US 20090160261A1

(19) United States

(12) Patent Application Publication

ELO

(10) Pub. No.: US 2009/0160261 A1

(43) Pub. Date: Jun. 25, 2009

(54) WIRELESS ENERGY TRANSFER

(75) Inventor: Harri Heikki Tapani ELO, Helsinki (FI)

Correspondence Address:
Locke Lord Bissell & Liddell LLP
Attn: IP Docketing
Three World Financial Center
New York, NY 10281-2101 (US)

(73) Assignee: NOKIA CORPORATION, Espoo (FI)

(21) Appl. No.: 11/960,072

(22) Filed: Dec. 19, 2007

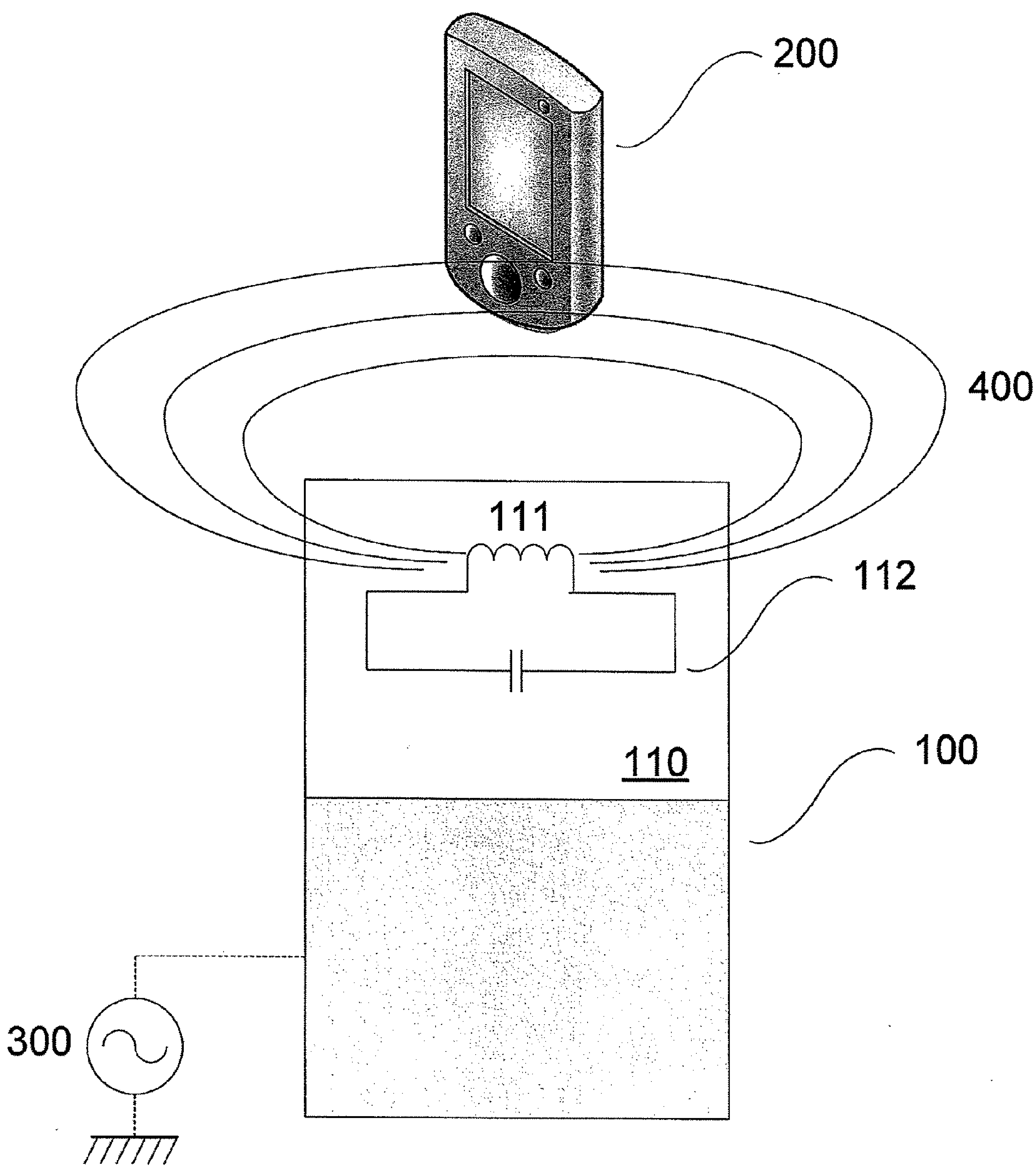
Publication Classification

(51) Int. Cl.
H01F 27/42 (2006.01)

(52) U.S. Cl. 307/104

(57) ABSTRACT

An apparatus comprising monitoring circuitry configured to monitor a resonant frequency of a supply source, a receiving component, and a control unit configured to vary a resonant frequency of said receiving component, wherein the apparatus is configured to vary the resonant frequency of said receiving component in dependence of the resonant frequency of said supply source.



