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(54) **Title:** SYSTEMS AND METHODS FOR RECEIVING AND MANAGING POWER IN WIRELESS DEVICES

(57) **Abstract:** A system and method harvest energy from radio frequency (RF)/microwave/millimeter-wave power. The system includes a receiving device with at least one antenna and at least one rectifier, the receiving device converting the RF/microwave/millimeter-wave power into direct current (DC) electricity. The system also has a power management. unit that (a) configures the receiving device based upon the DC electricity, (b) presents a desired load to the receiving device and (c) stores the DC electricity. A software product designs a power source by: interactively interacting with power management design software to select optimum power source configuration for overall combined power source and power management efficiency; optimizing power source circuitry based upon application; selecting appropriate DC network topology and operating characteristics; and selecting appropriate package for integration with power manager based upon simulation of package for power source compatibility.

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SYSTEMS AND METHODS FOR RECEIVING AND MANAGING POWER IN WIRELESS DEVICES

RELATED APPLICATIONS

[0001] This application claims priority to US Provisional Patent Application Serial Number 60/729,378 filed October 21, 2005, and US Provisional Patent Application Serial Number 60/760,040, filed January 17, 2006, both incorporated herein by reference.

BACKGROUND

[0002] Sensors and transmitters that are small and require low levels of power for operation are frequently used for collecting information without being intrusive to their operating environment. For example, a battery powered sensing and transmitting device may be surgically implanted within living tissue to sense and transmit characteristics of the body in which it is implanted.

[0003] The lifetime of the battery used within such a sensor often requires additional surgical procedures to periodically replace the battery. Similarly, where a sensor and transmitting device is located within controlled or hazardous environments, it is often a time-consuming and expensive task to periodically replace the battery.

[0004] Energy may be harvested from radio frequency ("RF") waves for use in remote sensors and transmitting devices. One example of this functionality is an RF identification ("RFID") tag that derives power from an RF wave (e.g., from a transmitting device operating to read the RFID tag) and uses that power to transmit an identification signal. One drawback of this technology is that the RFID tags typically only operate over short distances.

[0005] A rectenna is an antenna that includes a rectifier; the rectenna receives RF waves, rectifies the waves and produces direct current ("DC") electricity. The DC electricity produced by the rectenna is dependent on rectenna design, RF wave frequency, RF wave polarization and RF wave power level incident at the rectenna. Typically, the DC electricity output from the rectenna is conditioned by conditioning

electronics before being fed to a powered device (e.g., sensor, microprocessor, transmitter etc.). Where characteristics of the RF wave vary, the DC electricity output from the rectenna also varies; this affects power conversion efficiency due to loading upon the rectenna by the conditioning electronics which attempts to maintain a constant power output for the powered device.

SUMMARY

[0006] In one embodiment, a radio frequency (RF) reception device has a first periodic or aperiodic antenna array with one or more antenna elements. Electrical conductors provide connectivity of the antenna elements such that selective reception of radio frequency energy by the first periodic or aperiodic antenna array is determined by size and layout of each of the antenna elements, the connectivity, and coupling to one or more rectifiers.

[0007] In another embodiment, a reconfigurable radio frequency (RF) reception device has a plurality of antenna elements, each of the antenna elements having at least one rectifier, wherein a first set of antenna elements, selected from the plurality of antenna elements, has a first size and wherein a second set of antenna elements, selected from the plurality of antenna elements, has a second size. Electrical conductors provide connectivity to each of the plurality of antenna elements and rectifiers such that selective reception of RF energy by the plurality of antenna elements is determined by size, shape, layout and substrate characteristics of the plurality of antenna elements, the connectivity, and coupling of one or more rectifiers to the plurality of antenna elements.

[0008] In another embodiment, a system for selective radio frequency (RF) reception has a periodic or aperiodic antenna array with a plurality of first antenna elements. Electrical conductors provide connectivity to each of the first and second sets of antenna elements such that selective polarized reception of RF energy by the aperiodic antenna array is determined by orientation and feed points of the antenna elements, the connectivity, and coupling of one or more rectifiers to each antenna element.

[0009] In another embodiment, a system collects and conditions variable DC electrical power from at least one source. The system includes conditioning

electronics for converting the variable DC electrical power to storable DC electricity, the conditioning electronics presenting a desired impedance to the at least one source, and a storage device for storing the storable DC electricity.

[0010] In another embodiment, a system harvests energy from radio frequency (RF)/microwave/millimeter-wave power. The system includes a receiving device with at least one antenna and at least one rectifier, the receiving device converting the RF/microwave/millimeter-wave power into direct current (DC) electricity. The system also has a power management unit that (a) configures the receiving device based upon the DC electricity, (b) presents a desired load to the receiving device and (c) stores the DC electricity.

[0011] In another embodiment, a method converts radio frequency (RF) energy into usable direct current (DC) electricity, including the steps of: receiving the RF energy using at least one rectenna, loading the at least one rectenna with a desired impedance, transferring the received power to a storage device, and conditioning the stored power to provide the DC electricity.

[0012] In another embodiment, a method converts variable low power DC electricity into usable direct current (DC) electricity, including the steps of: sensing characteristics of the variable low power DC electricity; selecting, based upon the sensed characteristics, a DC to DC converter module and operating characteristics to convert the variable low power DC electricity to electricity suitable for storage; storing the converted electricity in a suitable storage device; and conditioning the stored electricity to produce usable DC electricity.

[0013] In another embodiment, a software product has instructions, stored on computer-readable media, wherein the instructions, when executed by a computer, perform steps for designing a system for harvesting energy from RF waves, including steps of: interacting with rectenna design software to select desired rectenna configuration for overall combined rectenna and power manager efficiency; solving appropriate converter topology; selecting converter components and operating conditions for maximum efficiency based upon selected rectenna configuration and output characteristics over designated incident power characteristics; and selecting appropriate control approach and settings for maximum overall system efficiency over given system characteristics.

[0014] In another embodiment, a method designs a rectenna, including the steps of: selecting element size of the rectenna based upon available area, incident radiation power levels and operating frequency range; selecting element polarization based upon the RF environment of operation; selecting rectenna material based upon propagation medium and frequency range; selecting rectenna array shape and size based upon required output power levels, available power storage, operational duty cycles and available space; selecting a number of elements connected to each rectifier based upon incident power levels and selected element size; and selecting a radome appropriate for intended use.

[0015] In another embodiment, a software product has instructions, stored on computer-readable media, wherein the instructions, when executed by a computer, perform steps for designing a rectenna, including instructions for: interactively using power management design software to select optimum rectenna configuration for overall combined rectenna and power management efficiency; optimizing rectifier circuitry based upon application; solving rectifier circuit topology based upon optimized rectifier circuitry; solving antenna topology based upon optimized rectifier circuitry, polarization, incident radiation power level and frequency using full-wave electromagnetic simulations; solving DC network at RF frequencies using a combination of full-wave electromagnetic and high-frequency circuit simulations; selecting appropriate combined antenna and rectifier topology; selecting appropriate DC network topology and operating characteristics; selecting appropriate array configuration; and selecting appropriate package for integration with power manager based upon simulation of package for RF compatibility.

[0016] In another embodiment, a software product has instructions, stored on computer-readable media, wherein the instructions, when executed by a computer, perform steps for designing a system for harvesting energy from power sources, including instructions for: interacting with power source design software to select one or more desired power sources for overall combined power source and power manager efficiency; solving appropriate converter topology; selecting converter components and operating conditions for maximum efficiency based upon selected power source configuration and output characteristics over designated incident power characteristics; and selecting appropriate control approach and settings for maximum

overall system efficiency over given system characteristics.

[0017] In another embodiment, a software product has instructions, stored on computer-readable media, wherein the instructions, when executed by a computer, perform steps for designing a power source, including instructions for: interactively interacting with power management design software to select optimum power source configuration for overall combined power source and power management efficiency; optimizing power source circuitry based upon application; selecting appropriate DC network topology and operating characteristics; and selecting appropriate package for integration with power manager based upon simulation of package for power source compatibility.

[0018] In another embodiment, a system collects and conditions variable DC electrical power from at least one source. Conditioning electronics converts the variable DC electrical power to storable DC electricity and presents a positive resistance load to the at least one source. A storage device stores the storable DC electricity. The positive resistance load corresponds to optimal load resistance of the source over a range of input power levels.

[0019] In another embodiment, an integrated converter collects and conditions variable DC electrical power from at least one source. Conditioning electronics converts the variable DC electrical power to storable DC electricity and presents a positive resistance load to the at least one source. A controller controls the topology and switching frequency of the conditioning electronics. A storage device stores the storable DC electricity. The controller adaptively adjusts one or more of the switching frequency and topology to extract power from the rectenna while storing the harvested energy.

BRIEF DESCRIPTION OF THE FIGURES

[0020] FIG. 1 shows one embodiment of a power harvesting system that includes power sources and a controlled impedance, voltage or current power controller.

[0021] FIG. 2 shows one exemplary periodic and uniform rectenna array.

[0022] FIG. 3 shows one exemplary aperiodic and non-uniform rectenna array.

[0023] FIG. 4 illustrates exemplary energy coupling including a plurality of DC-to-DC converters.

[0024] FIG. 5 is a flowchart illustrating one exemplary process for converting variable power DC electricity into usable DC electricity.

[0025] FIG. 6 is a flowchart illustrating one process for designing a system for harvesting energy from a power source.

[0026] FIG. 7 is a flowchart illustrating one process for designing a rectenna.

[0027] FIG. 8 is a flowchart illustrating another exemplary process for designing a rectenna.

[0028] FIG. 9 is a flowchart illustrating one exemplary process for designing a system for harvesting energy from power sources.

[0029] FIG. 10 shows one exemplary block diagram of one exemplary rectenna and sensor system embodiment.

[0030] FIG. 11 shows an exemplary model and a layout of a rectenna.

[0031] FIG. 12 shows an exemplary graph illustrating simulated and measured output power of the rectenna of FIG. 11 as a function of output resistance, and an exemplary graph illustrating simulated and measured output voltage of the rectenna of FIG. 11 as a function of output resistance.

[0032] FIG. 13 shows a block diagram illustrating one exemplary DC power processing circuit for obtaining plus and minus 15V power.

[0033] FIG. 14 shows one exemplary graph illustrating measured DC output power of the circuit of FIG. 13 against polarization angle of radiation incident on the rectenna array and one exemplary graph illustrating DC output power and efficiency of the circuit of FIG. 13 against power received by the rectenna array

[0034] FIG. 15 shows one exemplary circuit for a boost converter in variable frequency critical conduction mode (CRM).

[0035] FIG. 16 shows one exemplary circuit for a buck-boost converter in fixed frequency discontinuous conduction mode (DCM).

[0036] FIG. 17 shows two exemplary waveforms illustrating operation of the converter circuit of FIG. 15.

[0037] FIG. 18 shows one exemplary circuit for generating the gate driving signals for the circuit of FIG. 15.

[0038] FIG. 19 shows two exemplary equations that define operation of the circuit of FIG. 15.

[0039] FIG. 20 shows one exemplary two-stage adaptable switching-capacitor topology of one embodiment.

DETAILED DESCRIPTION OF THE FIGURES

[0040] FIG. 1 shows an embodiment of a power harvesting system 100 that includes power sources 102 and a controlled impedance, voltage or current power controller 104. Power harvesting system 100 is illustratively shown powering a powered device 106. Powered device 106 is, for example, a sensor and/or transceiver device. Power source 102 may represent one or more of: a rectenna, a photovoltaic cell, a piezoelectric device or other power collecting device.

[0041] Power controller 104 is illustratively shown with energy storage 108, energy coupling 110 and energy management 112. Energy storage 108 is for example a battery or a capacitor; it may be internal to power controller 104, as shown, or external to power controller 104 without departing from the scope hereof.

[0042] Energy management 112 instructs energy coupling 110 to convert energy received from power source 102 into a form suitable for storage by energy storage 108. Accordingly, energy coupling 110 may include a DC-to-DC voltage converter 116 that changes the DC voltage received from power source 102 such that it is suitable for storage in energy storage 108. The DC-to-DC voltage converter 116 may represent a step-up voltage converter or a step down voltage converter. Or, DC-to-DC voltage converter 116 may include a plurality of different types of DC-to-DC voltage converters that are selectively chosen to convert DC electricity received from power source 102 into a form suitable for storage by energy storage 102.

