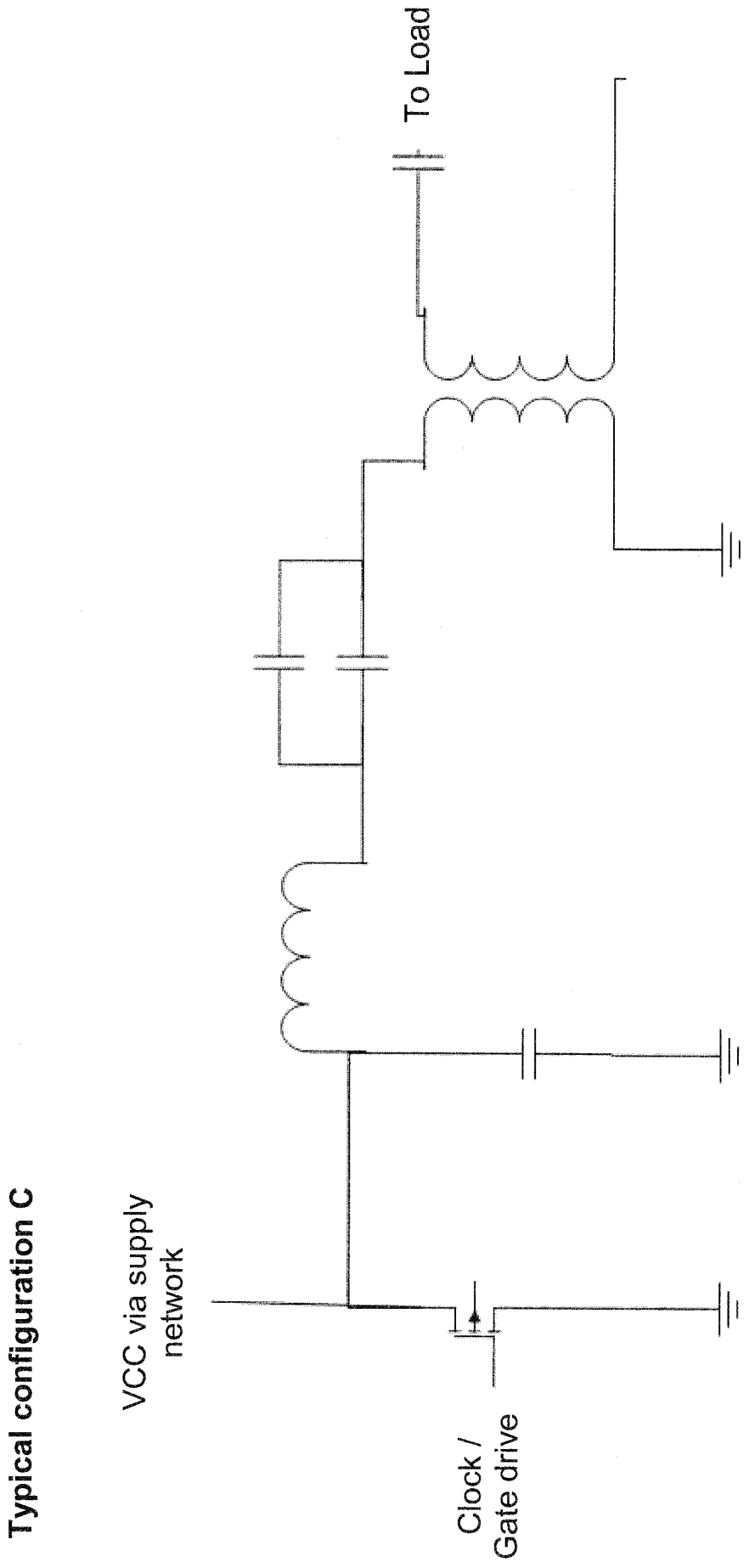

Typical configuration C
VCC via supply network
Clock / Gate drive
To Load

FIG. 82