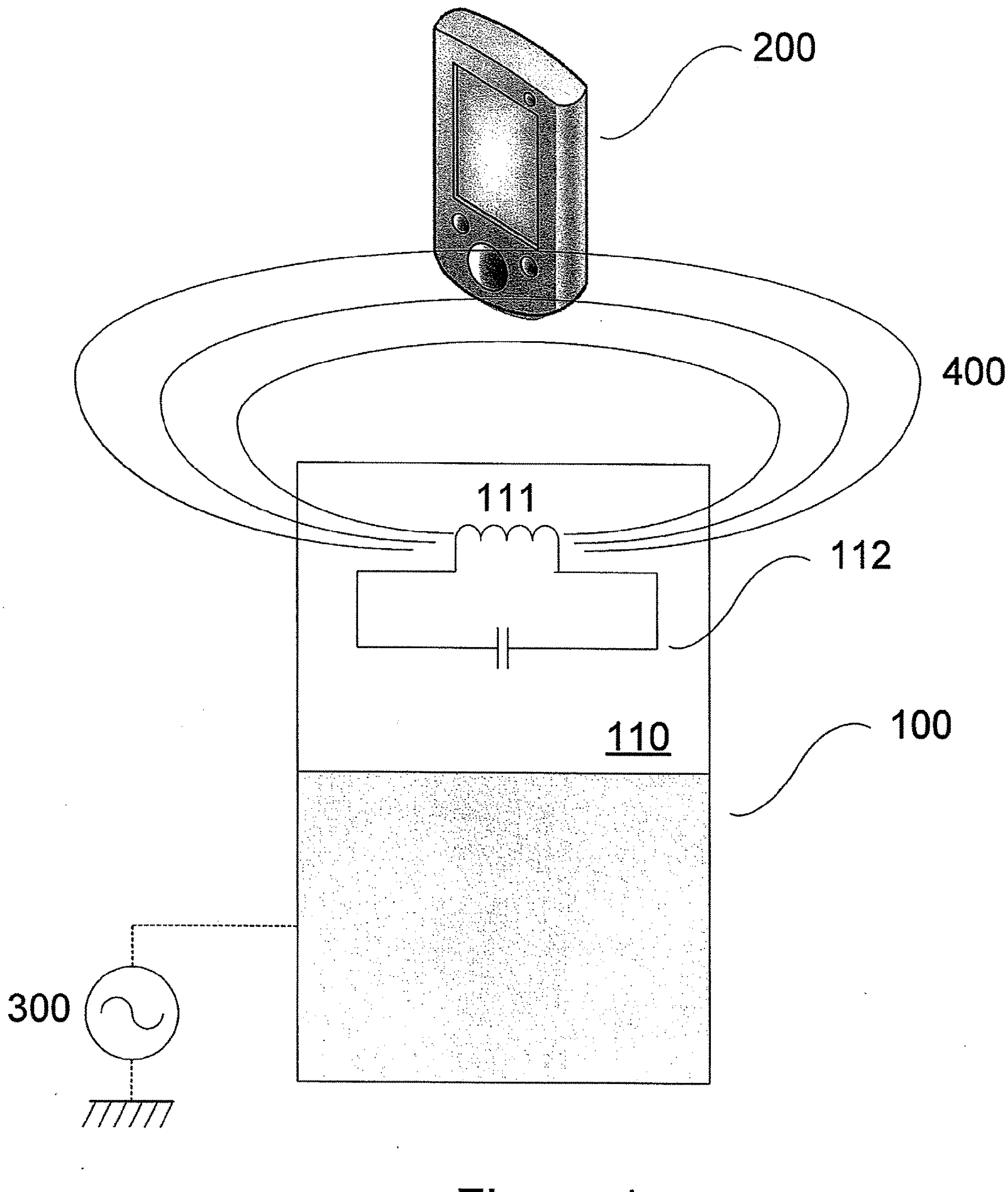


Figure 1

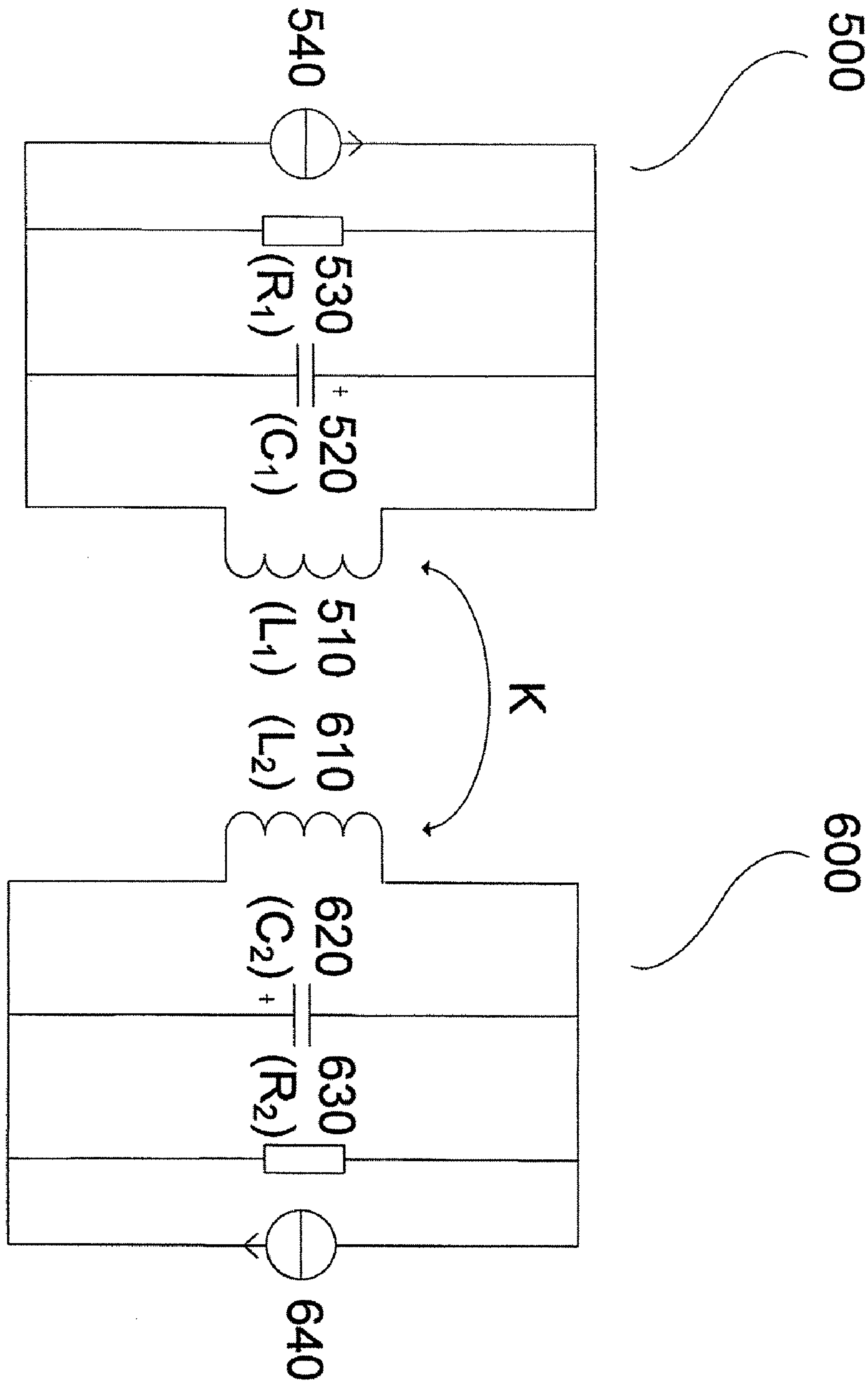


Figure 2

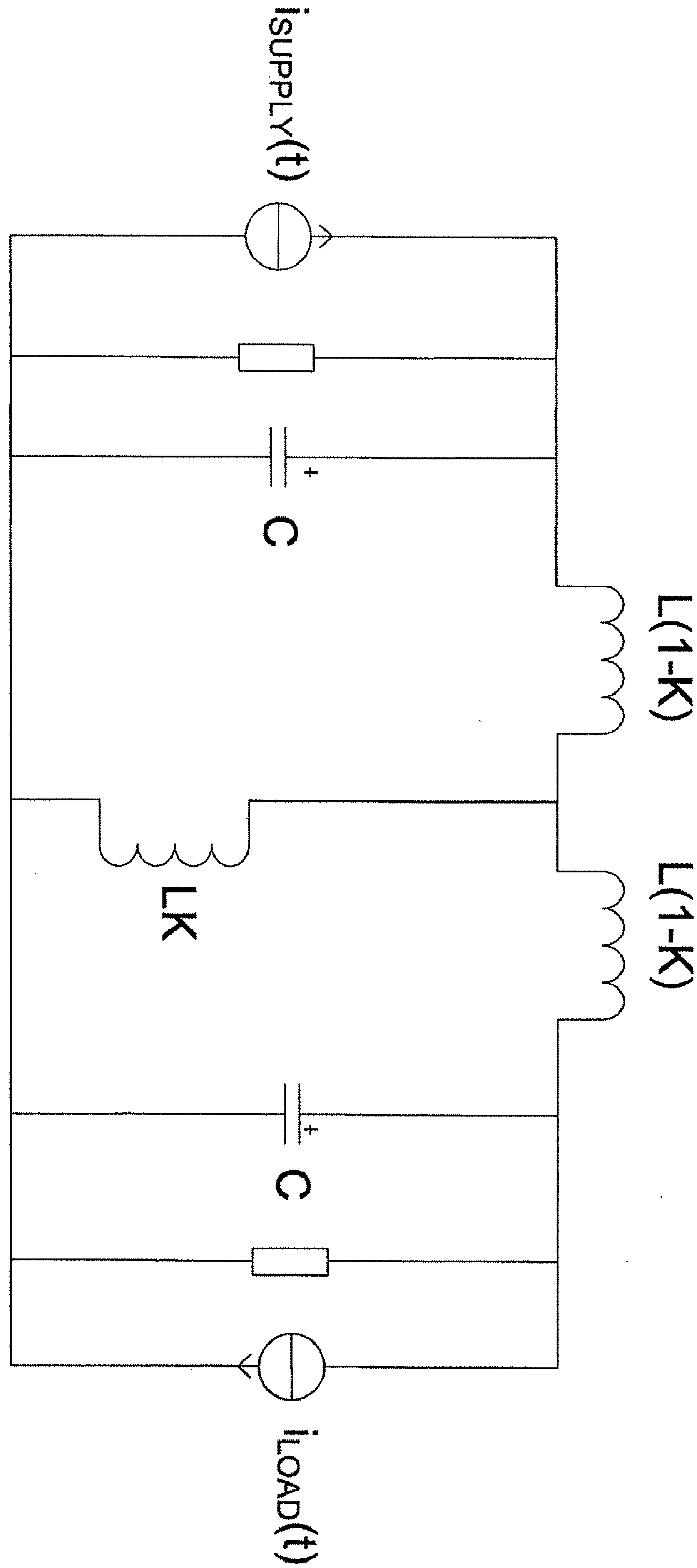


Figure 3

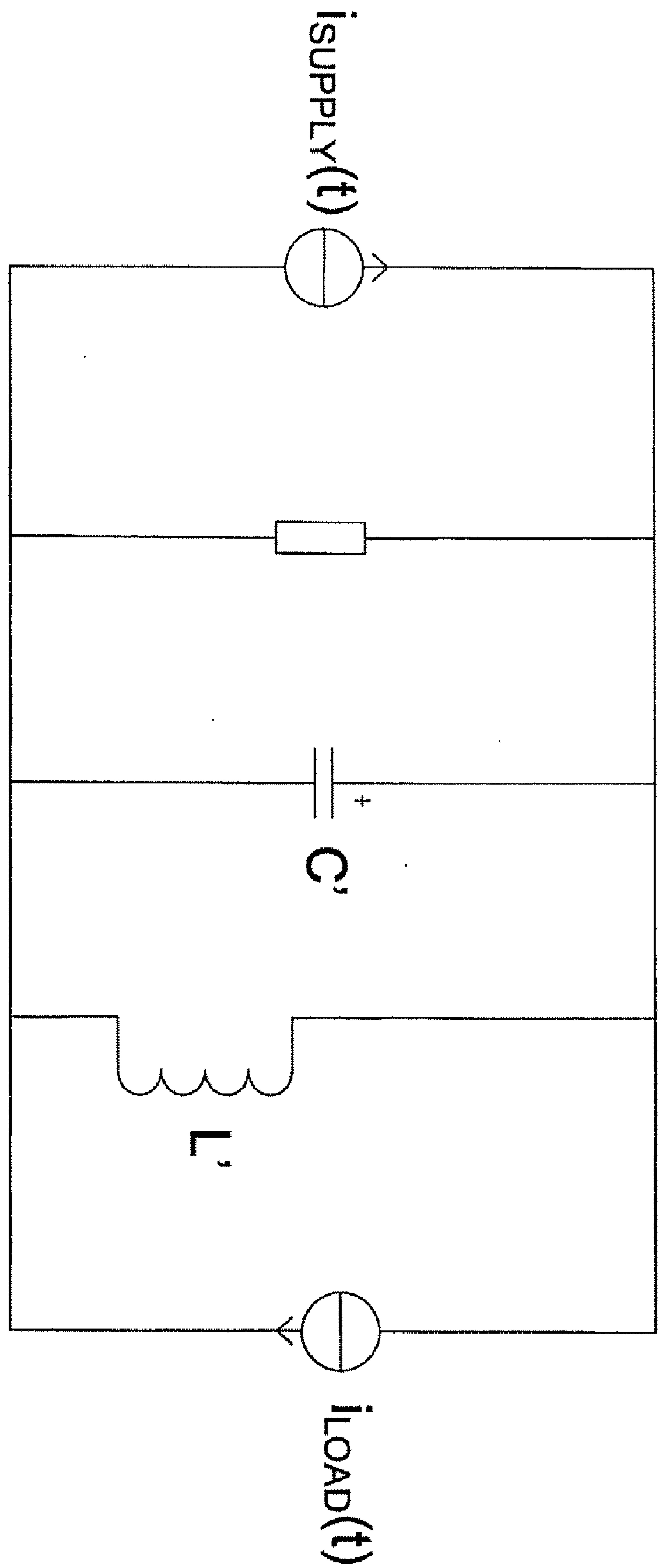


Figure 4

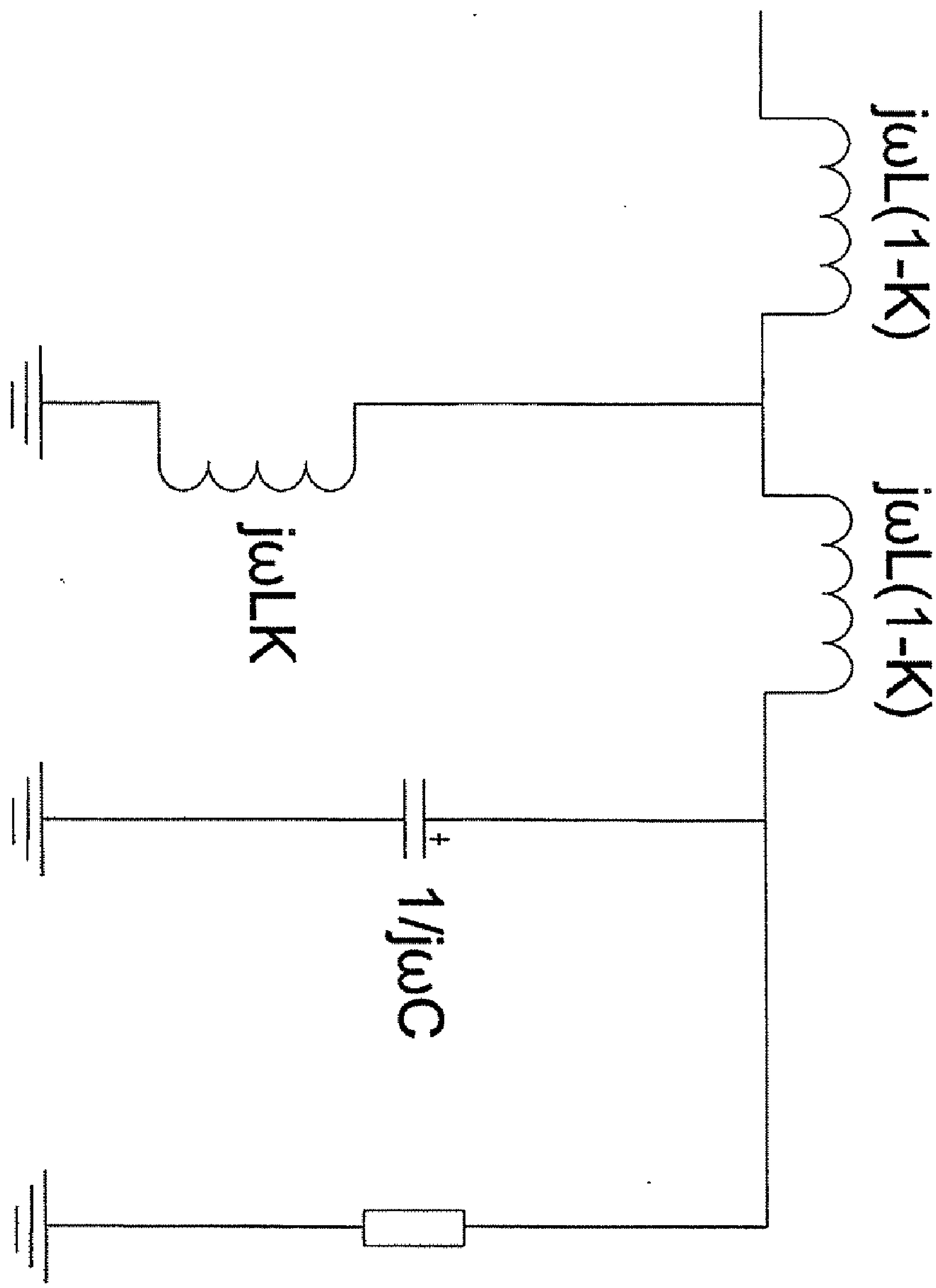


Figure 5

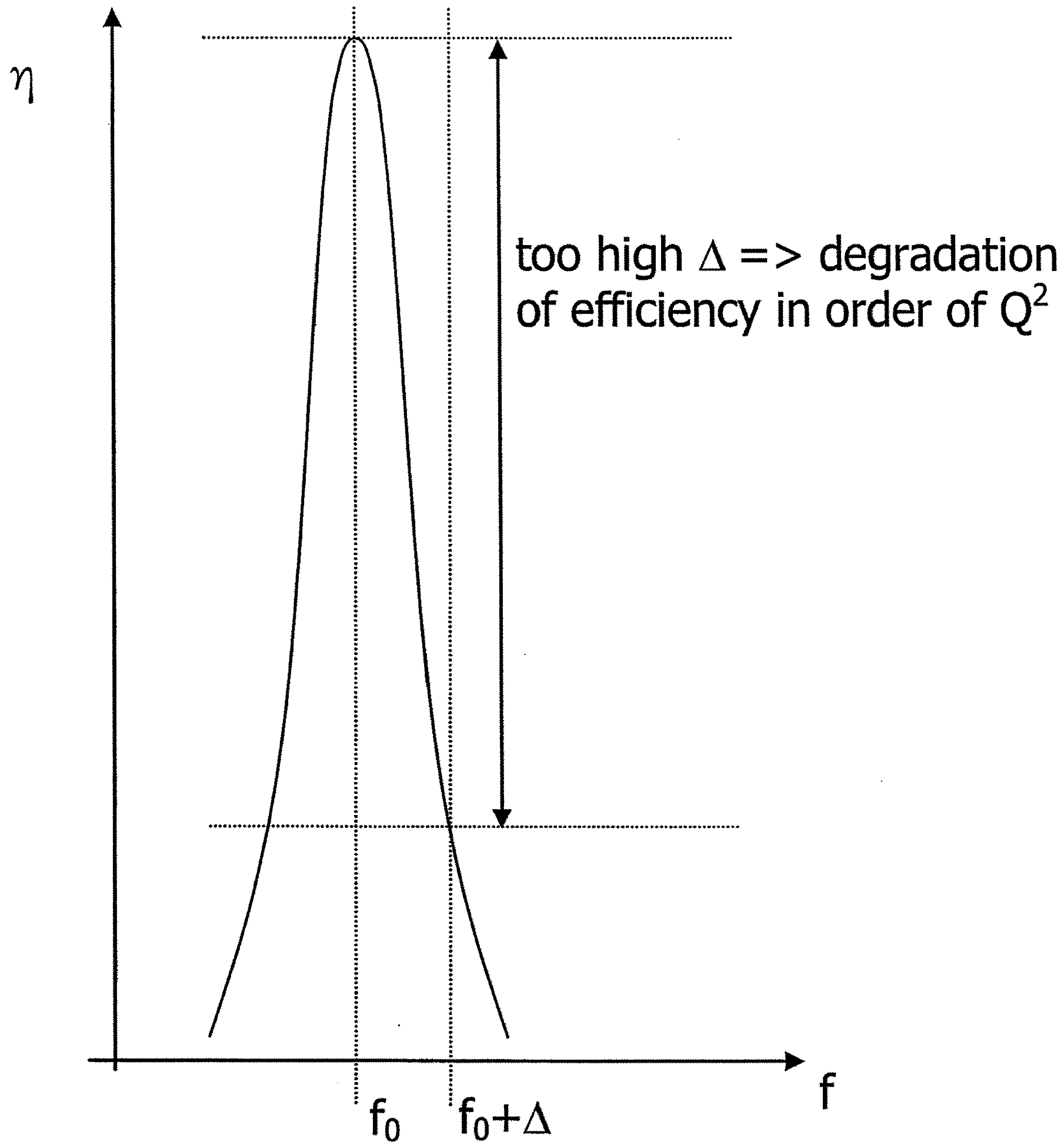


Figure 6

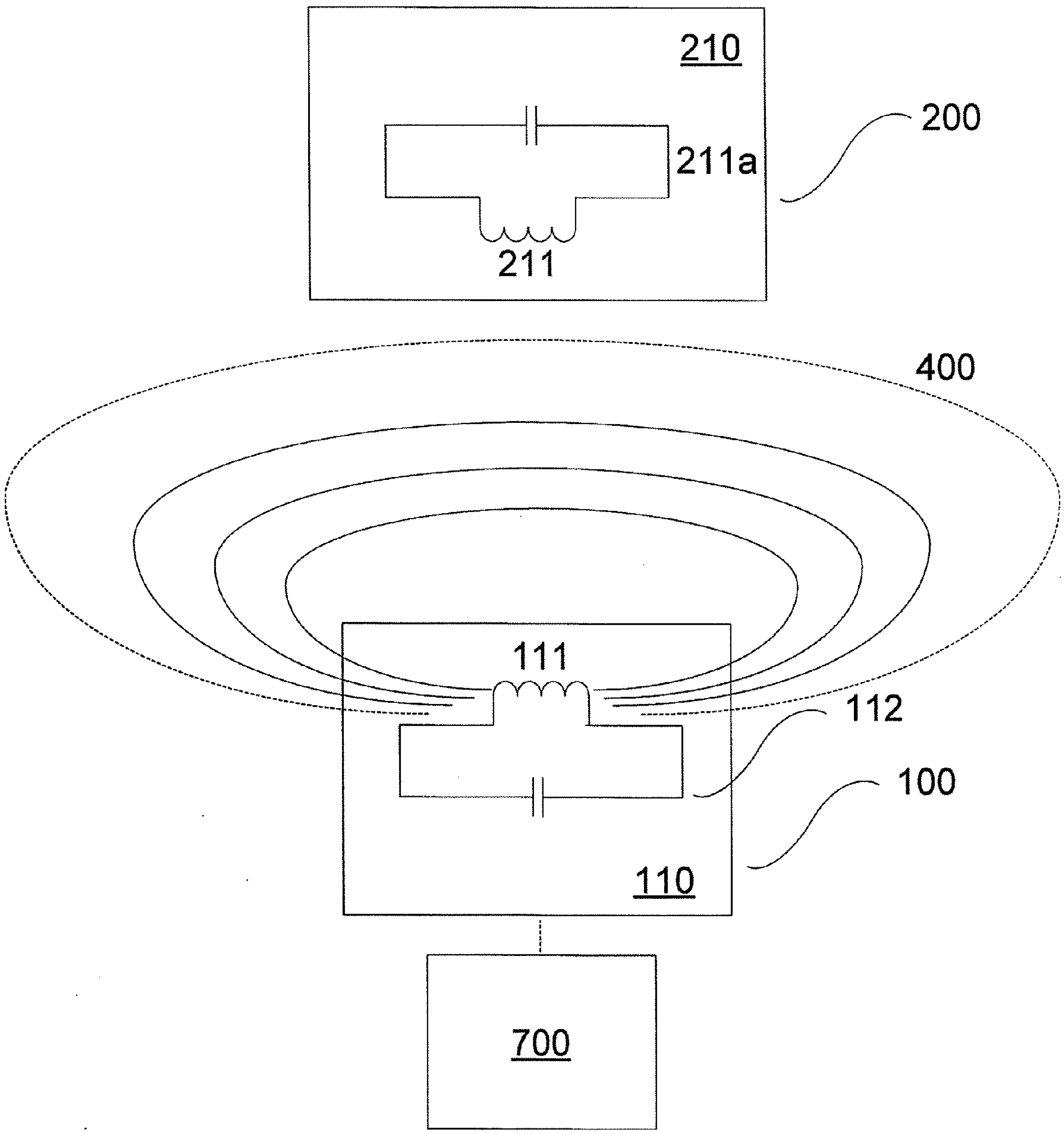


Figure 7

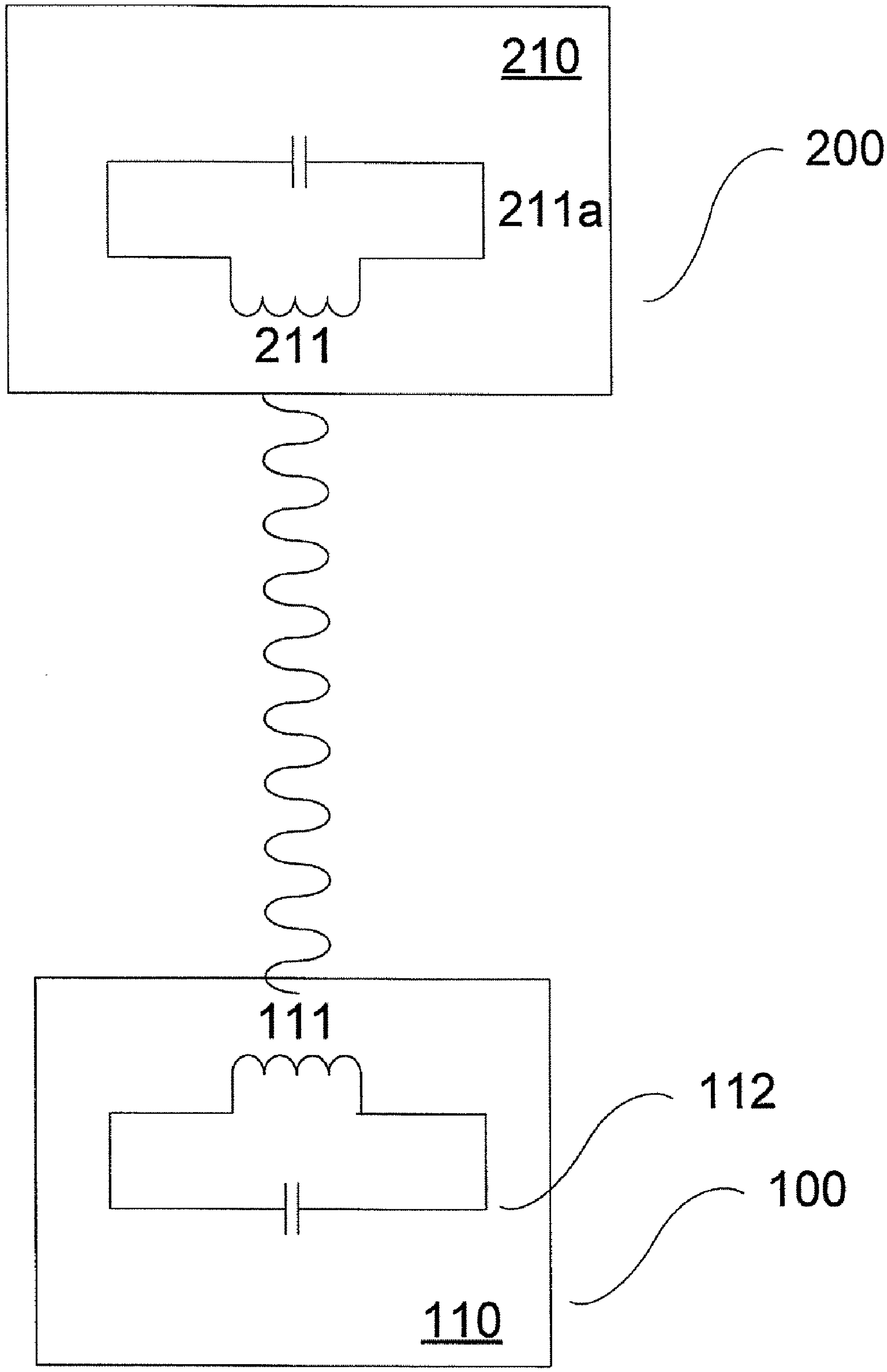


Figure 8

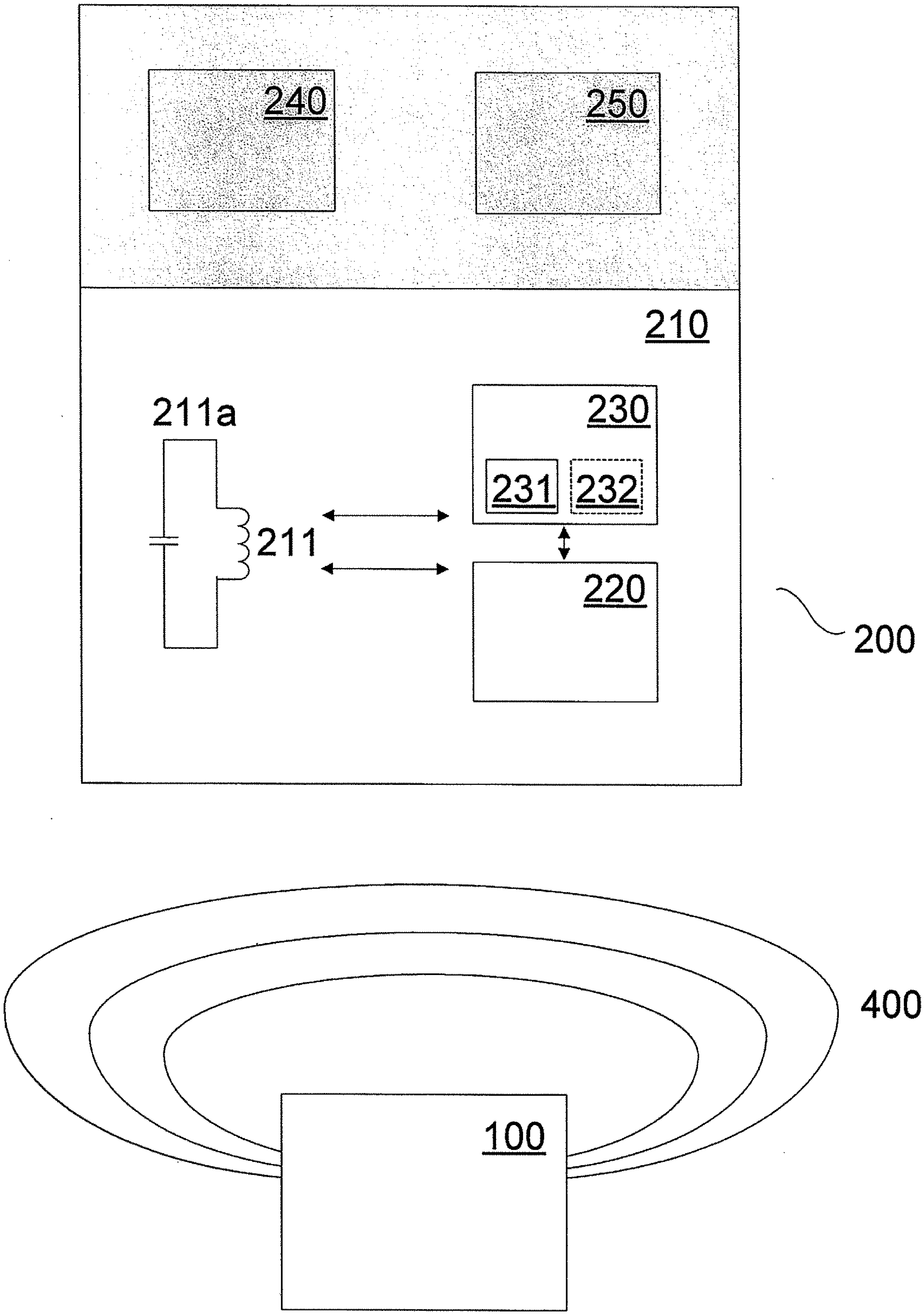


Figure 9

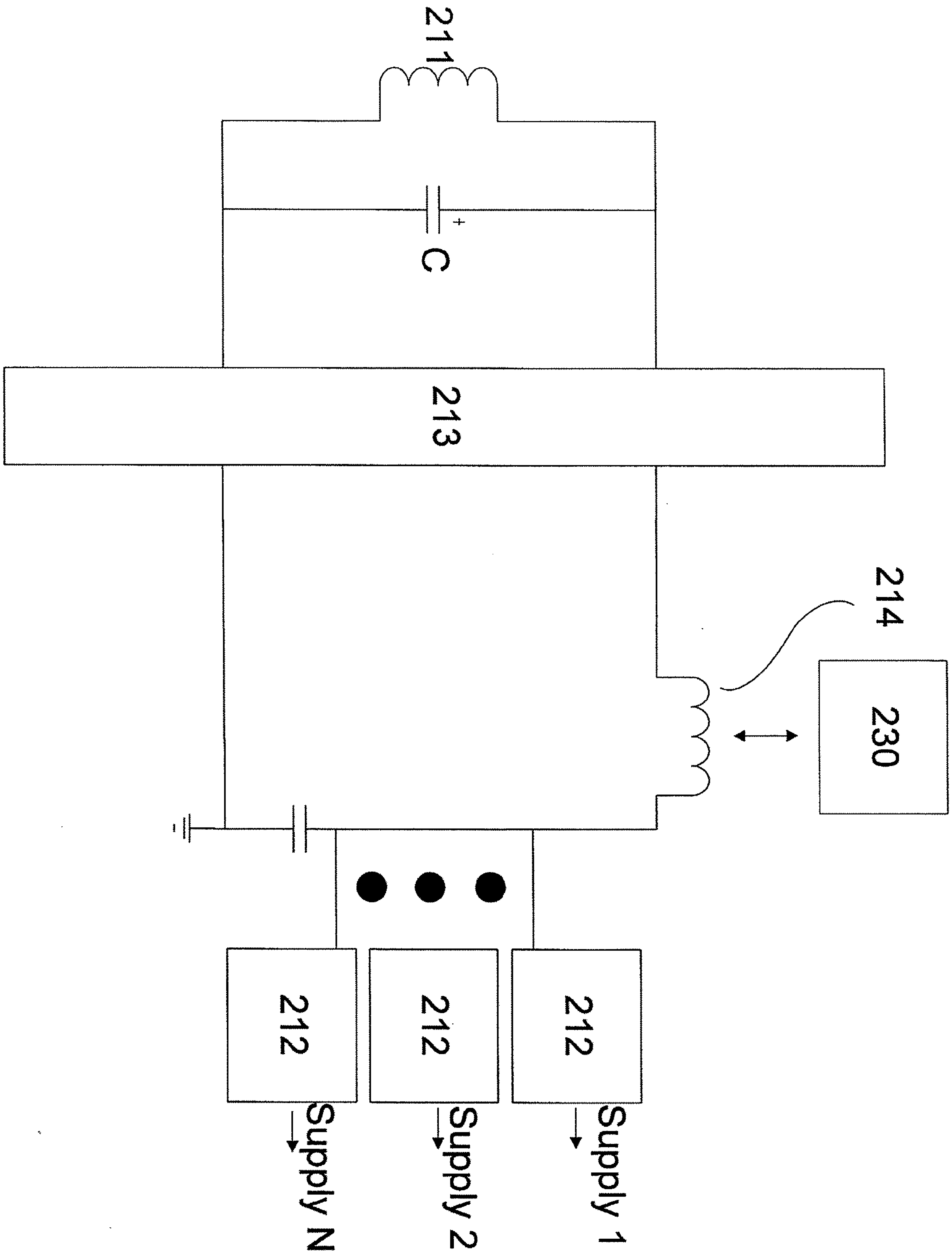


Figure 10

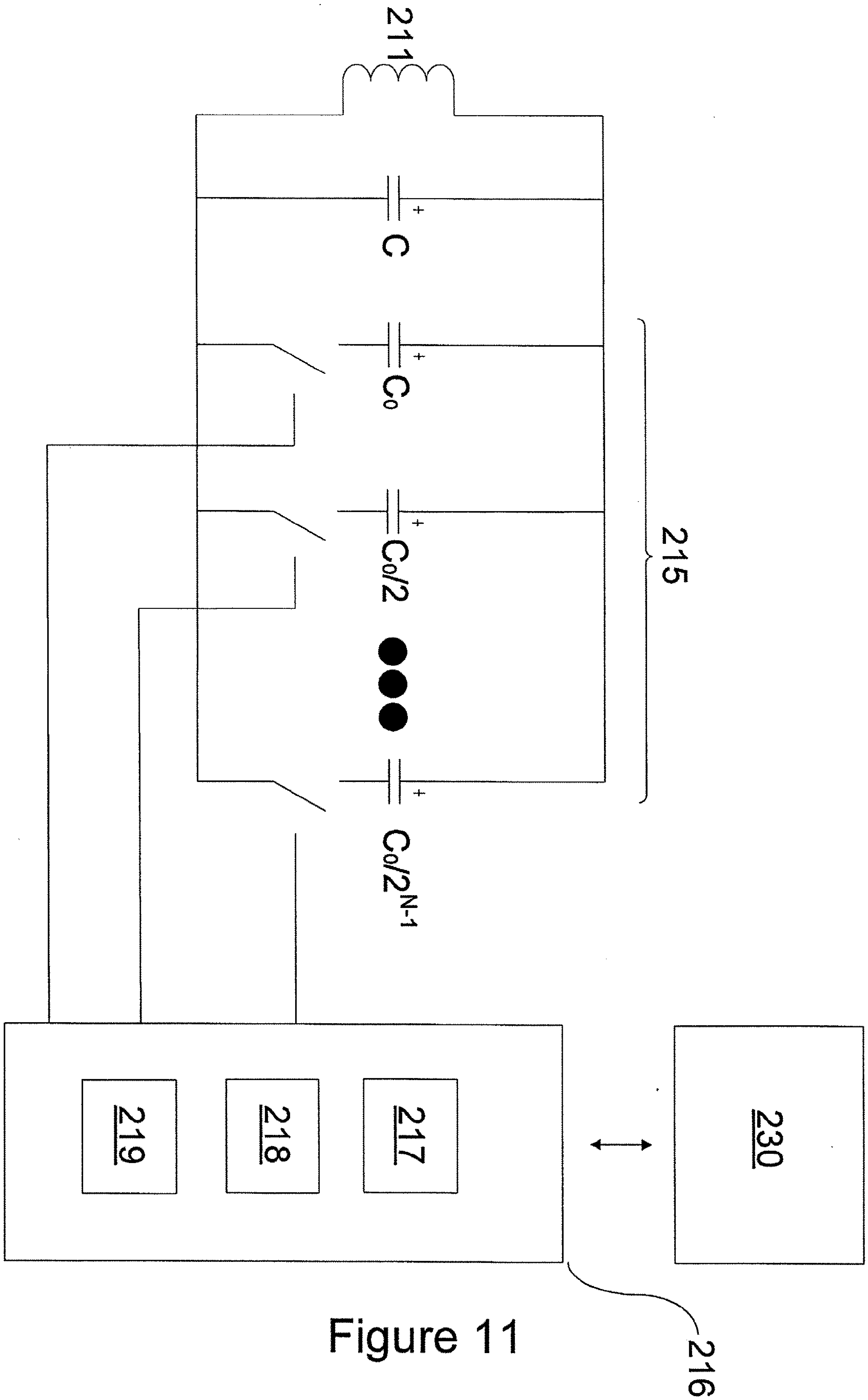


Figure 11

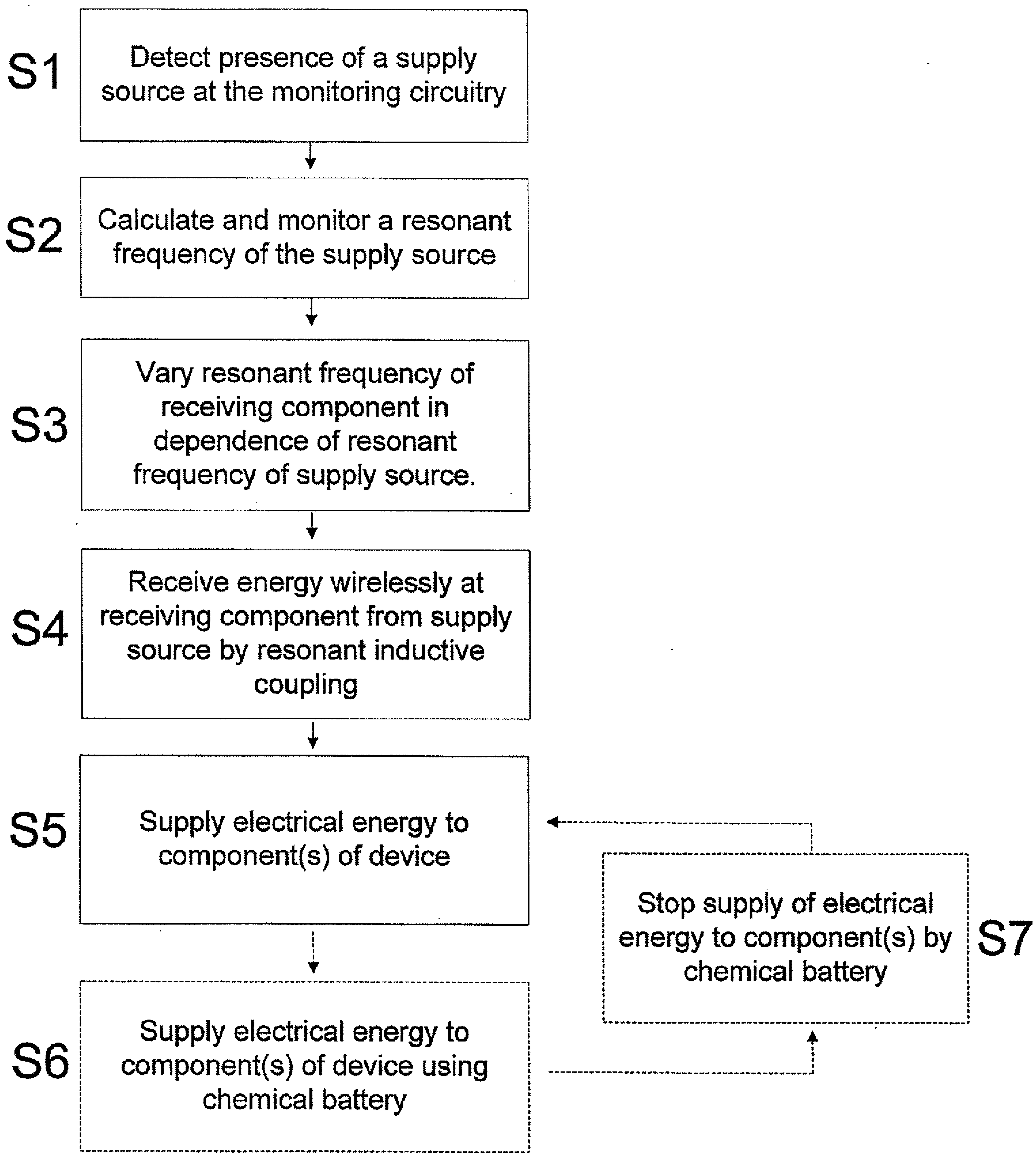

S1
Detect presence of a supply source at the monitoring circuitry
S2
Calculate and monitor a resonant frequency of the supply source
S3
Vary resonant frequency of receiving component in dependence of resonant frequency of supply source.
S4
Receive energy wirelessly at receiving component from supply source by resonant inductive coupling
S5
Supply electrical energy to component(s) of device
S6
Supply electrical energy to component(s) of device using chemical battery
S7
Stop supply of electrical energy to component(s) by chemical battery

Figure 12

WIRELESS ENERGY TRANSFER

FIELD OF THE INVENTION

[0001] The present invention relates to wireless energy transfer, particularly, but not exclusively, to wireless energy transfer between a supply source and a receiving component.

BACKGROUND OF THE INVENTION

[0002] It is common practice for a portable electronic device, for example a mobile telephone or a laptop computer, to be powered by a rechargeable chemical battery. Generally speaking, such a battery is releasably connected to the body of a portable device.

[0003] The use of a battery for supplying power to a portable electronic device is not ideal because the energy storage capacity of a chemical battery is limited. As such, it is necessary for the chemical battery to be recharged at regular intervals.