[0043] Energy coupling 110 is further shown with optional DC combining circuit 114, which operates to combine DC inputs from power source 102 where multiple power sources 102 provide power to controlled impedance power controller 104. DC combining circuit 114 may include one or more switches selected by energy management 112 to configure connectivity of multiple power sources 102. For example, where power source 102 is a rectenna array (e.g., rectenna array 200, FIG. 2) that has a plurality of antenna elements (e.g., antenna elements 202), depending on

sensed characteristics of received power from the aperiodic rectenna, energy management 112 may control DC coupling circuit 114 to configure antenna elements in series and/or parallel for optimum operation. In particular, as power levels, frequencies and polarizations of incident RF waves change, energy management 112 may reconfigure connectivity of the rectenna array to improve energy harvesting efficiency.

[0044] Energy management 112 may also receive information from powered device 106 via signal 118 that indicates power requirements of powered device 106. This information is used by energy management 112 to optimally configure energy coupling 110.

[0045] In the following examples, power source 102 is represented by one or more rectennas. However, other power sources may also be used in place of the rectennas shown.

[0046] FIG. 2 shows one exemplary periodic and uniform rectenna array 200, illustrating nine square patch antenna elements 202 on a grounded substrate 204. Each antenna element 202 has a rectifier 206, thereby forming a rectenna 208. Interconnectivity of periodic rectenna array 200 is not shown for clarity if illustration. Size and layout of each antenna element, connectivity of each rectifier thereto and substrate characteristics determine the frequency range and polarization of radio frequency waves received by rectenna array 200.

[0047] Array 200 may be formed with alternate antenna designs without departing from the scope hereof. Moreover, additional rectifiers may connect in parallel or series to rectifiers 206, also without departing from the scope hereof.

[0048] FIG. 3 shows one exemplary aperiodic and non-uniform rectenna array 300 with five patch antenna elements 302 of a first size formed on a substrate 304, each antenna element 302 having a rectifier 306 to form a rectenna 312. Aperiodic rectenna array 300 also has a patch antenna element 308 of a second size formed on substrate 304; antenna element 308 has a rectifier 310 thus forming a rectenna 314. Rectenna 312 is designed for receiving radio frequency waves of a first frequency range, and rectenna 314 is designed for receiving radio frequency waves of a second frequency range. Thus, the aperiodic and non-uniform rectenna array 300 may receive radio frequency waves within both the first frequency range and the second frequency

range.

[0049] Additional or different rectennas may be included within array 300. Size, layout and type of each antenna element, connectivity of each rectifier thereto determine the frequency range and polarization of radio frequency waves received by aperiodic non-uniform rectenna array 300.

[0050] Although not shown in FIGs. 2 and 3, connectivity of rectennas 208 within periodic rectenna array 200 and connectivity of rectennas 312 and 314 within aperiodic rectenna array 300 may be based upon radio frequency waves incident at each rectenna array and the desired power output of the rectenna array. For example, rectennas 208 may be connected in series or parallel.

[0051] Selection of a suitable rectifier topology and rectification device, based upon frequency range and power levels received, is also important for efficient operation of these rectenna arrays.

[0052] Multiple periodic or aperiodic, uniform or non-uniform, rectenna arrays may be used to harvest RF energy. For example, output from two periodic rectenna arrays, each having different sized antenna elements (i.e., each receiving RF waves of different frequency ranges and/or polarizations) may be combined for conditioning by controlled impedance (or DC input parameter) power controller 104, FIG. 1.

[0053] A rectenna array (e.g., periodic rectenna array 200, FIG. 2) may also be reconfigured during operation. For example, if energy management 112 determines that output of rectenna array 200 is low, energy management 112 instructs energy coupling 110 to modify connectivity of rectenna array 200 (e.g., using DC combining circuit 114) to increase output voltage. DC combining circuit 114 for example contains switching components (e.g., MOSFETs, BJT, IGBT, relays, etc.) that allow dynamic configuration of connectivity to power source 102.

[0054] If energy management 112 determines that output power of the rectenna array is high, energy management 112 may instruct energy coupling 110 to reconfigure antenna elements of rectenna array 200 into parallel and/or serial connectivity combinations, thereby reducing changing output voltage and current.

[0055] Connectivity of one or more rectenna arrays is for example based upon one or more of output voltages, open circuit voltage, short circuit current, output

current and output power of one or more antenna elements. Groups of antenna elements producing similar currents may be connected in serial, whereas groups of antenna elements producing similar voltages may be connected in parallel. Operating parameters of the power controller 104 may also be based upon one or more of output voltages, open circuit voltage, short circuit current, output current and output power of one or more antenna elements and / or other power sources.

[0056] Controlled impedance power controller 104 may include one or more sense circuits for monitoring characteristics of input power.

[0057] The rectenna array may be designed such that RF power from two or more antenna elements are combined before rectification.

[0058] FIGs. 15, 16 and 18, described below, show exemplary circuits for presenting desired impedance to one or more power sources (e.g., power source 102, FIG. 1, periodic rectenna array 200, FIG. 2, and aperiodic rectenna array 300, FIG. 3). Prior art DC-to-DC converters typically implement inverse resistive loading: as input power decreases, resistance presented to the input power source is reduced, thereby further loading the input source. Controlled impedance power controller 104, on the other hand, maintains resistance presented to the input source at a substantially constant level, even as input power levels vary. The controlled impedance may also be varied based on sensed conditions of the power source to emulate a desired impedance, input voltage or input current in order to improve the energy harvesting efficiency, for example by emulating a positive resistance load where resistance presented to the source increases as input power decreases.

[0059] Selection of circuitry for power controller 104 depends on the desired application. Where high efficiency of energy harvesting is required, additional circuitry may be included to sense characteristics of the input power, whereas if the power source provides ample power, high efficiency may not be necessary, allowing simplified circuitry to be used.

[0060] Alternative power sources may be combined for use with an RF power source 102. For example, an RF wave rectenna array, a mechanical generator and a photovoltaic cell may be used as input to combining circuit 114 and power controller 104. Power controller 104 may then dynamically configure these inputs depending on sensed input characteristics and/or desired output requirements in order to improve

energy harvesting efficiency. In particular, energy sources may be combined in such a way as to provide biasing to each other, thereby increasing overall energy harvesting efficiency. Optionally, powered device 106 may provide feedback to energy management 112 to indicate its power needs. Energy management 112 may then configure power input connectivity as needed to provide the necessary power.

[0061] Power controller 104 may also transfer energy from energy storage 108 to one or more power source 102 outputs in order to increase the overall energy harvesting efficiency. For example, energy can be transferred to the DC output of a rectenna for improved biasing, resulting in improved energy harvesting efficiency.

[0062] Where input power conditions vary, DC-to-DC converter 116 may be selected from a plurality of converters to match the input power characteristics. FIG. 4 shows one exemplary energy coupling 402 that includes a plurality of DC-to-DC converters 404 and an optional DC combining circuit 406. DC combining circuit 406 may represent DC combining circuit 114, FIG. 1. Energy coupling 402 may represent energy coupling 110, FIG. 1. For example, each of DC-to-DC converters 404 may represent one of: a four-switch buck-boost converter, a two-switch buck-boost converter, a boost converter operating in critical-conduction mode, a buck converter controlled to regulate input current or voltage as a function of the corresponding input voltage or current, and a switched capacitor converter. DC-to-DC converters 404 are selectable based upon input power characteristics and the type of storage device used for energy storage 108. As input power characteristics change, energy management 112 may select an alternate DC-to-DC converter as needed.

[0063] Where input power conditions vary, energy management 112 may change the operating characteristics of DC to DC converter 116 to match the emulated input impedance of the converter to the desired load of the power source 102. For example, based upon one or more of: sensed open circuit voltage of power source 102, short circuit current of power source 102, operating voltage and current of power source 102, and output power of power source 102, characteristics of DC to DC converter 116 may be adjusted to emulate an appropriate resistance.

[0064] FIG. 5 is a flowchart illustrating one process 500 for converting variable power DC electricity into usable DC electricity, in accord with an embodiment. Process 500 is for example performed by controller 104, FIG. 1. In step

502, process 500 senses characteristics of the variable low power DC electricity and then selects, in step 504, a DC-to-DC converter module and operating characteristics based upon the sensed characteristics, to convert the variable power DC electric into electricity suitable for storage. In step 506, electricity suitable for storage is stored. For example, the electricity may be stored in energy storage 108, FIG. 1. The stored energy is then conditioned into the usable electricity. For example, the energy from energy store 108 is conditioned and provided as DC electricity to powered device 106.

[0065] FIG. 6 is a flowchart illustrating one process 600 for designing a system for harvesting energy from a power source. In step 602, process 600 interacts with power source design software to select a power source configuration. In step 604, process 600 solves the appropriate converter topology. In step 606, process 600 selects the converter components and operating conditions. In step 608, process 600 selects the appropriate control approach and settings.

[0066] FIG. 7 is a flowchart illustrating one process 700 for designing a rectenna. In step 702, process 700 selects the element size of the rectenna based upon available area, incident radiation power levels and operating frequency range. In step 704, process 700 selects element polarization based upon the RF environment of operation. In step 706, process 700 selects rectenna material based upon propagation medium and frequency range. In step 708, process 700 selects a shape and size for the rectenna array based upon required output power levels, available power storage, operational duty cycles and available space. In step 710, process 700 selects a radome appropriate for intended use.

[0067] FIG. 8 is a flowchart illustrating another exemplary process 800 for designing a rectenna. In step 802, process 800 uses power management design software to interactively select optimum rectenna configuration for overall combined rectenna and power management efficiency. In step 804, process 800 optimizes the selected rectenna circuitry based upon application. In step 806, process 800 solves rectifier circuit topology based upon optimized rectifier circuitry. In step 808, process 800 solves antenna topology based upon optimized rectifier circuitry, polarization, incident radiation power level and frequency using full-wave electromagnetic simulations. In step 810, process 800 solves the DC network at RF frequencies using a combination of full-wave electromagnetic and high-frequency circuit simulations. In

step 812, process 800 selects combined antenna and rectifier topology. In step 814, process 800 selects appropriate rectenna array configuration. In step 816, process 800 selects an appropriate package for integration with power manager based upon simulation of package for RF compatibility.

[0068] FIG. 9 is a flowchart illustrating one process 900 for designing a system for harvesting energy from power sources. In step 902, process 900 interacts with power source design software to select one or more desired power sources for overall combined power source and power manager efficiency. In step 904, process 900 solves appropriate converter topology. In step 906, process 900 selects converter components and operating conditions for maximum efficiency based upon selected power source configuration and output characteristics over designated incident power characteristics. In step 908, process 900 selects an appropriate control approach and settings for maximum overall system efficiency over given system characteristics.

[0069] FIG. 10 shows a block diagram of one exemplary rectenna and sensor system 1000. In particular, system 1000 has a rectenna array 1002, DC power processing 1004, sensor query electronics 1006, information processing 1008 and a piezoelectric sensor array 1010. In one example, system 1000 is used to sense structural failures from fatigue within an aircraft. Rectenna array 1002 is formed on a flexible substrate that may be conformed to a moderate curve of an aircraft.

[0070] FIG. 11 shows an exemplary model 1100 and a layout 1150 of an ADS rectenna 1101. Model 1100 is shown with an antenna 1102, a diode 1104, an inductor 1106, a capacitor 1108 and a resistor 1110. As shown in layout 1150, a commercial lumped element capacitor 1158 representing capacitor 1108 and a small 0.24mm diameter wire 1156 representing inductor 1106 provide necessary impedance for an output filter of rectenna 1101. Output voltage of rectenna 1101 is measured across a variable resistor and the DC power is calculated as V^2/R.

[0071] FIG. 12 shows an exemplary graph 1200 illustrating simulated and measured output power of rectenna 1101 as a function of output resistance, and an exemplary graph 1250 illustrating simulated and measured output voltage of rectenna 1101 as a function of output resistance.

[0072] FIG. 13 shows a block diagram illustrating one exemplary DC power processing circuit 1300 for obtaining plus and minus 15V power. Circuit 1300 is

powered, for example, by an array of rectenna 1101, FIG. 11, not shown.

[0073] FIG. 14 shows one exemplary graph 1400 illustrating measured DC output power of circuit 1300 against polarization angle of incident radiation against the rectenna array and one exemplary graph 1450 illustrating DC output power and efficiency of circuit 1300 against received power by the rectenna array.

[0074] FIG. 15 shows one exemplary circuit 1500 for a boost converter in variable frequency critical conduction mode (CRM). FIG. 16 shows one exemplary circuit 1600 for a buck-boost converter in fixed frequency discontinuous conduction mode (DCM). Note that in both circuits 1500 and 1600, a two-switch implementation is possible due to the floating input power source. The converter circuits 1500, 1600 may be operated continuously at higher input power levels, or operated in a pulsed mode at lower power levels, as shown in waveforms 1700 and 1750 of FIG. 17.