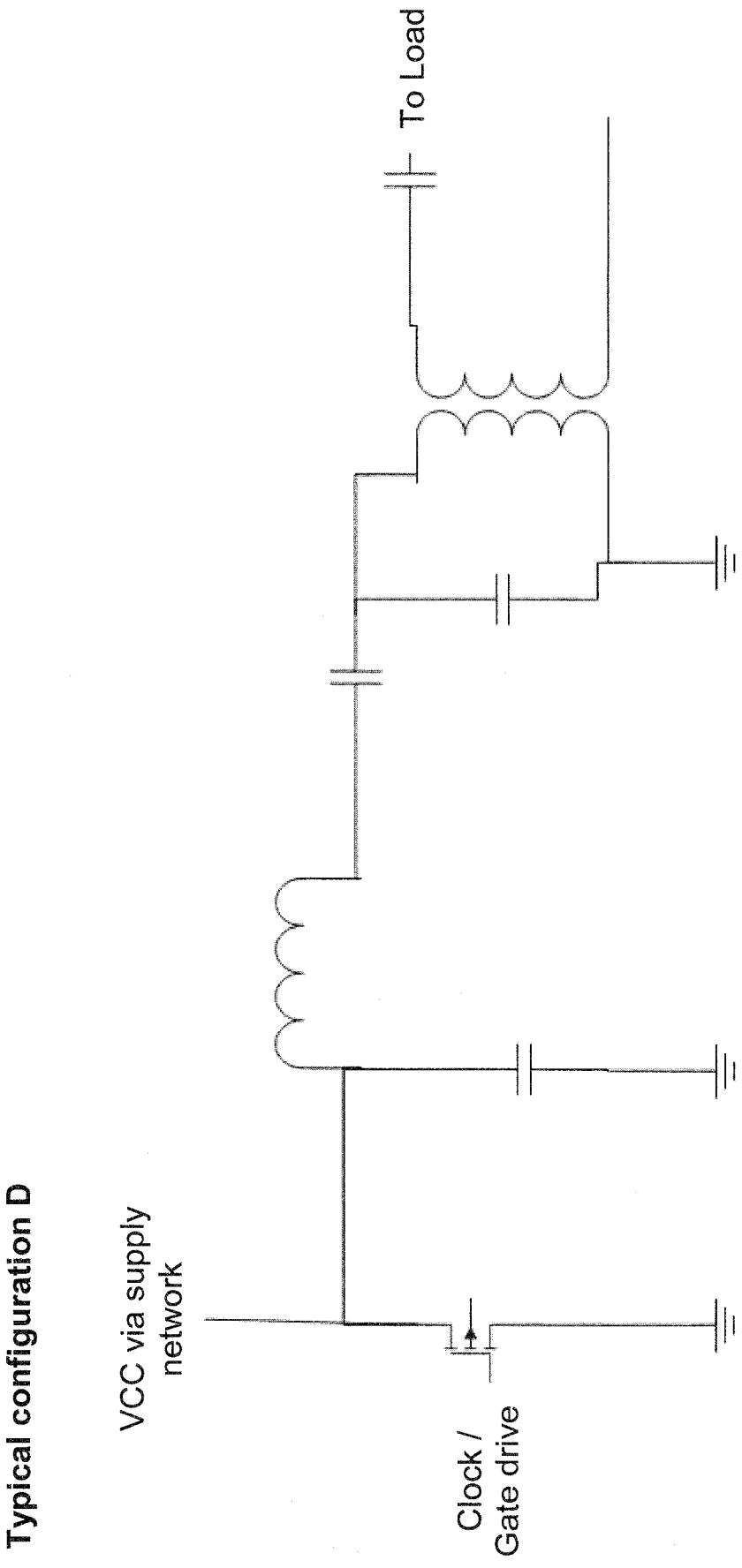

Typical configuration D
VCC via supply network
Clock / Gate drive
To Load

FIG. 83