[0004] In order to provide a means for recharging the battery, the portable device is normally supplied with a charging means for allowing electrical energy to flow from a mains power supply to the rechargeable battery. The charging means is usually in the form of a charger unit, which conventionally comprises an electrical plug for connecting to a mains power supply socket and an electrical cable for connecting the electrical plug to the portable device.

[0005] This is disadvantageous because, if there is no convenient mains power supply socket, as is the case in most outdoor and public environments, the rechargeable battery will run out of power and the portable device will need to be switched off.

[0006] The use of such a charger unit is further disadvantageous in that it requires a physical connection between the portable device and a mains power supply socket. This severely restricts the movement of the portable device during charging, thereby negating the portability of the device.

[0007] Another type of charger unit makes use of the principle of conventional, short-range inductive coupling, which involves the transfer of energy from a primary inductor in a charger unit to a secondary inductor in the portable device. Such charger units are commonly used, for example, for charging rechargeable batteries in electric toothbrushes.

[0008] Chargers utilising this type of conventional inductive coupling are able to transfer power wirelessly and hence do not require a physical connection between the mains supply and the portable device. However, the maximum distance over which effective power transfer can be achieved is limited to distances of the same order of magnitude as the physical dimensions of the inductors. For portable electronic devices, the dimensions of the inductor are limited by the size of the portable electronic device. Accordingly, in general, at distances of anything greater than a few centimetres, the efficiency of energy transfer between primary and secondary inductors is too small for this type of power transfer to be viable.