[0075] In particular, waveform 1700 of FIG. 17 shows inductor current under steady-state operation of circuit 1500, FIG. 15. In a first transition of circuit 1500, transistor Q_1 is turned on and Q_2 is turned off during t_{on}, and thus the inductor current ramps up from zero to i_{pk} over that time. After this transition, Q_1 is turned off, and Q_2 is turned on to move the energy to the load. This second transition lasts until the inductor current drops to zero. When this occurs, the first transition is repeated. The converter of circuit 1500 runs in this mode for a certain duty cycle, k, of a low frequency period, T_{lf}. At kT_{lf}, the converter turns off and starts up again at T_{lf}. By adjusting k or t_{on}, the emulated input resistance seen by the source is changed. Changing the emulated input resistance to match the optimum rectenna load maximizes energy harvesting.

[0076] In circuit 1500, the input voltage source is shown as V_g, and the output energy is stored in an energy storage element such as a capacitor or micro-battery. The voltage, V_{zcrs}, is a sense point used by a comparator to find a zero crossing of the inductor current. Optionally, the open circuit voltage, V_{oc}, or a short circuit current, I_{sc}, may be used by additional control circuitry to find the operating input power level and set k. The gate driving signals, $gate_n$ and $gate_p$, are essentially the same signal when the converter is operating in critical conduction mode. However, both drive their respective MOSFETs off after kT_{lf}; thus $gate_n$ is a low voltage signal and $gate_p$ is a high voltage signal. C_1 and C_2 are input and output filter

capacitors. Diode Q_2 may be used to precharge the energy storage element, thus enabling start-up from zero energy. The control circuitry for this boost converter generates the gate driving signals, given the zero crossing point of the inductor current and the parameters: t_{on}, T_{lf}., and k. This is for example achieved with the exemplary circuit 1800 shown in FIG. 18.

[0077] The voltage, V_{zcrs}, from the power stage is the positive input into a comparator with the negative input tied to ground. V_{zcrs} is a negative voltage most of the time. Detection of a zero-crossing by the comparator triggers a pulse, from a one-shot circuit, with width t_{on}. This pulse is passed through two OR-gates and then to circuit 1500 as $gate_n$ and $gate_p$. A second input into the $gate_p$ OR-gate is a signal from a low frequency oscillator that is logic high after kT_{lf}. This ensures that both Q_1 and Q_2 are off after that point. The low frequency oscillator operating at period, T_{lf}, also provides the same signal to power off the comparator and one-shot circuitry when the converter is not in operation for reduced control power loss and to power them back on afterwards.

[0078] As can be seen from equation 1950, FIG. 19, if the boost converter operates continuously, the emulated resistance $R_{emulated}$ is only be dependent on t_{on} since $k = 1$. This simplifies the control circuitry since only the zero crossing detecting comparator and the one-shot are used. However, these circuits are on continuously, even at low input power. Implementation of the low frequency duty cycle control method allows some of the circuitry to be powered off at times, depending on the input power level. Note that peak power tracking components in the control sample the open circuit voltage, V_{oc}, of the input source when the converter is not in operation. These components may also sample the short circuit current, I_{sc}. These values maybe used to adjust k or t_{on} and thus change $R_{emulated}$ to be the optimum impedance load. If operation at lower power levels is desired, these additional control blocks may be implemented.

[0079] Prior art power converters for very low power levels have low efficiency due to parasitic leakage currents and parasitic capacitance to the substrate. These limitations are removed by developing a set of integrated converters for high efficiency energy harvesting using an RF process. This process is based on fully-depleted silicon-on-insulator (FD-SOI) with a thick upper metal layer for inductors

and a high resistivity substrate. The primary advantages in this process for power processing are reduced parasitic capacitances, which are up to 1000 times lower than in a traditional CMOS silicon process. Such low parasitics facilitate high efficiency operation, even at very low power levels and frequencies as high as hundreds of kHz (allowing small component sizes). An integrated power converter IC may be constructed with single and two-stage switched capacitor (SC) circuits, which have high efficiency at very low power levels since parasitic capacitance is small.

[0080] FIG. 20 shows one exemplary two-stage SC topology 2000. On-chip buffers may be provided for each of the switches (S_1-S_{11}) and external control logic (e.g., controller 2002) may be used to determine the switching configuration. Topology 2000 generates eight distinct power conversion ratios from the input voltage (V_{in}) to the output voltage (V_{out}) for ratios from one third to three. The external control chip adaptively adjusts the switching frequency and topology to continuously extract maximum power from attached rectennas while storing the harvested energy to the output capacitor ($C_{storage}$). As the output capacitor voltage builds, the converter sequences through topologies to maintain optimal loading of the rectenna and high efficiency.

[0081] Changes may be made in the above methods and systems without departing from the scope hereof. It should thus be noted that the matter contained in the above description or shown in the accompanying drawings should be interpreted as illustrative and not in a limiting sense. The following claims are intended to cover all generic and specific features described herein, as well as all statements of the scope of the present method and system, which, as a matter of language, might be said to fall there between.

CLAIMS

1. A radio frequency (RF) reception device, comprising:

a first periodic or aperiodic antenna array having one or more antenna elements; and

electrical conductors for providing connectivity of the antenna elements;

wherein selective reception of radio frequency energy by the first periodic or aperiodic antenna array is determined by size and layout of each of the antenna elements, the connectivity, and coupling to one or more rectifiers.

2. The RF reception device of claim 1, wherein the first periodic or aperiodic antenna array has three or more antenna elements with uniform spacing.

3. The RF reception device of claim 1, wherein the first periodic or aperiodic antenna array has three or more antenna elements with non-uniform spacing.

4. The RF reception device of claim 1, wherein each of the antenna elements has at least one rectifier integrated therewith.

5. The RF reception device of claim 1, wherein two or more of the antenna elements couple to one rectifier.

6. The RF reception device of claims 4 and 5, wherein the rectifier is a Schottky diode.

7. The RF reception device of claims 4 and 5, wherein the rectifier is selected based upon turn-on voltage and frequency range of the radio frequency energy.

8. The RF reception device of claim 1, wherein the first periodic or aperiodic antenna array is configured to receive multiple polarizations.

9. The RF reception device of claim 1, wherein the first periodic or aperiodic antenna array is configured to receive multiple frequencies.

10. The RF reception device of claim 1, wherein feed points of each of the antenna elements are selected based upon desired polarization for each of the antenna elements.

11. The RF reception device of claim 1, wherein feed points of each of the antenna elements are selected based upon desired impedance of each of the antenna elements, the impedance selected to match rectifier impedance.

12. The RF reception device of claim 10, wherein at least one rectifier is positioned at each feed point.

13. The RF reception device of claim 11, wherein at least one rectifier is positioned at each feed point.

14. The RF reception device of claim 1, further comprising:

at least one second periodic or aperiodic antenna array, the second periodic or aperiodic antenna array having one or more second antenna elements differing from the antenna elements of the first periodic or aperiodic antenna array;

wherein the electrical conductors also provide connectivity for the second antenna elements, and wherein selective reception of RF energy by the first and second periodic or aperiodic antenna array is determined by (a) size and layout of each antenna element of the first and second periodic or aperiodic antenna arrays, (b) the connectivity of the first and second periodic or aperiodic antenna arrays, and (c) coupling of the rectifiers within each antenna element of the first and second periodic or aperiodic antenna arrays.

15. The RF reception device of claim 14, wherein size, shape and substrate characteristics of the first and second periodic or aperiodic antenna array antenna elements define a frequency range of the RF energy received.

16. The RF reception device of claim 15, wherein ground plane proximity of the first and second periodic or aperiodic antenna array antenna elements and

spacing of the first and second periodic or aperiodic antenna array antenna elements define the frequency range of the RF energy received.

17. The RF reception device of claim 1, further comprising an enclosure for containing the first periodic or aperiodic antenna array, rectifiers and electrical conductors to allow use in biomedical implants.

18. A reconfigurable radio frequency (RF) reception device, comprising:

a plurality of antenna elements, each of the antenna elements having at least one rectifier, wherein a first set of antenna elements selected from the plurality of antenna elements has a first size and wherein a second set of antenna elements selected from the plurality of antenna elements has a second size; and

electrical conductors providing connectivity to each of the plurality of antenna elements and rectifiers;

wherein selective reception of RF energy by the plurality of antenna elements is determined by size, shape, layout and substrate characteristics of the plurality of antenna elements, the connectivity, and coupling of one or more rectifiers to the plurality of antenna elements.

19. The RF device of claim 18, wherein feed points of the first and second sets of antenna elements defines polarization of the RF energy received.

20. The RF device of claim 18, wherein shape, size, spacing, substrate characteristics and ground plane proximity of the first and second sets of antenna elements defines the frequency range of the RF energy received.

21. A reconfigurable radio frequency (RF) reception device, comprising:

a periodic or aperiodic antenna array having a plurality of antenna elements, wherein a first set of antenna elements of the periodic or aperiodic antenna array has a first shape, size and spacing and wherein a second set of antenna elements of the periodic or aperiodic antenna array has a second shape, size and spacing; and

electrical conductors for providing connectivity to each of the first and second sets of antenna elements, wherein selective polarized reception of RF energy by the aperiodic antenna array is determined by orientation and feed points of the antenna elements, the connectivity, and coupling of one or more rectifiers to each antenna element.

22. A system for selective radio frequency (RF) reception, comprising:

a first periodic or aperiodic antenna array having a plurality of first antenna elements;

first electrical conductors providing connectivity to each of the first antenna elements; and

one or more first rectifiers reconfigurably connected to the first electrical conductors via one or more first switches that are responsive to first control signals to select reception of RF energy by the first periodic or aperiodic antenna array.

23. The system of claim 22, further comprising:

a second periodic or aperiodic antenna array having a plurality of second antenna elements, the second antenna elements sized differently from the first antenna elements;

second electrical conductors providing connectivity to each of the second antenna elements; and

one or more second rectifiers reconfigurably connected to the second antenna elements via one or more second switches that are responsive to second control signals to select reception of RF energy by the second periodic or aperiodic antenna array.

24. The system of claim 23, wherein orientation of the first and second antenna elements and connectivity of the one or more first and second rectifiers define polarization of the RF energy received.

25. The system of claim 23, wherein spacing of the first and second antenna elements is uniform.

26. The system of claim 23, wherein spacing of the first and second antenna elements is non-uniform.

27. The system of claim 22, wherein orientation of the first antenna elements and connectivity of the first rectifiers define polarization of the RF energy received.

28. A system for collecting and conditioning variable DC electrical power from at least one source, comprising:

conditioning electronics for converting the variable DC electrical power to storable DC electricity, the conditioning electronics presenting a desired impedance to the at least one source; and

a storage device for storing the storable DC electricity.

29. The system of claim 28, wherein the storage device is a capacitor and the conditioning electronics vary the voltage of the storable DC electricity based upon accumulated electricity within the capacitor.

30. The system of claim 28, wherein the storage device is a battery and the conditioning electronics maintain the voltage of the storable DC electricity.

31. The system of claim 28, further comprising sensing electronics for sensing characteristics of the variable DC electrical power.

32. The system of claim 31, wherein the sensing electronics sense one or both of short-circuit current and open-circuit voltage of one or more of the at least one source.

33. The system of claim 31, wherein the sensing electronics sense one or more of current and voltage of one or more of the at least one source.

34. The system of claim 31, wherein the sensing electronics sense current and voltage of the storable DC electricity.

35. The system of claim 31, where the number of sources is greater than one, further comprising selection electronics for configuring and connecting the sources to the conditioning electronics based upon the sensed characteristics.

36. The system of claim 35, wherein the selection electronics comprise a plurality of switches.

37. The system of claim 36, the switches being controlled to reconfigure two or more power sources in series when sensed characteristics indicate reduced levels of variable DC electrical power.

38. The system of claim 36, the switches being controlled to reconfigure two or more power sources in parallel when the sensed characteristics indicate an increased levels of variable DC electrical power.

39. The system of claim 31, the one or more power sources comprising one or more of: an RF reception device, a rectenna, a light to electrical conversion element, a mechanical to electrical conversion element, a thermal to electrical conversion element and a chemical to electrical conversion element.

40. The system of claim 28, wherein the conditioning electronics vary operation based upon sensed characteristics of the variable DC electrical power.

41. The system of claim 28, wherein the conditioning electronics comprise a commercial DC to DC power converter.

42. The system of claim 28, wherein the conditioning electronics comprise a first type of DC to DC converter selected from the group of: a four-switch buck-boost converter, a two-switch buck-boost converter, a boost converter operating in critical-conduction mode, a buck converter controlled to regulate input current proportional to input voltage, and a switched capacitor converter.

43. The system of claim 28, wherein the conditioning electronics comprise:

an isolated or non-isolated step up/down converter using four-switch or two-switch implementations using either synchronous or diode rectifiers

operated to achieve a desired input impedance for proper loading of the source or sources; and

wherein discontinuous conduction mode is used to achieve constant averaged input resistance to achieve desired loading of the at least one source.