[0009] Therefore, as with the electrical cable discussed above, power transfer using conventional inductive coupling requires the charger unit and the portable device to be in very close proximity, meaning that the movement of the portable device is severely restricted.

[0010] In addition to the above problems associated with recharging, the use of a chemical battery as a power supply presents a number of further disadvantages. For example, rechargeable chemical batteries have a limited lifespan and tend to experience a decrease in their maximum storage capacity as they get older. Furthermore, chemical batteries are relatively heavy, meaning that the inclusion of a chemical battery in a portable device generally adds a significant percentage to the device's overall weight. If the device's reliance on the chemical battery could be reduced, then it would be possible for portable electronic devices such as mobile telephones to become significantly lighter.

SUMMARY OF THE INVENTION

[0011] According to a first example of the invention, there is provided an apparatus comprising monitoring circuitry configured to monitor a resonant frequency of a supply source, a receiving component, and a control unit configured to vary a resonant frequency of said receiving component, wherein the apparatus is configured to vary the resonant frequency of said receiving component in dependence of the resonant frequency of said supply source

[0012] The receiving component of the apparatus described in the immediately preceding paragraph may be adapted to receive energy wirelessly from the supply source by resonant inductive coupling.

[0013] The receiving component of the apparatus described in either of the immediately preceding paragraphs may comprise an adaptive receiving component having a variable resonant frequency.

[0014] The apparatus described in any of the three immediately preceding paragraphs may be configured to match the resonant frequency of said receiving component with the resonant frequency of said supply source.

[0015] A voltage may be induced in the receiving component of the apparatus described in any of the four immediately preceding paragraphs by a magnetic field generated by the supply source, and the control unit may be configured to vary the resonant frequency of the receiving component to match the resonant frequency of the supply source.

[0016] The apparatus described in any of the four immediately preceding paragraphs may further comprise a plurality of electrical components, and the apparatus may be configured to supply electrical energy to at least one of these electrical components.

[0017] The apparatus described in the immediately preceding paragraph may further comprise a battery for supplying electrical energy to at least one of the electrical components when energy is not being received from the supply source.

[0018] The apparatus described in any of the preceding paragraphs may comprise a portable electronic device.

[0019] The apparatus described in any of the preceding paragraphs may comprise a mobile telephone, personal digital assistant (PDA) or laptop computer.

[0020] According to a second example of the invention, there is provided an apparatus comprising means for detecting a presence of a supply source, means for monitoring a resonant frequency of said supply source, and means for varying a resonant frequency of a receiving component in dependence of the resonant frequency of said supply source.

[0021] According to a third example of the invention, there is provided an apparatus comprising a receiving component having variable resonance characteristics for receiving energy wirelessly from a supply source, wherein the resonance characteristics of the receiving component may be varied to match resonance characteristics of the supply source to increase the efficiency at which energy is received from the supply source.

[0022] The apparatus described in the immediately preceding paragraph may further comprise monitoring circuitry for detecting and monitoring the resonance characteristics of the supply source.

[0023] The receiving component of the apparatus described in either of the two immediately preceding paragraphs may comprise an adaptive receiving component having variable resonance characteristics and the apparatus may further comprise a control unit configured to automatically vary the resonance characteristics of the adaptive receiving component to match the resonance characteristics of the supply source.

[0024] The apparatus described in any of the three immediately preceding paragraphs may further comprise one or more electrical components and the receiving component may be coupled to power supply circuitry to supply power to at least one of these electrical components.

[0025] The apparatus described in the immediately preceding paragraph may further comprise a battery for supplying electrical energy to at least one of the electrical components when energy is not being received from the supply source.

[0026] The apparatus described in any of the five immediately preceding paragraphs may comprise a portable electronic device.

[0027] The apparatus described in any of the six immediately preceding paragraphs may comprise a mobile telephone, personal digital assistant (PDA) or laptop computer.

[0028] According to a fourth example of the invention, there is provided a system comprising a supply source, and an apparatus comprising monitoring circuitry configured to monitor a resonant frequency of the supply source, a receiving component, and a control unit configured to vary a resonant frequency of said receiving component, wherein the apparatus is configured to vary the resonant frequency of said receiving component in dependence of the resonant frequency of said supply source.

[0029] According to a fifth example of the invention, there is provided a method comprising detecting a presence of a supply source, monitoring a resonant frequency of said supply source, and varying a resonant frequency of a receiving component in dependence of the resonant frequency of said supply source.

[0030] The method described in the immediately preceding paragraph may further comprise matching the resonant frequency of said receiving component with the resonant frequency of said supply source.

[0031] The method described in either of the two immediately preceding paragraphs may further comprise receiving energy wirelessly at the receiving component from the supply source by resonant inductive coupling.

[0032] The receiving component of the method described in any of the three immediately preceding paragraphs may comprise an adaptive receiving component having a variable resonant frequency and the method may further comprise inducing a voltage in the adaptive receiving component using a magnetic field generated by the supply source, and varying the resonant frequency of the adaptive receiving component to match the resonant frequency of the supply source.

[0033] The method described in any of the four immediately preceding paragraphs may further comprise supplying electrical energy to an electrical apparatus.

[0034] The method of the immediately preceding paragraph may further comprise supplying energy to at least one component of an electrical device from a battery when energy is not being received at the receiving component from the supply source.

[0035] The method of the paragraph six paragraphs above this one may further comprise receiving energy at the receiving component from the supply source by resonant inductive coupling, and supplying energy received by resonant inductive coupling to at least one component of an electrical device.

[0036] According to a sixth example of the invention, there is provided a computer program stored on a storage-medium which, when executed by a processor, is arranged to perform a method comprising detecting a presence of a supply source, monitoring a resonant frequency of said supply source, and varying a resonant frequency of a receiving component in dependence of the resonant frequency of said supply source.

BRIEF DESCRIPTION OF THE DRAWINGS

[0037] In order that the invention may be more fully understood, embodiments thereof will now be described by way of illustrative example with reference to the accompanying drawings in which:

[0038] FIG. **1** is a diagram showing a flow of energy from a feeding device to a portable electronic device.

[0039] FIG. **2** is a circuit diagram of primary and secondary RLC resonator circuits with coupling coefficient K.

[0040] FIG. **3** is a circuit diagram of an equivalent transformer circuit for the first and second RLC resonator circuits shown in FIG. **2**.

[0041] FIG. **4** is a circuit diagram of a reduced circuit of the equivalent transformer circuit shown in FIG. **3**.

[0042] FIG. **5** shows the impedances of the individual components of the equivalent transformer circuit shown in FIG. **3**.

[0043] FIG. **6** is a graphical illustration of the relationship between the efficiency of power transfer between two resonators and the difference between the resonators' resonant frequencies.

[0044] FIG. **7** is an illustration of a wireless transfer of energy from a feeding device to a portable electronic device at mid-range using conventional inductive coupling.

[0045] FIG. **8** is an illustration of a wireless transfer of energy from a feeding device to a portable electronic device at mid-range using resonant inductive coupling.

[0046] FIG. **9** is a schematic diagram of a portable electronic device, including a reactance and monitoring circuitry.

[0047] FIG. **10** is a schematic diagram showing components of a wireless power transfer apparatus in a portable electronic device.

[0048] FIG. **11** is a schematic diagram showing an adaptive receiving component in a wireless power transfer apparatus of a portable electronic device.

[0049] FIG. **12** is a flow diagram showing steps associated with the initiation of wireless power transfer by resonant inductive coupling.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0050] Referring to FIG. **1**, a feeding device **100** comprises a supply source **110** for supplying power wirelessly to a portable electronic device **200**. The supply source **110** comprises a primary reactance, for example comprising a primary inductor **111**, adapted to receive an electrical current from an electrical circuit **112**. The electrical circuit **112** may be optionally connected to a power supply, for example comprising a mains power supply **300**, for supplying electrical current to the electrical circuit **112**. The primary inductor **111** has an inductance L_{111}, Q-factor Q_{111} and resonant frequency $f_{0(111)}$.

[0051] As will be understood by a skilled person, a flow of electrical current through the primary inductor **111** causes a magnetic field **400** to be created around the primary inductor **111**. As is shown by FIG. **1**, the magnetic field **400** created around the inductor **111** penetrates the exterior of the feeding device **100**, meaning that the effects of the magnetic field **400** may be experienced in the surrounding environment. For instance, the magnetic field **400** may be used to induce a voltage in a receiving component comprising a secondary reactance, such as a secondary inductor in an electrical device. This is the principle upon which wireless energy transfer through conventional short-range inductive coupling is based. However, efficient wireless energy transfer by such conventional short-range inductive coupling is limited to distances of the same order of magnitude as the physical dimensions of the inductors involved in the energy transfer.

[0052] As is fully described below, the portable electronic device **200** is adapted to receive energy wirelessly by an alternative type of inductive coupling. This alternative type of inductive coupling will be referred to as resonant inductive coupling.

[0053] Using resonant inductive coupling, is it possible to efficiently transfer energy over longer distances than over those possible with conventional inductive coupling. This means that resonant inductive coupling provides a greater degree of freedom and flexibility than conventional inductive coupling when used for the transfer of energy. As is described in more detail below, resonant inductive coupling is based on inductive coupling in which the resonant frequency f_0 of a supply source and the resonant frequency f_0 of a receiving component are equal to one another.

[0054] More specifically, if the resonant frequency f_0 associated with a primary reactance, for example the resonant frequency $f_{0(111)}$ associated with the inductor **111** in the feeding device **100**, is equal to the resonant frequency f_0 associated with a secondary reactance, for example a receiving component comprising a secondary inductor in a portable electronic device **200**, placed in a magnetic field generated by the primary reactance, efficient wireless energy transfer between the primary and secondary reactances can be achieved at longer ranges than is possible with conventional inductive coupling.

[0055] For example, wireless energy transfer with an efficiency of tens of percent may be achieved by resonant inductive coupling over distances at least one order of magnitude greater than the physical dimensions of the inductors being used for the transfer.

[0056] A general example of wireless energy transfer between two inductors by resonant inductive coupling is given below.

[0057] Referring to FIG. **2**, there are shown primary and secondary RLC resonator circuits **500**, **600**. The primary RLC circuit **500** comprises a first inductor (L_1) **510**, a first capacitor (C_1) **520** and a first resistor (R_1) **530**. The secondary RLC circuit **600** comprises a second inductor (L_2) **610**, a second capacitor (C_2) **620** and a second resistor (R_2) **630**. In this example, $L_1=L_2$ and $C_1=C_2$.

[0058] The primary RLC circuit **500** is connected to a power source, comprising a time-dependent current source ($i_{SUPPLY}(t)$) **540**. The time-dependency of the current source **540** is such that the current may take the form of a sine wave, tuned to the resonant frequency

$$f_0 = \frac{1}{2\pi\sqrt{L_1C_1}} = \frac{1}{2\pi\sqrt{L_2C_2}}$$

of both the first and second RLC circuits **500**, **600**.

[0059] The second RLC circuit **600** is connected to a load, represented in FIG. **2** as a DC current source (i_{LOAD}) **640**. The current from the DC current source **640** is zero when energy is not being transferred between the first and second RLC circuits **500**, **600**.

[0060] The Q-values associated with the first and second resonator circuits **500**, **600** are represented by the first and second resistors **530**, **630**. As is explained in more detail below, the magnitude of the Q-values of the resonator circuits **500**, **600** is proportional to the efficiency of energy transfer between the circuits **500**, **600**.

[0061] In this general example, the inductors **510**, **610** are separated by a distance approximately one order of magnitude greater than the physical dimensions of the inductors **510**, **610** themselves. At this range, the coupling coefficient K between the inductors **510**, **610** is small, for example 0.001 or less, meaning that any attempt to transfer energy between the resonator circuits **500**, **600** by conventional inductive coupling would be extremely inefficient.

[0062] FIG. **3** shows an equivalent transformer circuit for the first and second RLC resonator circuits **500**, **600**. When the frequency of the time-dependent current source **540** is not equal to the resonant frequency f_0 of the second RLC resonator circuit **600**, the second resonator circuit is bypassed due to negligible inductance LK. As such, very little or no power is transferred to the load. However, when the conditions for resonant inductive coupling are met, this situation is reversed as is explained below.

[0063] A first condition for energy transfer by resonant inductive coupling is that the Q-values (represented by the resistors **530**, **630**) of the resonator circuits **500**, **600** are very high, for example one hundred or more. A second condition for energy transfer by resonant inductive coupling is that the resonant frequencies f_0 of the circuits **500**, **600** are equal to one another. When these conditions are met, and current is supplied by the current source **540** at

$$f_0 = \frac{1}{2\pi\sqrt{L_1C_1}},$$

current in the first inductor **510** is routed via the second inductor **610**. Under these conditions, the inductance LK in the equivalent transformer circuit shown in FIG. **3** is tuned with the secondary resonator circuit. As such, the equivalent transformer circuit shown in FIG. **3** can be reduced to the circuit of a single electrical resonator, as shown by FIG. **4**. There is no limit on the number of secondary resonator circuits which could receive current from a primary resonator circuit in this way.