44. The system of claim 43, wherein the isolated or non-isolated step up/down converter is selected from the group consisting of: buck-boost, sepic and Cuk.

45. The system of claim 43, wherein the four-switch implementation has ground referenced source & load.

46. The system of claim 43, wherein the two-switch implementation has floating source.

47. The system of claim 28, wherein the conditioning electronics comprise:

an isolated or non-isolated step up converter using diode or synchronous rectifier to achieve a desired input impedance for proper loading of the source or sources; and

wherein critical-conduction mode is used to achieve a constant averaged input resistance to achieve desired loading of power source or sources.

48. The system of claim 47, wherein the isolated or non-isolated step up converter is a boost converter.

49. The system of claim 28, wherein the conditioning electronics comprise:

an isolated or non-isolated step down converter using a diode or a synchronous rectifier to achieve a desired input impedance for proper loading of the at least one source.

50. The system of claim 49, wherein the isolated or non-isolated step down converter is a buck converter.

51. The system of claim 28, wherein the conditioning electronics comprise:

a single stage or multi-stage switched capacitor (SC) converter operated with frequency and configuration control used to maintain desired input impedance for proper loading of the power source or sources; and

wherein maximum and minimum frequency limits in a control loop are used as a decision point for changing SC configuration, the limits being unique to each configuration or set for all operating modes.

52. The system of claim 42, wherein the conditioning electronics operate to step up or step down an output voltage based upon sensed characteristics of the variable DC power and the storage device.

53. The system of claim 42, wherein the conditioning electronics operate in pulse mode, the pulse width indicating an operational period and the pulse frequency indicating an operational frequency.

54. The system of claim 53, wherein the frequency and width of a pulse used in the pulse mode are selected based upon sensed characteristics of the variable DC power and the storage device.

55. The system of claim 53, wherein components of the control circuit are powered down when not operational.

56. The system of claim 42, wherein the conditioning electronics further comprise a second type of DC to DC conversion module selected from the group, and wherein the first and second DC to DC converter are selected for operation based upon sensed characteristics of the variable DC power.

57. The system of claim 28, wherein the conditioned DC electricity is supplied to electronic devices selected from the group of: a medical device for implant into a brain, a medical device for implant into a spinal cord, a medical device for sensing electrocardiogram signals, a medical device for sensing electroencephalogram signals, a medical device for sensing electromyogram signals, a medical device for implant into a cochlea, a medical device for sensing blood sugar

levels, a medical device for nerve and cellular stimulation, an environmental hazard sensor, industrial and commercial sensors and devices for building and structure control and automation, critical area sensors, assistive technology devices, aircraft devices, marine devices, satellite devices, retail environment devices, fire sensors and devices and security sensors and devices.

58. The system of claim 28, wherein the system is encapsulated to allow for biomedical implantation.

59. An system for harvesting energy from RF power, comprising:

a receiving device with at least one antenna and at least one rectifier, the receiving device converting the RF power into direct current electricity; and

a power management unit that (a) configures the receiving device based upon the DC electricity, (b) presents a desired load to the receiving device and (c) stores the DC electricity.

60. The system of claim 59, wherein the RF power is microwave power.

61. The system of claim 59, wherein the RF power is millimeter-wave power.

62. The system of claim 59, wherein the power management unit first converts the DC electricity into electricity suitable for storage.

63. The system of claim 59, wherein the receiving device is configured with dual orthogonal linear polarization elements.

64. The system of claim 63, wherein each orthogonal linear polarization element has at least one rectifier.

65. The system of claim 59, wherein the receiving device is configured with dual orthogonal circular polarization elements.

66. The system of claim 65, wherein each orthogonal circular polarization element has at least one rectifier.

67. The system of claim 59, wherein the receiving device comprises a plurality of elements.

68. The system of claim 67, wherein the plurality of elements is configured as a periodic or aperiodic array.

69. The system of claim 67, wherein each of the plurality of elements is selected to receive a certain frequency range such that the receiving device receives each of the certain frequency ranges.

70. The system of claim 69, wherein certain of the plurality of elements are interleaved with one another to reduce size of the receiving device.

71. The system of claim 59, wherein the external electronic devices are selected from the group of: a medical device for implant into a brain, a medical device for implant into a spinal cord, a medical device for sensing electrocardiogram signals, a medical device for sensing electroencephalogram signals, a medical device for sensing electromyogram signals, a medical device for implant into a cochlea, a medical device for sensing blood sugar levels, a medical device for nerve and cellular stimulation, an environmental hazard sensor, industrial and commercial sensors and devices for building and structure control and automation, critical area sensors, assistive technology devices, aircraft devices, marine devices, satellite devices, retail environment devices, fire sensors and devices and security sensors and devices.

72. The system of claim 59, wherein the system powers sensors sealed within an environment.

73. The system of claim 59, wherein the system harvests radar power.

74. The system of claim 59, wherein the system harvests wireless signals produced for purposes other than powering the system.

75. A method of converting RF energy into usable direct current DC electricity, comprising the steps of:

receiving the RF energy using at least one rectenna;

loading the at least one rectenna with a desired impedance;

transferring the received power to a storage device; and

conditioning the stored power to provide the DC electricity.

76. The method of claim 75, further comprising sensing characteristics of the received RF energy to determine the method of converting the received power.

77. The method of claim 75, the step of receiving the RF energy comprising receiving the RF energy using a plurality of rectennas, each rectenna configured to receive the RF energy at a certain frequency.

78. The method of claim 75, the step of receiving the RF energy comprising receiving the RF energy using a plurality of rectennas, each rectenna configured to receive the RF energy at a certain polarity.

79. A method of converting variable low power DC electricity into usable direct current electricity, comprising the steps of:

sensing characteristics of the variable low power DC electricity;

selecting, based upon the sensed characteristics, a DC to DC converter module and operating characteristics to convert the variable low power DC electricity to electricity suitable for storage;

storing the converted electricity in a suitable storage device; and

conditioning the stored electricity to produce usable DC electricity.

80. A software product comprising instructions, stored on computer-readable media, wherein the instructions, when executed by a computer, perform steps for designing a system for harvesting energy from RF waves, comprising steps of:

interacting with rectenna design software to select desired rectenna configuration for overall combined rectenna and power manager efficiency;

solving appropriate converter topology;

selecting converter components and operating conditions for maximum efficiency based upon selected rectenna configuration and output characteristics over designated incident power characteristics; and

selecting appropriate control approach and settings for maximum overall system efficiency over given system characteristics.

81. A method for designing a rectenna, comprising the steps of:

selecting element size of the rectenna based upon available area, incident radiation power levels and operating frequency range;

selecting element polarization based upon the RF environment of operation;

selecting rectenna material based upon propagation medium and frequency range;

selecting rectenna array shape and size based upon required output power levels, available power storage, operational duty cycles and available space;

selecting a number of elements connected to each rectifier based upon incident power levels and selected element size; and

selecting a radome appropriate for intended use.

82. A software product comprising instructions, stored on computer-readable media, wherein the instructions, when executed by a computer, perform steps for designing a rectenna, comprising instructions for:

using power management design software to select optimum rectenna configuration for overall combined rectenna and power management efficiency;

optimizing rectifier circuitry based upon application;

solving rectifier circuit topology based upon optimized rectifier circuitry;

solving antenna topology based upon optimized rectifier circuitry, polarization, incident radiation power level and frequency using full-wave electromagnetic simulations;

solving DC network at RF frequencies using a combination of full-wave electromagnetic and high-frequency circuit simulations;

selecting appropriate combined antenna and rectifier topology;

selecting appropriate DC network topology and operating characteristics;

selecting appropriate array configuration; and

selecting appropriate package for integration with power manager based upon simulation of package for RF compatibility.

83. A software product comprising instructions, stored on computer-readable media, wherein the instructions, when executed by a computer, perform steps for designing a system for harvesting energy from power sources, comprising instructions for:

interacting with power source design software to select one or more desired power sources for overall combined power source and power manager efficiency;

solving appropriate converter topology;

selecting converter components and operating conditions for maximum efficiency based upon selected power source configuration and output characteristics over designated incident power characteristics; and

selecting appropriate control approach and settings for maximum overall system efficiency over given system characteristics.

84. A software product comprising instructions, stored on computer-readable media, wherein the instructions, when executed by a computer, perform steps for designing a power source, comprising instructions for:

interactively interacting with power management design software to select optimum power source configuration for overall combined power source and power management efficiency;

optimizing power source circuitry based upon application;

selecting appropriate DC network topology and operating characteristics; and

selecting appropriate package for integration with power manager based upon simulation of package for power source compatibility.

85. A system for collecting and conditioning variable DC electrical power from at least one source, comprising:

conditioning electronics for converting the variable DC electrical power to storable DC electricity, the conditioning electronics presenting a positive resistance load to the at least one source; and

a storage device for storing the storable DC electricity;

wherein the positive resistance load corresponds to optimal load resistance of the source over a range of input power levels.

86. The system of claim 85, wherein the conditioning electronics are based upon $P_{in} = V_g \cdot I_{avg} = V_g \cdot \frac{I_{pk}}{2} k = \frac{V_g^2 \cdot t_{on}}{2L} k$ and $I_{pk} = \frac{V_g \cdot t_{on}}{L} \Rightarrow R_{emulated} = \frac{2L}{t_{on} \cdot k}$.

87. An integrated converter for collecting and conditioning variable DC electrical power from at least one source, comprising:

conditioning electronics for converting the variable DC electrical power to storable DC electricity, the conditioning electronics presenting a positive resistance load to the at least one source;

a controller for controlling the topology and switching frequency of the conditioning electronics; and

a storage device for storing the storable DC electricity;

wherein the controller adaptively adjusts one or more of the switching frequency and topology to extract power from the rectenna while storing the harvested energy.

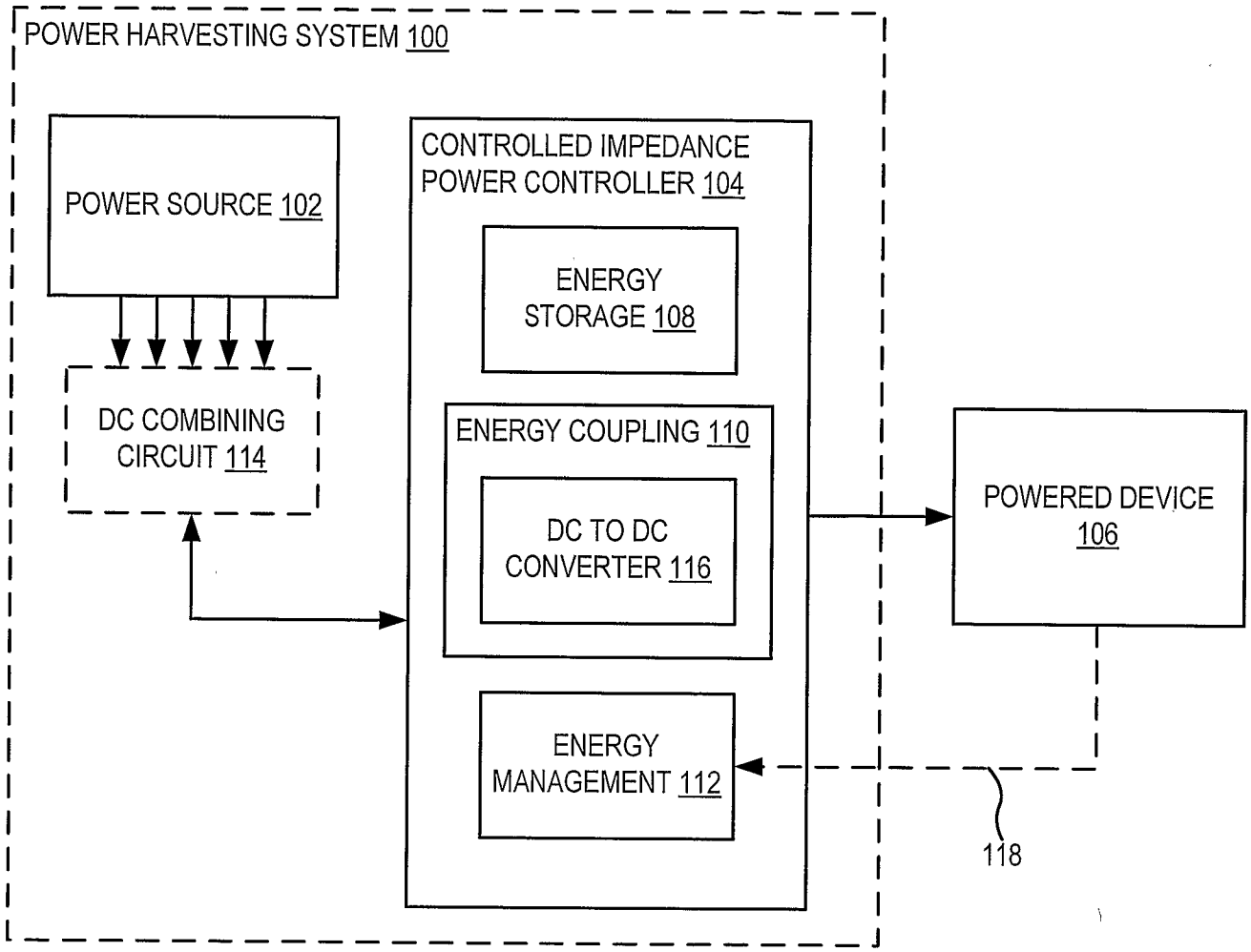

POWER HARVESTING SYSTEM 100
POWER SOURCE 102
DC COMBINING CIRCUIT 114
CONTROLLED IMPEDANCE POWER CONTROLLER 104
ENERGY STORAGE 108
ENERGY COUPLING 110
DC TO DC CONVERTER 116
ENERGY MANAGEMENT 112
POWERED DEVICE 106
118