[0064] The impedances of the individual components of the equivalent transformer circuit shown in FIG. **3** are shown in FIG. **5**. The impedance Z of the reduced circuit can thus be calculated as follows:

$$Z = \frac{j\omega LK \cdot Z_{secondary}}{j\omega LK + Z_{secondary}}$$

[0065] Assuming the Q-value of the secondary resonator circuit **600** is high, $Z_{secondary}$ may be written as:

$$Z_{secondary} = j\omega L(1-K) + 1/j\omega C$$

$$\therefore$$

$$\begin{aligned} Z &= \frac{j\omega LK \cdot (j\omega L(1-K) + 1/j\omega C)}{j\omega LK + (j\omega L(1-K) + 1/j\omega C)} \\ &= \frac{j\omega LK \cdot (j\omega L(1-K) - j\omega L)}{j\omega LK + (j\omega L(1-K) - j\omega L)} \\ &= \frac{j\omega LK \cdot (-j\omega LK)}{j\omega LK - j\omega LK} \end{aligned}$$

$\therefore |Z| \rightarrow \infty$ as the conditions for resonant inductive coupling are reached.

[0066] In this way, a secondary resonator circuit may be tuned so as to receive energy by resonant inductive coupling from any primary resonator circuit.

[0067] FIG. **6** illustrates a general relationship between the efficiency of wireless energy transfer η through inductive coupling between primary and secondary reactances separated by a distance one order of magnitude larger than the physical dimensions of the reactances. The efficiency of wireless energy transfer η is plotted on the vertical axis using a logarithmic scale, and the difference in resonant frequency f_0 between the reactances is plotted on the horizontal axis. This relationship is applicable to, for example, wireless energy transfer between the primary inductor **111** of the feeding device **100** and a secondary inductor **211** of a portable device **200** shown in FIG. **7**.

[0068] As can be seen, the efficiency of wireless energy transfer η between the reactances is at a maximum when the resonant frequencies f_0 associated with the reactances are equal to one another. Moreover, the efficiency of wireless energy transfer η between the reactances decreases markedly as the difference between the resonant frequencies f_0 associated with the reactances increases. Accordingly, as discussed above, in order to transfer energy at the maximum possible efficiency it is preferable for the reactances to have resonant frequencies f_0 which are as close to each other as possible. Ideally, the resonant frequencies f_0 should be identical.

[0069] In addition, as previously discussed, the efficiency of energy transfer between primary and secondary reactances is proportional to the magnitude of the Q-values associated with the reactances; for a high efficiency of energy transfer, the magnitude of the Q-values should be large. For example, in the case of the primary and secondary inductors **111**, **211** discussed above in relation to the transfer of energy from the feeding device **100** to the portable device **200**, efficient energy transfer may be achieved with Q-values Q_{111}, Q_{211} in the order of **100**. Furthermore, the relative difference between the resonant frequencies $f_{0(111)}$, $f_{0(211)}$ associated with the inductors **111**, **211** should be less that the reciprocal of their associated Q-values. At relative differences greater than the reciprocal of the Q-values, the efficiency of energy transfer decreases by $1/Q^2$.

[0070] FIGS. **7** and **8** illustrate the difference between conventional inductive coupling and resonant inductive coupling when the distance between reactances, for example the primary and secondary inductors **111**, **211**, is one order of magnitude greater than the reactances' physical dimensions. Referring to FIG. **7**, with conventional inductive coupling, i.e. when the difference between the resonant frequencies associated with the inductors **111**, **211** is outside of the limits discussed above, only a negligible amount of energy in the magnetic field **400** is passed from the primary inductor **111** to the secondary inductor **211** in the portable device **200**. In contrast, referring to FIG. **8**, when the resonant frequencies f_0 associated with the inductors **111**, **211** are matched, energy is able to tunnel by resonant inductive coupling from the primary inductor **111** in the feeding device **100** to the secondary inductor **211** in the portable electronic device **200** via the magnetic field **400**.

[0071] For the purposes of simplicity and clarity, the above example discusses the transfer of energy from a primary inductor **111** to a single secondary inductor **211**. However, alternatively, energy can be transferred from the primary inductor **111** to a plurality of secondary inductors **211** all being associated with the same resonant frequency f_0, potentially enabling multiple portable devices **200** to receive energy wirelessly from a single feeding device **100**.

[0072] In this way, feeding devices **100** are able to supply energy to portable electronic devices **200** over mid-ranges, for example several metres, in environments in which it is not convenient to install mains power sockets. As an example, in a similar manner to the installation of wireless LANS in cafés and restaurants, a network **700** of feeding devices **100** could be installed throughout a public space to provide members of the public with a power supply for their portable electronic devices **200**. Such a public space could be, for example, a café, restaurant, bar, shopping mall or library. Alternatively, feeding devices may be installed in private spaces such as, for example, the interior of a person's car or home.

[0073] In order to maximise the potential of such a network **700** of feeding devices **100**, it is preferable that the feeding devices **100** have the capacity to supply energy to as many portable devices **200** as possible. One way in which this could be achieved is to implement a degree of standardization in the properties of the reactances, for example the primary and secondary inductors **111**, **211**, used in the feeding devices **100** and portable electronic devices **200**. In particular, it would be preferable if the resonant frequency f_0 associated with the primary reactance in each feeding device **100** of the network **700** was the same. This would enable manufacturers of portable devices **200** and other electrical devices to equip their devices with secondary reactances associated with the same standardized resonant frequency f_0.

[0074] A skilled person will appreciate, however, that due to manufacturing tolerances, the mass production of inductors to a degree of accuracy in which all the inductors are associated with exactly the same resonant frequency f_0 may be difficult to achieve. This will lead to variations in both the resonant frequencies f_0 of feeding devices **100**, and to variations in the resonant frequencies f_0 of portable devices **200**. Furthermore, even if feeding devices **100** and portable devices **200** can be manufactured with identical resonant frequencies f_0 in free space, the resonant frequencies f_0 of each individual unit will be affected when in use by other inductors in the unit's surrounding environment. The amount by which the resonant frequency of each unit is altered will depend on the number and proximity of other inductors.

[0075] Thus, even when attempts have made to standardize the resonant frequencies f_0 of feeding devices and portable devices, manufacturing intolerances and environmental conditions still have the potential to cause problems for energy transfer by resonant inductive coupling.

[0076] One way to alleviate this problem is to provide portable electronic devices **200** with a wireless energy transfer apparatus **210** for altering the resonant frequency f_0 associated with their secondary inductors **211** post-manufacture in dependence of the properties of a nearby feeding device **100**. This provides portable electronic devices **200** with the ability to tune their inductor's resonant frequency f_0 to match that associated with the primary inductor **111** in a nearby feeding device **100** and thus receive energy wirelessly by resonant inductive coupling.

[0077] An exemplary embodiment of a portable electronic device **200** adapted to receive energy wirelessly by resonant inductive coupling is given below. Referring to FIG. **9**, the portable electronic device **200** comprises a wireless energy transfer apparatus **210**, comprising a power supply unit (PSU), for receiving energy from a magnetic field and supplying electrical energy to electrical components **240** of the portable device **200**. Alternatively, as discussed below, electrical energy may be supplied to a rechargeable chemical battery **250** of the portable electronic device **200**.

[0078] In the example discussed below, the magnetic field will be referred to in the context of the magnetic field **400** created by current flowing through the primary inductor **111** in a feeding device **100**. However, a skilled person will appreciate that the magnetic field could alternatively correspond to a magnetic field created by another feeding device, or any other suitable magnetic field source.

[0079] The wireless energy transfer apparatus **210** is controlled by a microcontroller **220** and comprises a receiving component **211***a*, comprising at least one reactance, for receiving energy wirelessly from the magnetic field **400** by resonant inductive coupling. In this example, the receiving component **211***a* comprises a secondary inductor **211**. The inductor **211** is associated with an inductance L_{211}, Q-factor Q_{211} and resonant frequency $f_{0(211)}$. The microcontroller **220** may be integrated into the energy transfer apparatus **210**.

[0080] The wireless energy transfer apparatus **210** further comprises monitoring circuitry **230** configured to detect a magnetic field **400** created by the primary inductor **111** in the feeding device **100**, as is described in more detail below. Upon detecting the magnetic field **400**, the monitoring circuitry **230** and microcontroller **220** are further configured to detect and monitor the resonant frequency $f_{0(111)}$ associated with the primary inductor **111**.

[0081] The features of the monitoring circuitry **230** allow the portable device **200** to wirelessly receive energy over mid-range distances, for example distances at least one order of magnitude greater than the physical dimensions of the primary and secondary inductors **111**, **211**.

[0082] Referring to FIG. **10** in combination with FIG. **9**, the secondary inductor **211** of the wireless energy transfer apparatus **210** has a parasitic capacitance C and is connected to a plurality of switched-mode power supplies (SMPSs) **212** via a diode-bridge **213** and LC filter **214**. The purpose of the LC filter **214** is to ensure that a constant reactive load is introduced to the secondary inductor **211**. If the inductor **211** were to be loaded resistively, there would be a significant decrease in the Q-value $Q_{(211)}$ associated with the inductor **211**, which would in turn significantly reduce the efficiency of the transfer of energy from the feeding device **100**, as previously discussed.

[0083] The diode-bridge **213** and LC filter **214** also protect the inductor **211** from direct exposure to the strongly time-varying load presented by the SMPSs **212**, which are configured to supply power received from the magnetic field **400** to various circuits of the portable electronic device **200**. The SMPSs **212** may be configured, for example, to supply power to a rechargeable chemical battery **250** of the portable electronic device **200**, as shown in FIG. **9**, for recharging.

[0084] Alternatively the SMPSs **212** may be configured to supply power directly to electrical components **240** of the portable electronic device **200**, with the chemical battery **250** acting as a reserve power source. For example, the chemical battery **250** may be configured only to supply power to electrical components **240** of the portable electronic device **200** when the wireless energy transfer apparatus **210** is not receiving power by resonant inductive coupling. If feeding devices **100** were to become widespread, the inclusion of the rechargeable battery **250** in the portable device **200** could become unnecessary.

[0085] Referring to FIG. **11**, in this example of the portable electronic device **200**, the receiving component **211***a* is adaptive. This allows the resonance characteristics associated with the secondary inductor **211** to be tuned to match the resonance characteristics associated with the primary inductor **111** in the feeding device **100**. This provides the degree of tuneability necessary for the resonant frequency $f_{0(211)}$ associated with the secondary inductor **211** to be varied, should the resonant frequency $f_{0(211)}$ not be identical to that associated with the primary inductor **111** in the feeding device **100**.

[0086] In more detail, as is shown by FIG. **11**, the receiving component **211***a* comprises the secondary inductor **211** optionally coupled to an array of capacitors **215**, each capacitor **215** having a different capacitance to each of the others. For example, as shown by FIG. **11**, the capacitors **215** may comprise N capacitors with capacitances C_0, $C_0/2$, . . . $C_0/2^{N-1}$. Each of the capacitors **215** may be optionally coupled to the secondary inductor **211** to affect the capacitance C_{211} of the receiving component **211***a*, thereby varying the resonant frequency $f_{0(211)}$ associated with the inductor **211** and providing a mechanism for the portable device **200** to match the resonant frequency $f_{0(211)}$ associated with the secondary inductor **211** with the resonant frequency $f_{0(111)}$ associated with the primary inductor **111** in the feeding device **100**. It will be appreciated that the resonant frequency $f_{0(211)}$ associated with the secondary inductor **211** could alternatively be varied by altering the inductance of the receiving component **211***a*.