FIG. 1

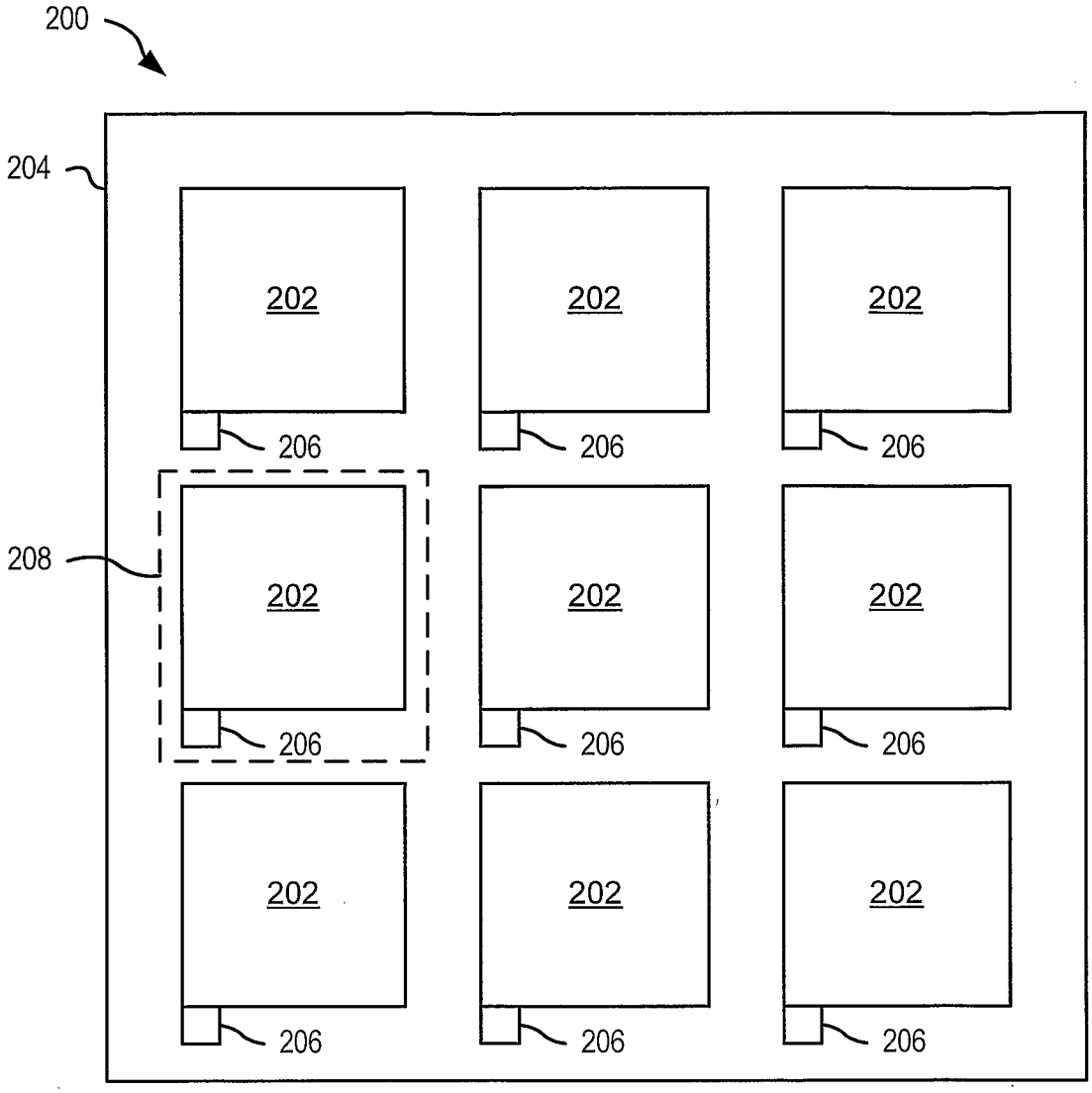


FIG. 2

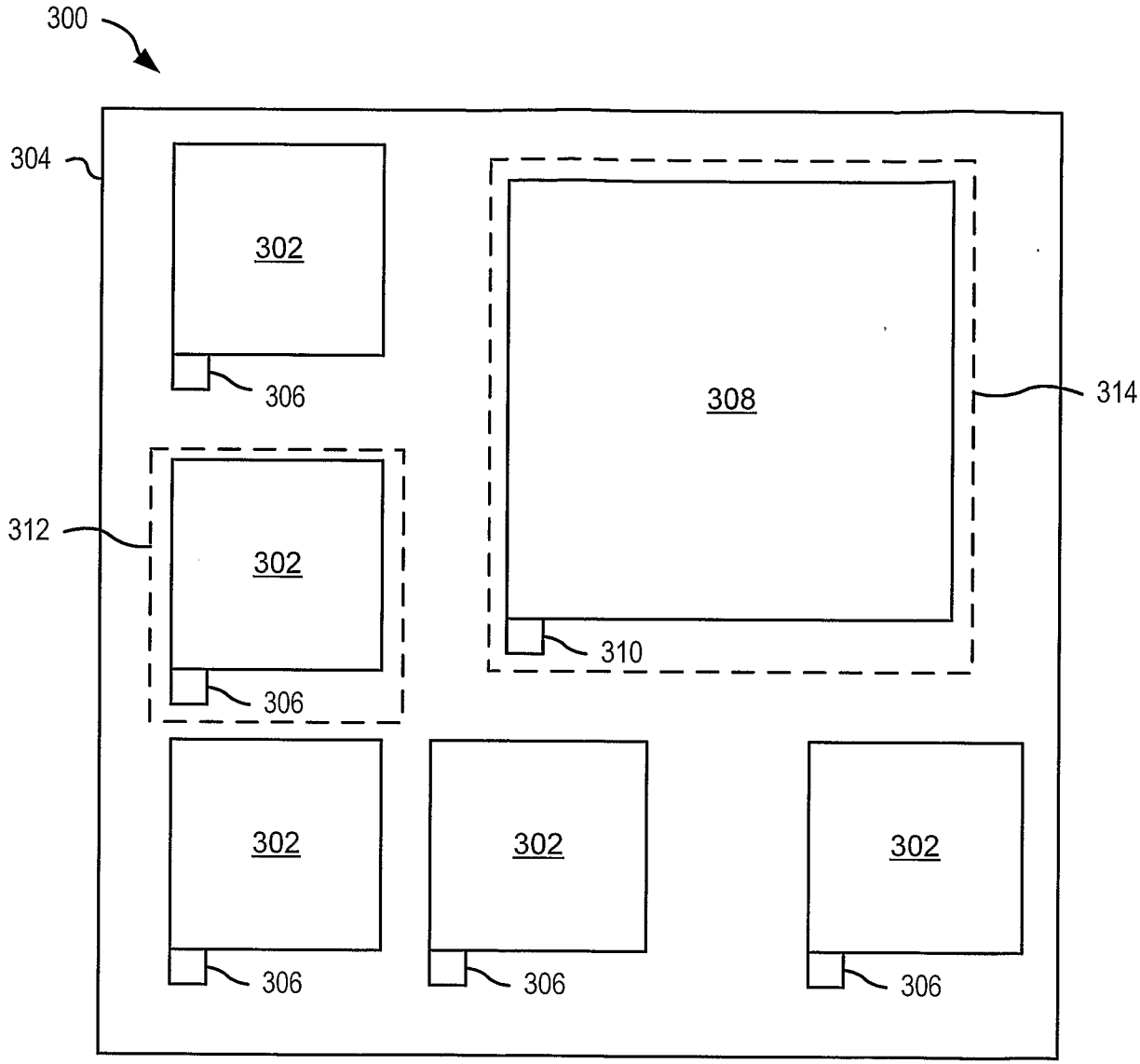


FIG. 3

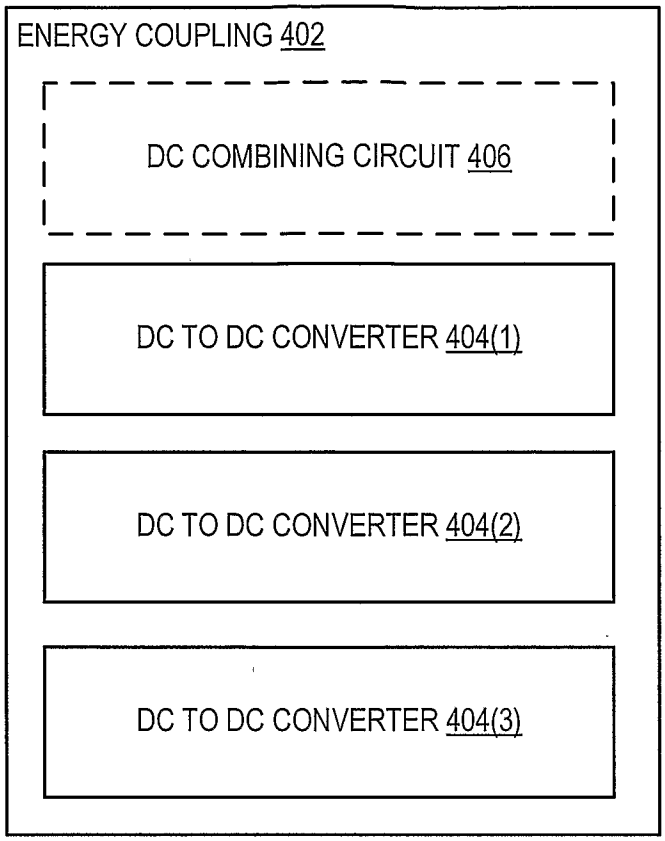

ENERGY COUPLING 402
DC COMBINING CIRCUIT 406
DC TO DC CONVERTER 404(1)
DC TO DC CONVERTER 404(2)
DC TO DC CONVERTER 404(3)

FIG. 4

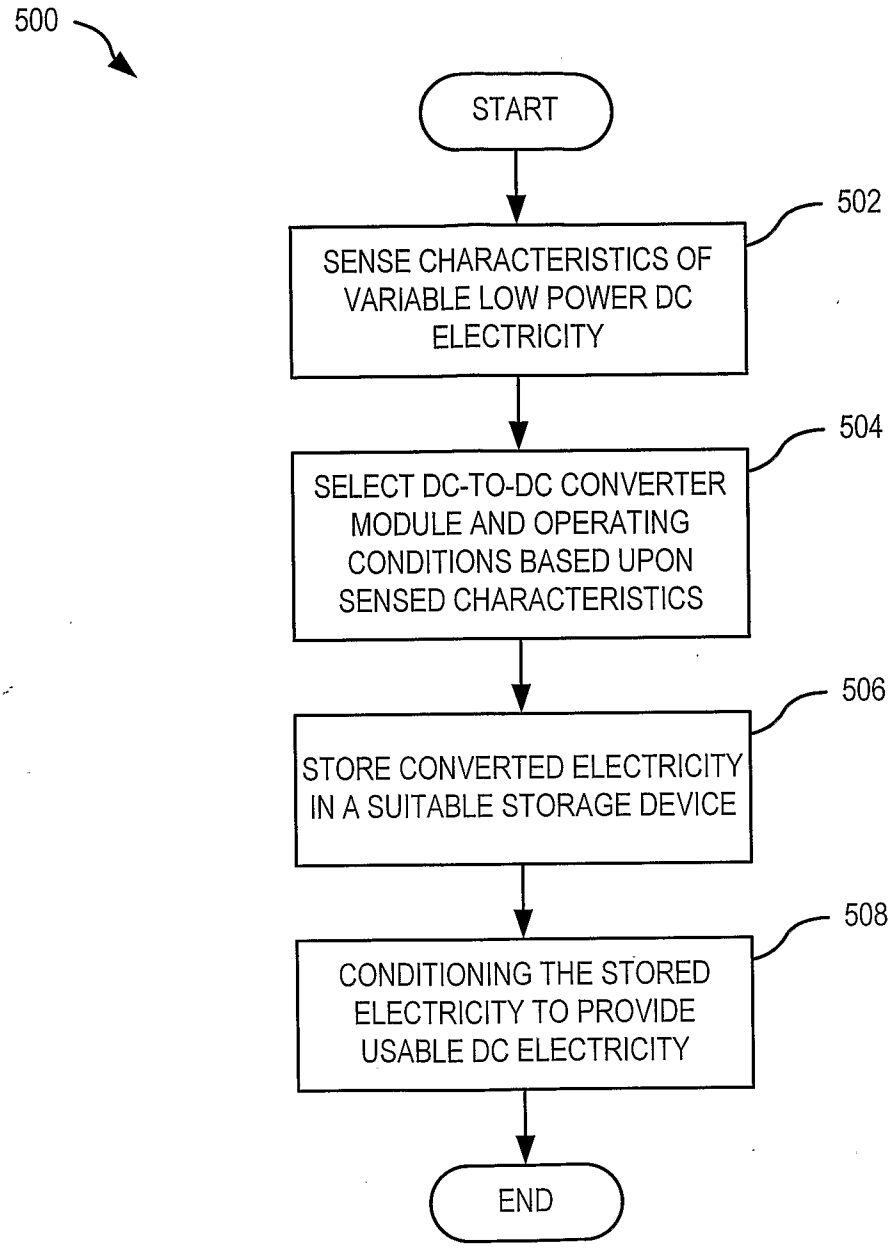

500
START
502
SENSE CHARACTERISTICS OF VARIABLE LOW POWER DC ELECTRICITY
504
SELECT DC-TO-DC CONVERTER MODULE AND OPERATING CONDITIONS BASED UPON SENSED CHARACTERISTICS
506
STORE CONVERTED ELECTRICITY IN A SUITABLE STORAGE DEVICE
508
CONDITIONING THE STORED ELECTRICITY TO PROVIDE USABLE DC ELECTRICITY
END

FIG. 5

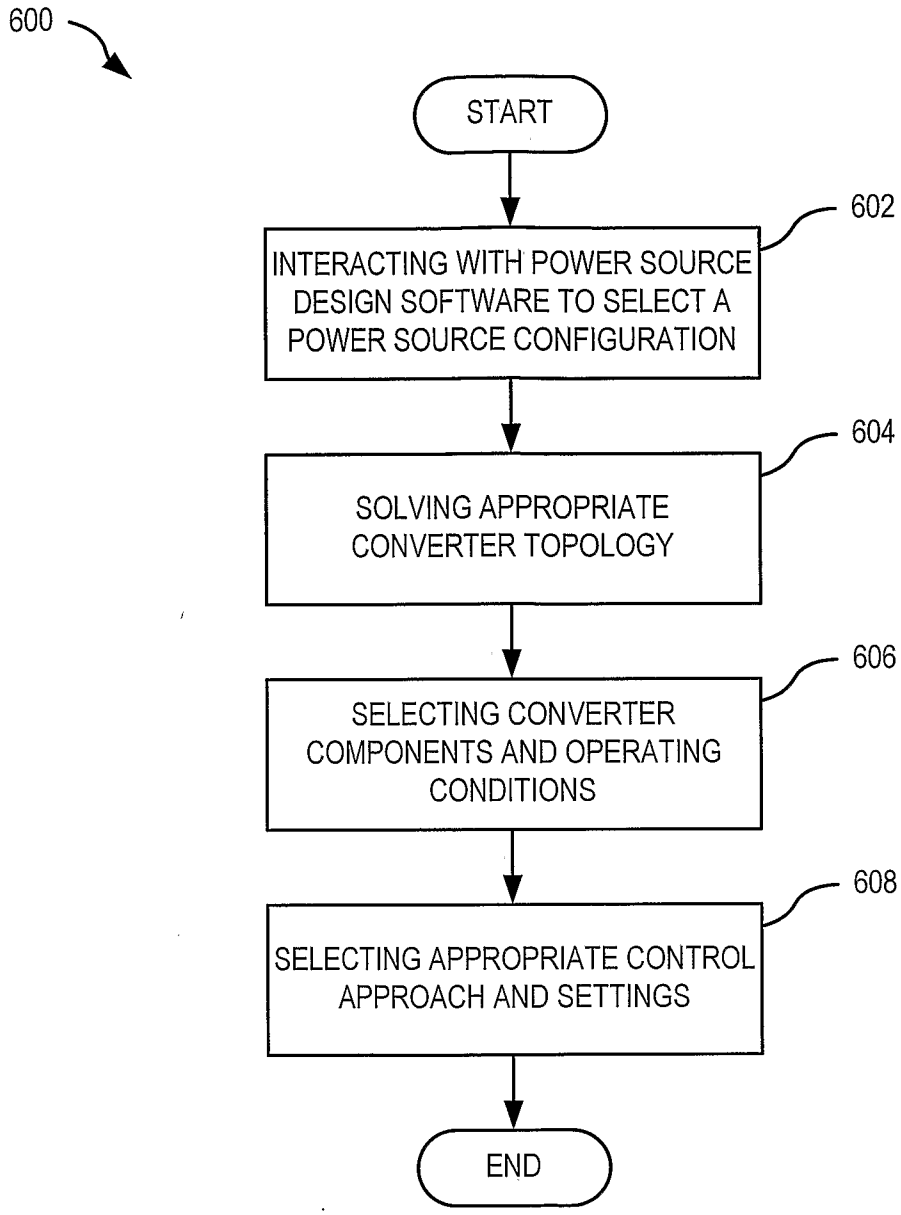

600
START
602
INTERACTING WITH POWER SOURCE DESIGN SOFTWARE TO SELECT A POWER SOURCE CONFIGURATION
604
SOLVING APPROPRIATE CONVERTER TOPOLOGY
606
SELECTING CONVERTER COMPONENTS AND OPERATING CONDITIONS
608
SELECTING APPROPRIATE CONTROL APPROACH AND SETTINGS
END

FIG. 6

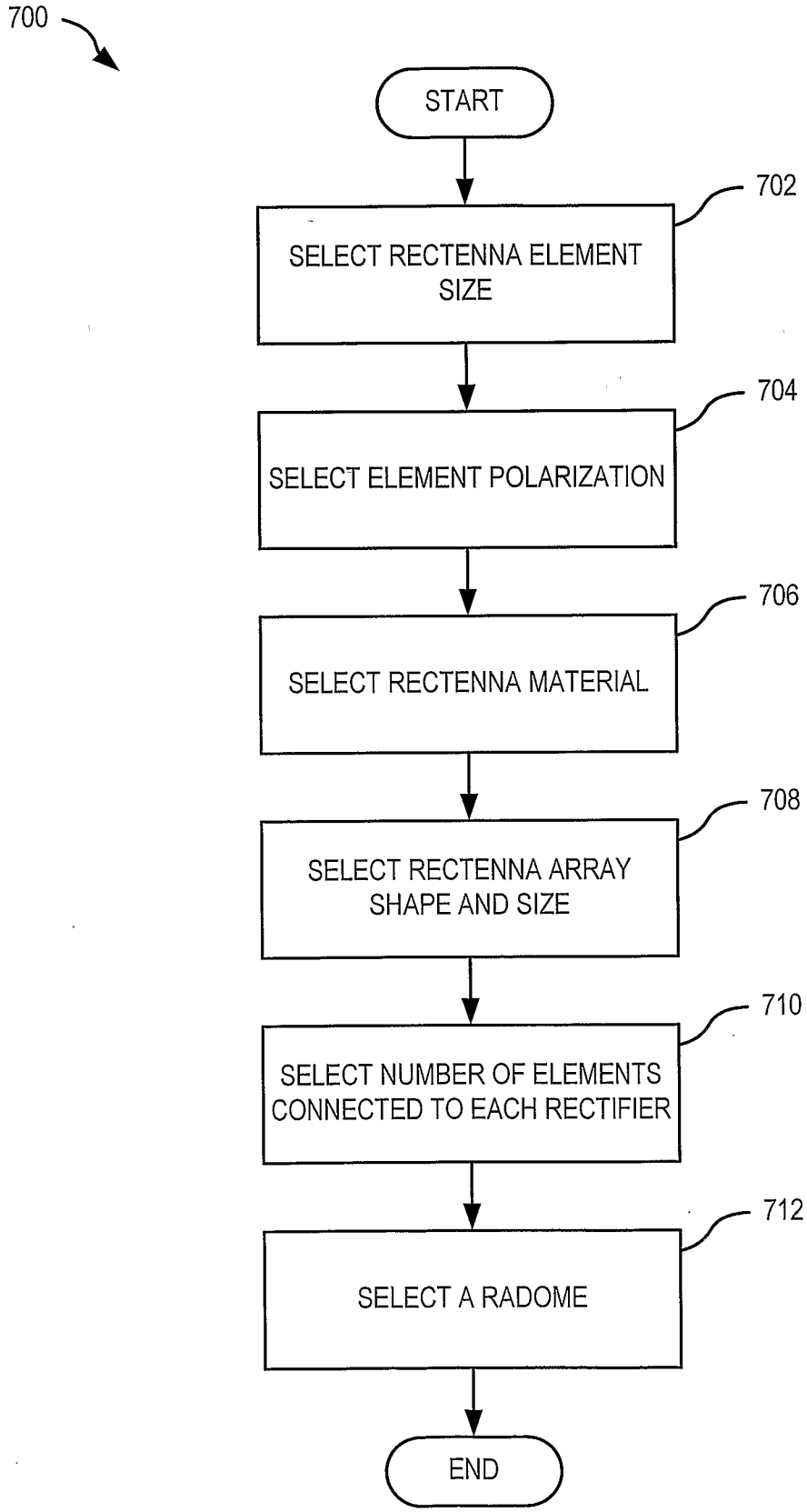

700
START
SELECT RECTENNA ELEMENT SIZE
702
SELECT ELEMENT POLARIZATION
704
SELECT RECTENNA MATERIAL
706
SELECT RECTENNA ARRAY SHAPE AND SIZE
708
SELECT NUMBER OF ELEMENTS CONNECTED TO EACH RECTIFIER
710
SELECT A RADOME
712
END