[0087] In this implementation, as is shown by FIG. **11**, the array of capacitors **215** is coupled to a control unit **216** in the microcontroller **220** for automatically controlling the capacitance C_{211} of the receiving component **211***a* in dependence of a control signal from the monitoring circuitry **230**. The microcontroller **220** may comprise a memory and signal processing means **217**, for example including a microprocessor **218**, configured to implement a computer program for detecting and monitoring the resonant frequency associated with the primary inductor **111** through the monitoring circuitry **230** and analysing the control signal from the monitoring circuitry **230** to vary the resonant frequency associated with the secondary inductor **211** by connecting and disconnecting the individual capacitors **215**.

[0088] In this way, the control unit **216** is able to adapt the resonant frequency $f_{0(211)}$ associated with the secondary inductor **211** to make it equal to the resonant frequency $f_{0(111)}$ associated with the primary inductor **111**, thereby initiating resonant inductive coupling between the primary inductor **111** and the secondary inductor **211**.

[0089] The monitoring circuitry **230** may be coupled to an output from the LC filter **214** to detect signals from the secondary inductor **211** and thus to detect when the portable electronic device **200** is in the presence of a magnetic field **400**. For example, the output of the LC filter **214** may be coupled to an input of an AD converter **231**, which may be integrated into the microcontroller **220**, for sensing a voltage induced in the secondary inductor **211** and for supplying corresponding signals to the microcontroller **220** for calculating the resonant frequency associated with the primary inductor **111**. The resonant frequency associated with the secondary inductor **211** may then be varied to match the calculated resonant frequency of the primary inductor **111**.

[0090] Alternatively, as shown by FIG. **9**, the monitoring circuitry **230** may comprise a separate coil **232** for supplying induced voltage signals to the AD converter **231**.

[0091] The monitoring circuitry **230** is sensitive to very small induced voltages, for example of the order of microvolts, and thus is configured such that it is able to detect a magnetic field **400** even when the secondary inductor **211** is in a detuned state. The monitoring circuitry **220** is thus able to detect the presence of a primary inductor **111** even when then the resonant frequency $f_{0(111)}$ associated with the primary inductor **111** is not equal to the resonant frequency $f_{0(211)}$ set for the secondary inductor **211** in the portable electronic device **200**.

[0092] As shown by FIG. **11**, the wireless energy transfer apparatus **210** may include a memory **219** for storing frequency values corresponding to resonant frequencies f_0 in different environments, such that the resonant frequency associated with the secondary inductor **211** can be automatically adjusted upon the portable electronic device **200** entering a particular environment. For example, such automatic adjustment could be prompted by a control signal, received through an aerial of the portable device **200**, indicating that the device **200** has entered a familiar environment. The memory **219** may also be suitable for storing tuning values between various life cycle states. The memory **219** may comprise non-volatile memory in order that the various resonant frequency values f_0 stored in the memory **219** are not lost when the device **200** is switched-off.

[0093] Steps associated with the initiation of a wireless energy transfer between a supply source **110**, for example comprising a primary inductor **111**, and the portable electronic device **200** in the manner described above are shown in FIG. **12**.

[0094] Referring to FIG. **12**, as described above, the first step S**1** is to detect the presence of the supply source **110** by detecting the presence of its associated magnetic field **400** from an induced voltage at the monitoring circuitry **230**. The supply source **110** may comprise a primary inductor **111** in a feeding device **100**. The second step S**2** is to calculate and monitor the resonant frequency of the supply source **110**, and the third step S**3** is vary the resonant frequency of the receiving component **211***a*, comprising the secondary inductor **211**, in dependence of the resonant frequency of the supply source **110**. In order to initiate wireless energy transfer with the highest possible efficiency, the third step S3 involves matching the resonant frequency of the receiving component **211***a* with the resonant frequency of the supply source **110**. Upon completing these steps, the fourth step S**4** is to receive energy wirelessly from the supply source **110** at the receiving component **211***a* by resonant inductive coupling, and the fifth step S**5** is to supply the energy to one or more components **240** of the portable device **200**.

[0095] If wireless energy transfer between the supply source **110** and portable device **200** stops, for example because the portable device **200** moves out of range, then, as described above, the chemical battery **250** may be configured to supply electrical energy to the components **240** of the portable device **200** in step S**6**. As shown by FIG. **12**, in step S7, the supply of electrical energy from the battery **250** is ceased when wireless energy transfer by resonant inductive coupling is reinitiated.

[0096] The above example discusses the use of an adaptive receiving component **211***a* to vary the resonant frequency associated with the secondary inductor **211** in a portable electronic device **200** so as to match the resonant frequency associated with the secondary inductor **211** to a detected resonant frequency associated with a primary inductor **111** in a feeding device **100**. However, it will be appreciated that an adaptive component could alternatively be employed in a feeding device **100** so as match the resonant frequency associated with a primary inductor in the feeding device **100** to that of a secondary inductor in a portable electronic device.

[0097] For example, a portable electronic device **200** may be configured to supply a control signal to a feeding device **100** in order to supply the feeding device **100** with the resonance characteristics of the secondary inductor in the portable electronic device. The feeding device **100** would then be able to match the resonant frequency associated with its primary inductor to the resonant frequency associated with the secondary inductor in the portable device **200**, thereby initiating wireless energy transfer by resonant inductive coupling.

[0098] In another alternative, the supply source of a feeding device may comprise a primary inductor driven by an amplifier, and the microcontroller of the portable electronic device may be configured to match a resonant frequency of the adaptive receiving component to a detected frequency of a magnetic field associated with the supply source.

[0099] In the example discussed above, the portable device **200** comprises a mobile telephone or PDA. However, it will be appreciated that the portable device may alternatively comprise any number of other devices, for example a laptop computer or digital music player. It will further be appreciated that the invention is not limited to the supply of power to portable electronic devices, but may be used for powering a wide variety of other electrical devices. For example, a network of feeding devices may be installed in the home for supplying power to electric lamps and other household appliances. The above-described embodiments and alternatives may be used either singly or in combination to achieve the effects provided by the invention.

1. An apparatus comprising:

monitoring circuitry configured to monitor a resonant frequency of a supply source;

a receiving component; and

a control unit configured to vary a resonant frequency of said receiving component, wherein the apparatus is configured to vary the resonant frequency of said receiving component in dependence of the resonant frequency of said supply source.

2. An apparatus according to claim **1**, wherein the receiving component is adapted to receive energy Tirelessly from the supply source by resonant inductive coupling.

3. An apparatus according to claim **2**, wherein the apparatus further comprises a plurality of electrical components, and the apparatus is configured to supply electrical energy to at least one of these electrical components.

4. An apparatus according to claim **3**, further comprising a battery for supplying electrical energy to at least one of the electrical components when energy is not being received from the supply source.

5. An apparatus according to claim **1**, wherein the receiving component comprises an adaptive receiving component having a variable resonant frequency.

6. An apparatus according to claim **1**, wherein the apparatus is configured to match the resonant frequency of said receiving component with the resonant frequency of said supply source.

7. An apparatus according to claim **1**, wherein a voltage is induced in the receiving component by a magnetic field generated by the supply source, and the control unit is configured to vary the resonant frequency of the receiving component to match the resonant frequency of the supply source.

8. An apparatus according to claim **1**, wherein the apparatus comprises a portable electronic device.

9. An apparatus according to claim **1**, wherein the apparatus comprises a mobile telephone.

10. An apparatus according to claim **1**, wherein the apparatus comprises a personal digital assistant (PDA).

11. An apparatus according to claim **1**, wherein the apparatus comprises a laptop computer.

12. An apparatus comprising:

means for detecting a presence of a supply source;

means for monitoring a resonant frequency of said supply source; and

means for varying a resonant frequency of a receiving component in dependence of the resonant frequency of said supply source.

13. An apparatus comprising a receiving component having variable resonance characteristics for receiving energy wirelessly from a supply source, wherein the resonance characteristics of the receiving component may be varied to match resonance characteristics of the supply source to increase the efficiency at which energy is received from the supply source.

14. An apparatus according to claim **13**, further comprising monitoring circuitry for detecting and monitoring the resonance characteristics of the supply source.

15. An apparatus according to claim **13**, wherein the receiving component comprises an adaptive receiving component having variable resonance characteristics and the apparatus further comprises:

a control unit configured to automatically vary the resonance characteristics of the adaptive receiving component to match the resonance characteristics of the supply source.

16. An apparatus according to claim **13**, wherein the apparatus further comprises one or more electrical components and the receiving component is coupled to power supply circuitry to supply power to at least one of these electrical components.

17. An apparatus according to claim **16**, further comprising a battery for supplying electrical energy to at least one of the electrical components when energy is not being received from the supply source.

18. An apparatus according to claim **13**, wherein the apparatus comprises a portable electronic device.

19. An apparatus according to claim **13**, wherein the apparatus comprises a mobile telephone.

20. An apparatus according to claim **13**, wherein the apparatus comprises a personal digital assistant (PDA).

21. An apparatus according to claim **13**, wherein the apparatus comprises a laptop computer.

22. A system comprising:

a supply source; and

an apparatus comprising:

monitoring circuitry configured to monitor a resonant frequency of the supply source;

a receiving component; and

a control unit configured to vary a resonant frequency of said receiving component, wherein the apparatus is configured to vary the resonant frequency of said receiving component in dependence of the resonant frequency of said supply source.

23. A method comprising:

detecting a presence of a supply source;

monitoring a resonant frequency of said supply source; and

varying a resonant frequency of a receiving component in dependence of the resonant frequency of said supply source.

24. A method according to claim **23**, further comprising:

matching the resonant frequency of said receiving component with the resonant frequency of said supply source.

25. A method according to claim **23**, further comprising:

receiving energy wirelessly at the receiving component from the supply source by resonant inductive coupling.

26. A method according to claim **23**, wherein said receiving component comprises an adaptive receiving component having a variable resonant frequency and the method further comprises:

inducing a voltage in the adaptive receiving component using a magnetic field generated by the supply source; and

varying the resonant frequency of the adaptive receiving component to match the resonant frequency of the supply source.

27. A method according to claim **23**, further comprising supplying electrical energy to an electrical apparatus.

28. A method according to claim **23**, further comprising:

receiving energy at the receiving component from the supply source by resonant inductive coupling;

supplying energy received by resonant inductive coupling to at least one component of an electrical device; and

supplying energy to at least one component of an electrical device from a battery when energy is not being received at the receiving component from the supply source.

29. A computer program product comprising a computer-readable medium having computer-readable program code embodied in said medium, comprising:

a computer-readable program code configured to detect a presence of a supply source;

a computer-readable program code configured to monitor a resonant frequency of said supply source; and

a computer-readable program code configured to vary a resonant frequency of a receiving component in dependence of the resonant frequency of said supply source.

* * * * *