FIG. 7

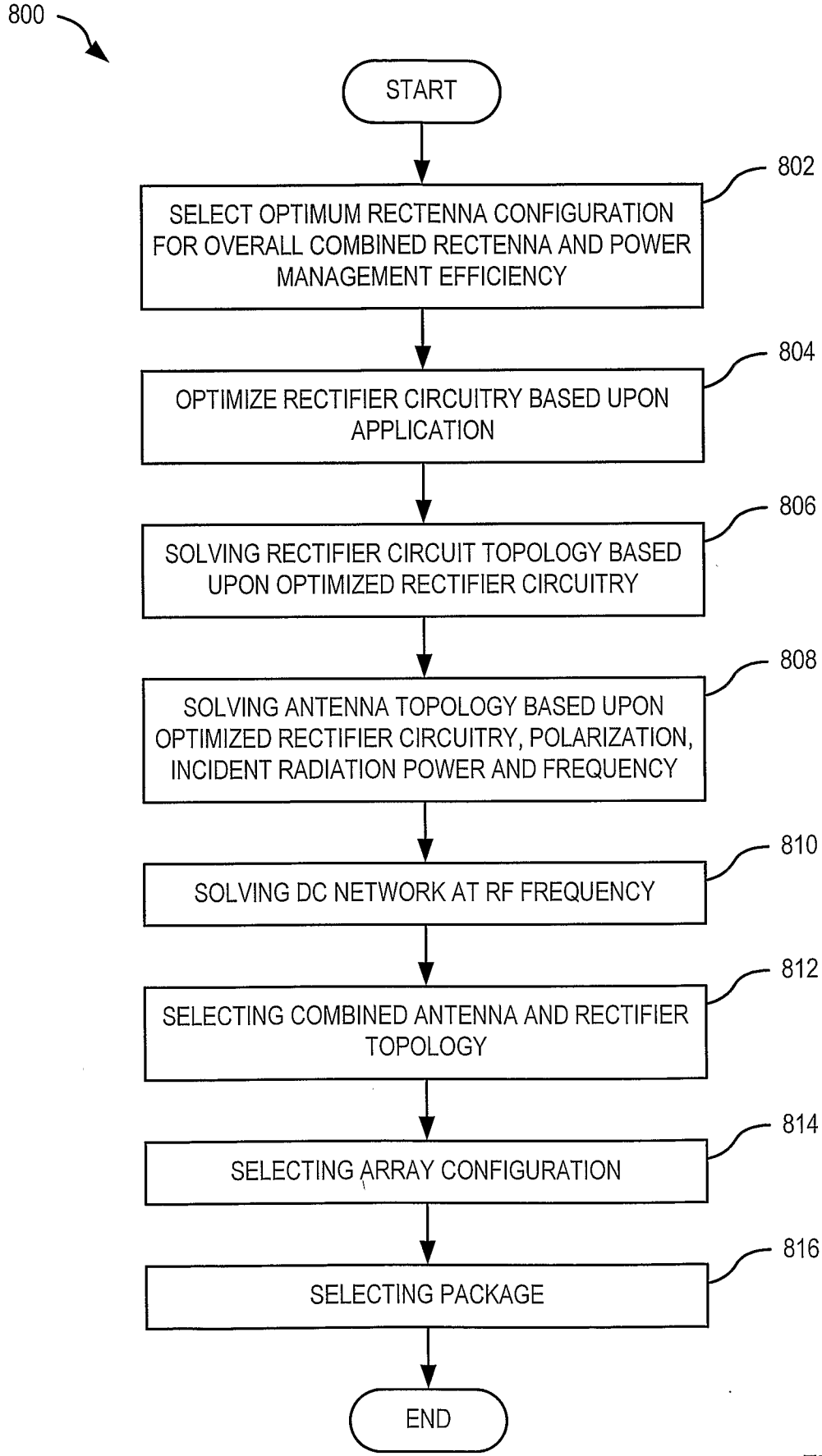

800
START
802
SELECT OPTIMUM RECTENNA CONFIGURATION FOR OVERALL COMBINED RECTENNA AND POWER MANAGEMENT EFFICIENCY
804
OPTIMIZE RECTIFIER CIRCUITRY BASED UPON APPLICATION
806
SOLVING RECTIFIER CIRCUIT TOPOLOGY BASED UPON OPTIMIZED RECTIFIER CIRCUITRY
808
SOLVING ANTENNA TOPOLOGY BASED UPON OPTIMIZED RECTIFIER CIRCUITRY, POLARIZATION, INCIDENT RADIATION POWER AND FREQUENCY
810
SOLVING DC NETWORK AT RF FREQUENCY
812
SELECTING COMBINED ANTENNA AND RECTIFIER TOPOLOGY
814
SELECTING ARRAY CONFIGURATION
816
SELECTING PACKAGE
END

FIG. 8

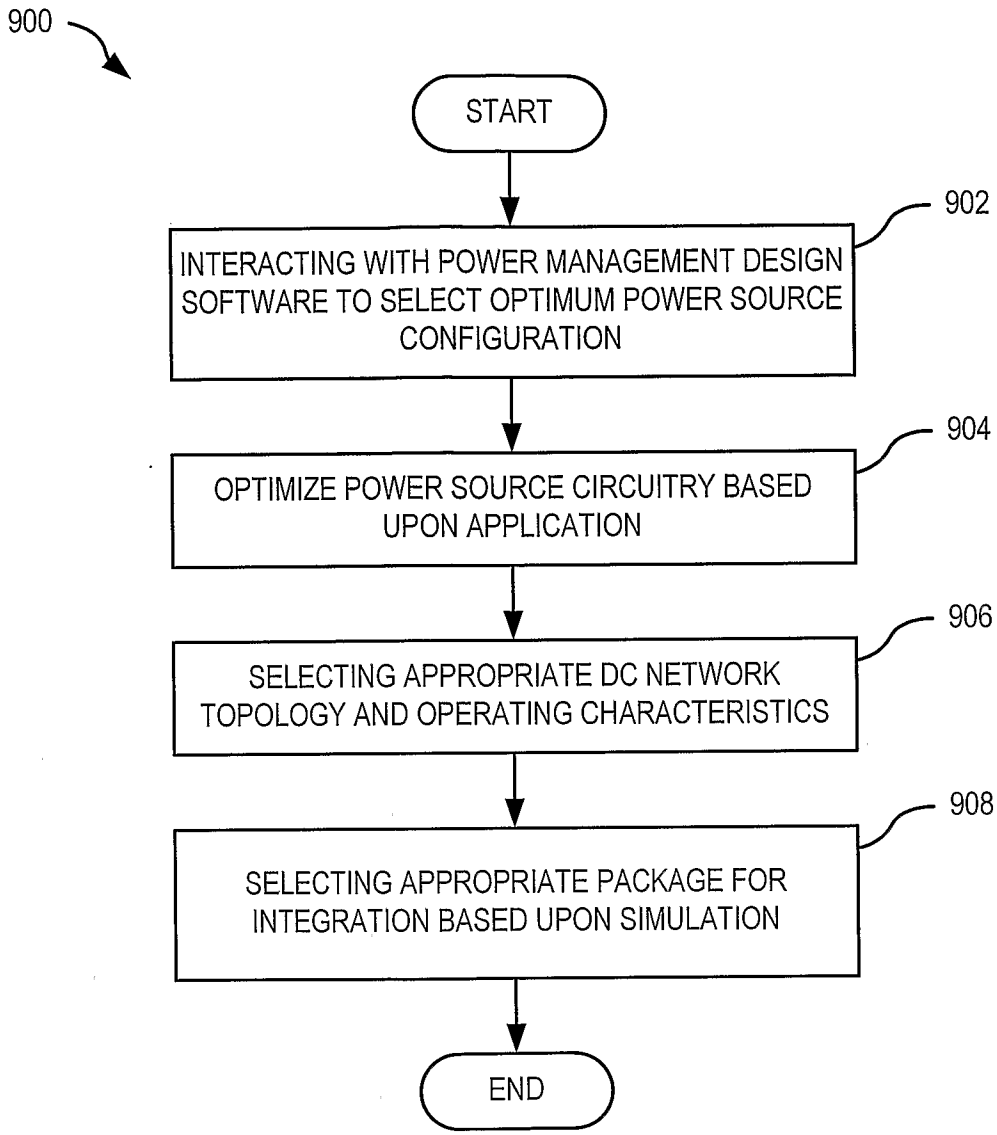

900
START
INTERACTING WITH POWER MANAGEMENT DESIGN SOFTWARE TO SELECT OPTIMUM POWER SOURCE CONFIGURATION
902
OPTIMIZE POWER SOURCE CIRCUITRY BASED UPON APPLICATION
904
SELECTING APPROPRIATE DC NETWORK TOPOLOGY AND OPERATING CHARACTERISTICS
906
SELECTING APPROPRIATE PACKAGE FOR INTEGRATION BASED UPON SIMULATION
908
END

FIG. 9

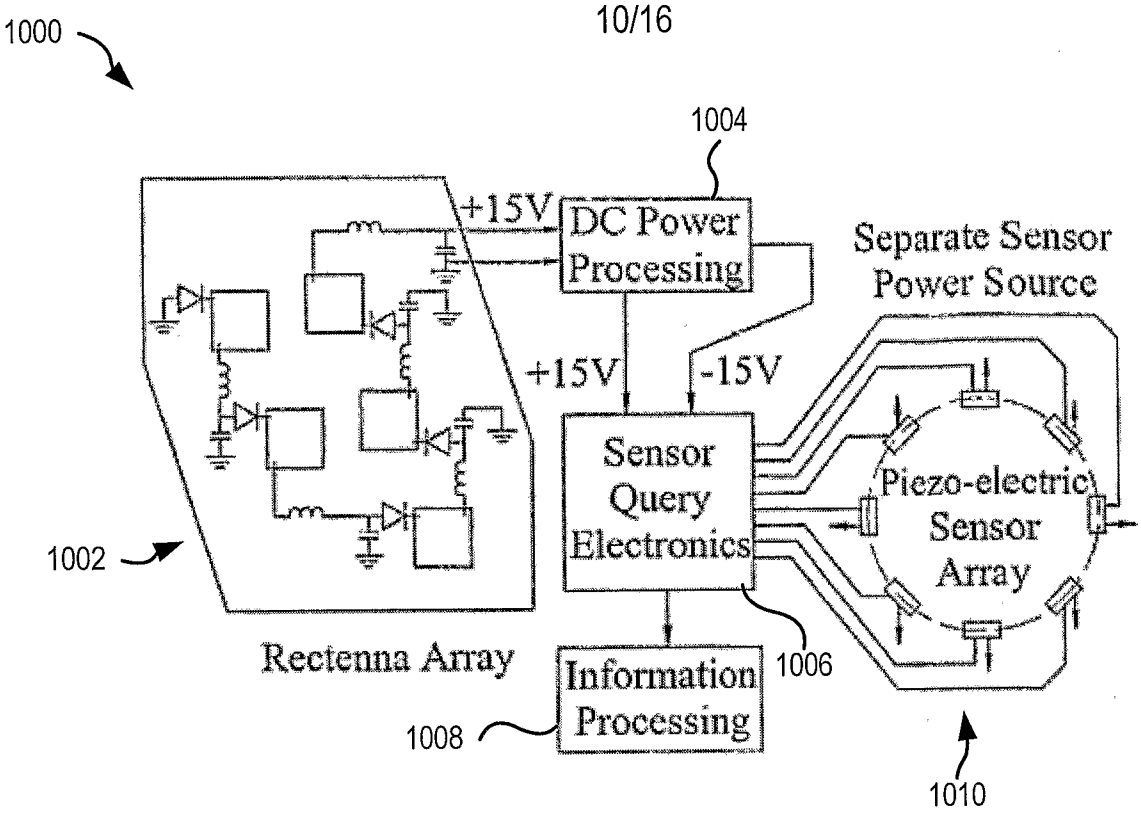

1000
1004
+15V
DC Power Processing
Separate Sensor Power Source
+15V
-15V
Sensor Query Electronics
Piezo-electric Sensor Array
1002
Rectenna Array
Information Processing
1006
1008
1010

FIG. 10

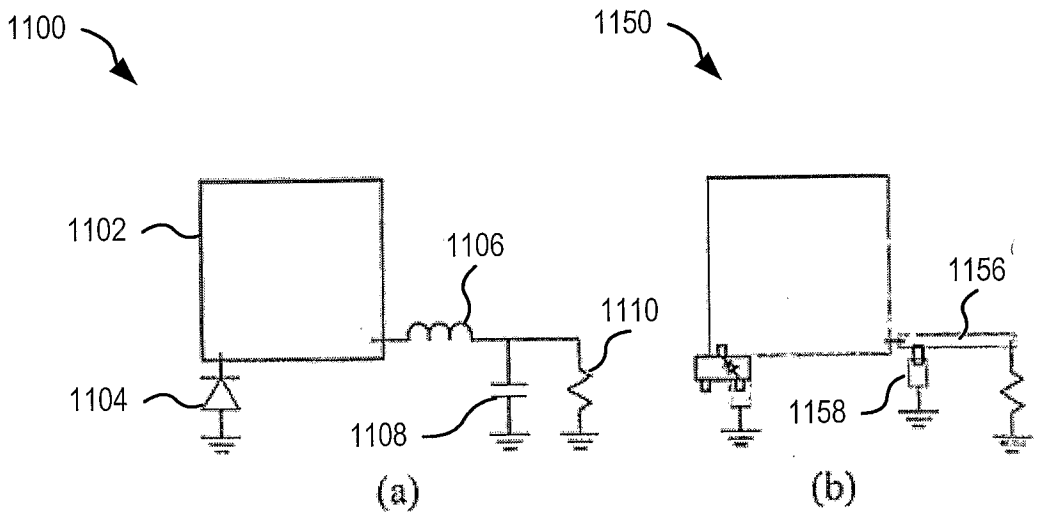
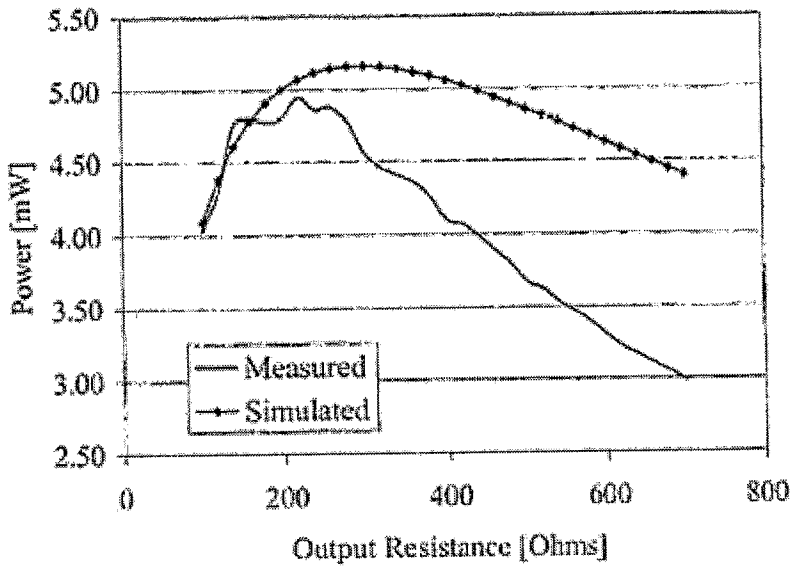

1100
1150
1102
1106
1110
1104
1108
1156
1158
(a)
(b)

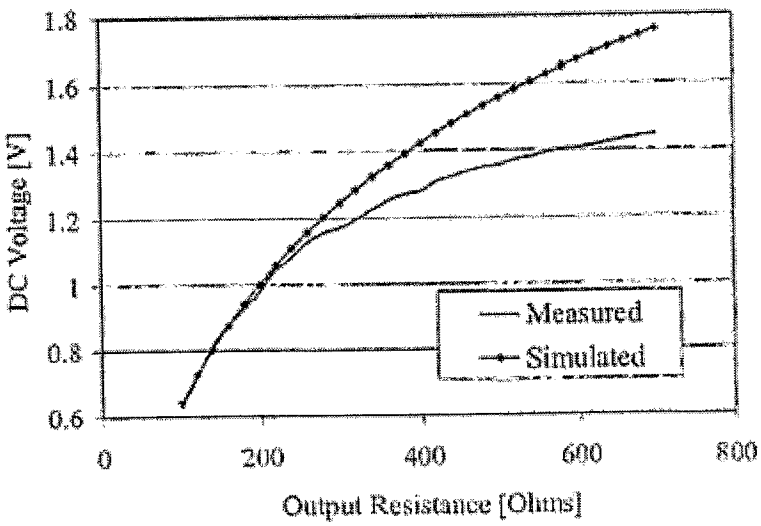
FIG. 11

1200



(a)

1250



(b)

FIG. 12

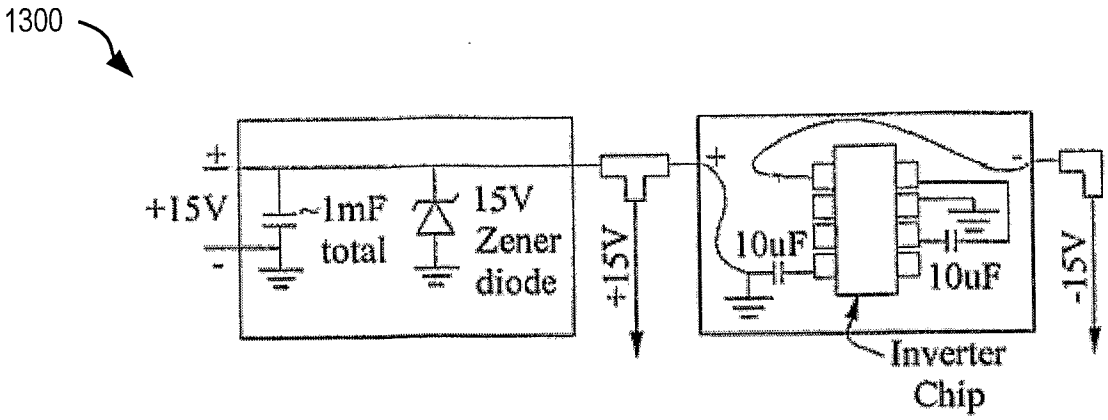

1300
+
+15V
-
~1mF
total
15V
Zener
diode
+15V
+
-
10uF
10uF
-15V
Inverter
Chip

FIG. 13

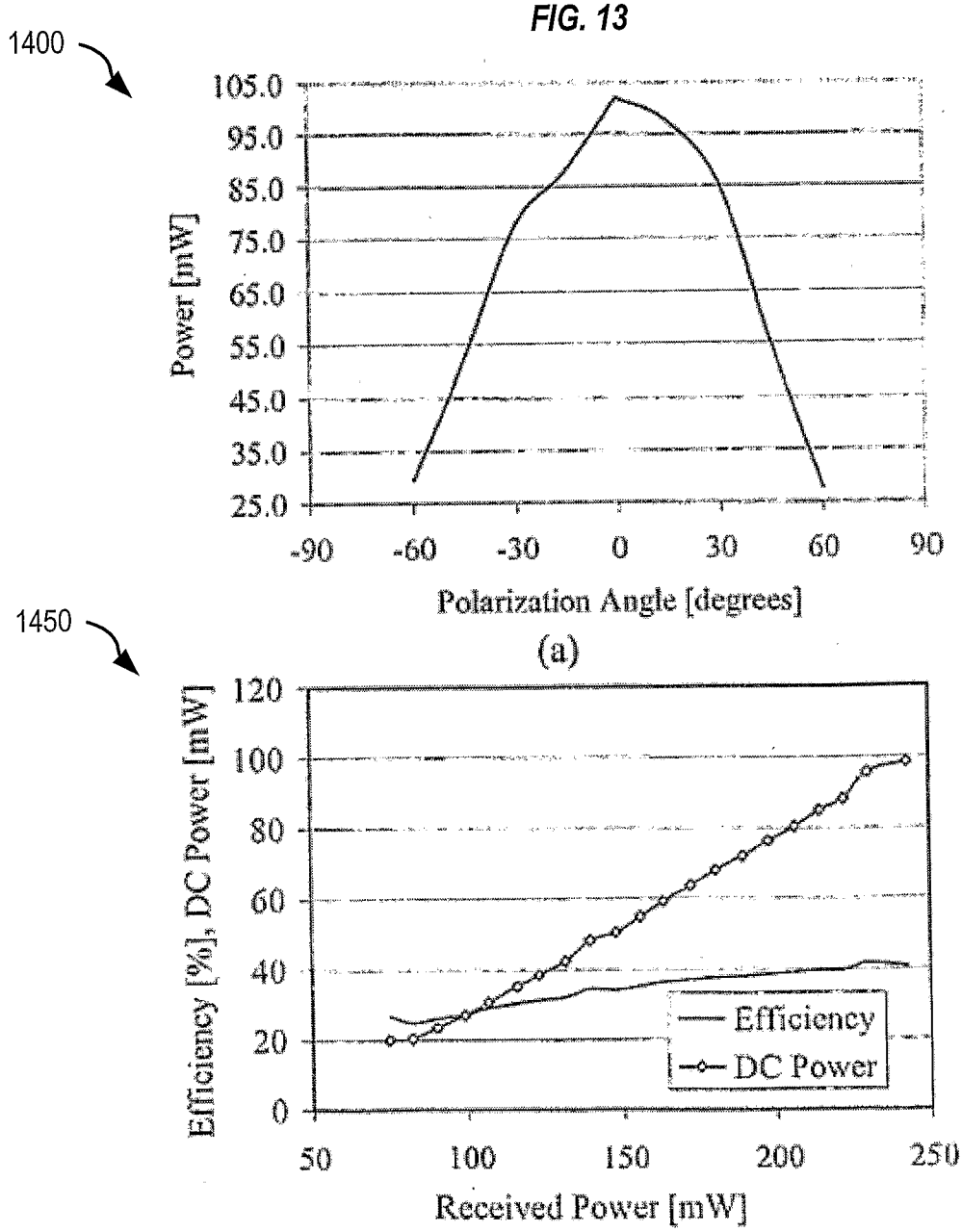

1400
105.0
95.0
85.0
75.0
65.0
55.0
45.0
35.0
25.0
Power [mW]
-90
-60
-30
0
30
60
90
Polarization Angle [degrees]
(a)
1450
120
100
80
60
40
20
0
Efficiency [%], DC Power [mW]
Efficiency
DC Power
50
100
150
200
250
Received Power [mW]
(b)

FIG. 14

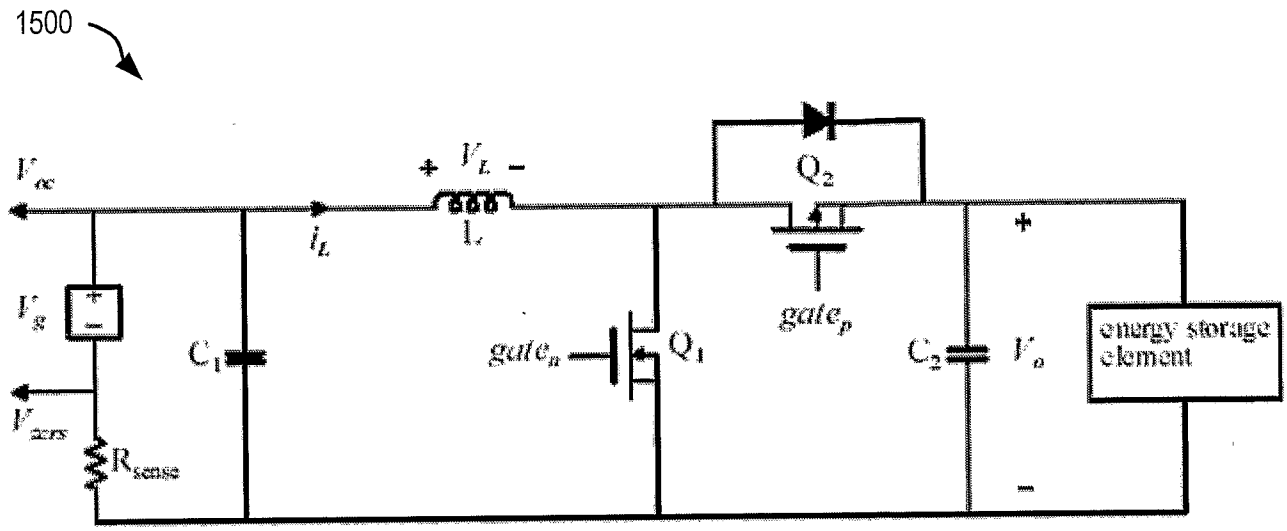

1500
V_{ac}
$+ V_L -$
Q_2
i_L
L
V_g
C_1
$gate_n$
Q_1
$gate_p$
C_2
V_o
energy storage element
V_{zcrs}
R_{sense}

FIG. 15

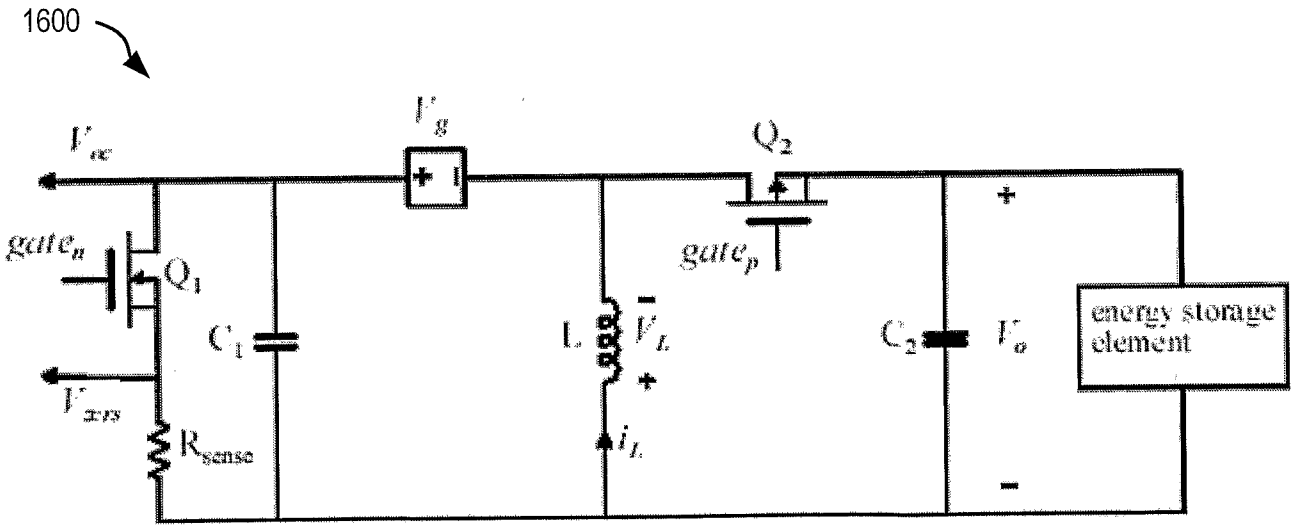

1600
V_{ac}
V_g
Q_2
$gate_n$
Q_1
$gate_p$
C_1
L
V_L
C_2
V_o
energy storage element
V_{zcrs}
R_{sense}
i_L

FIG. 16

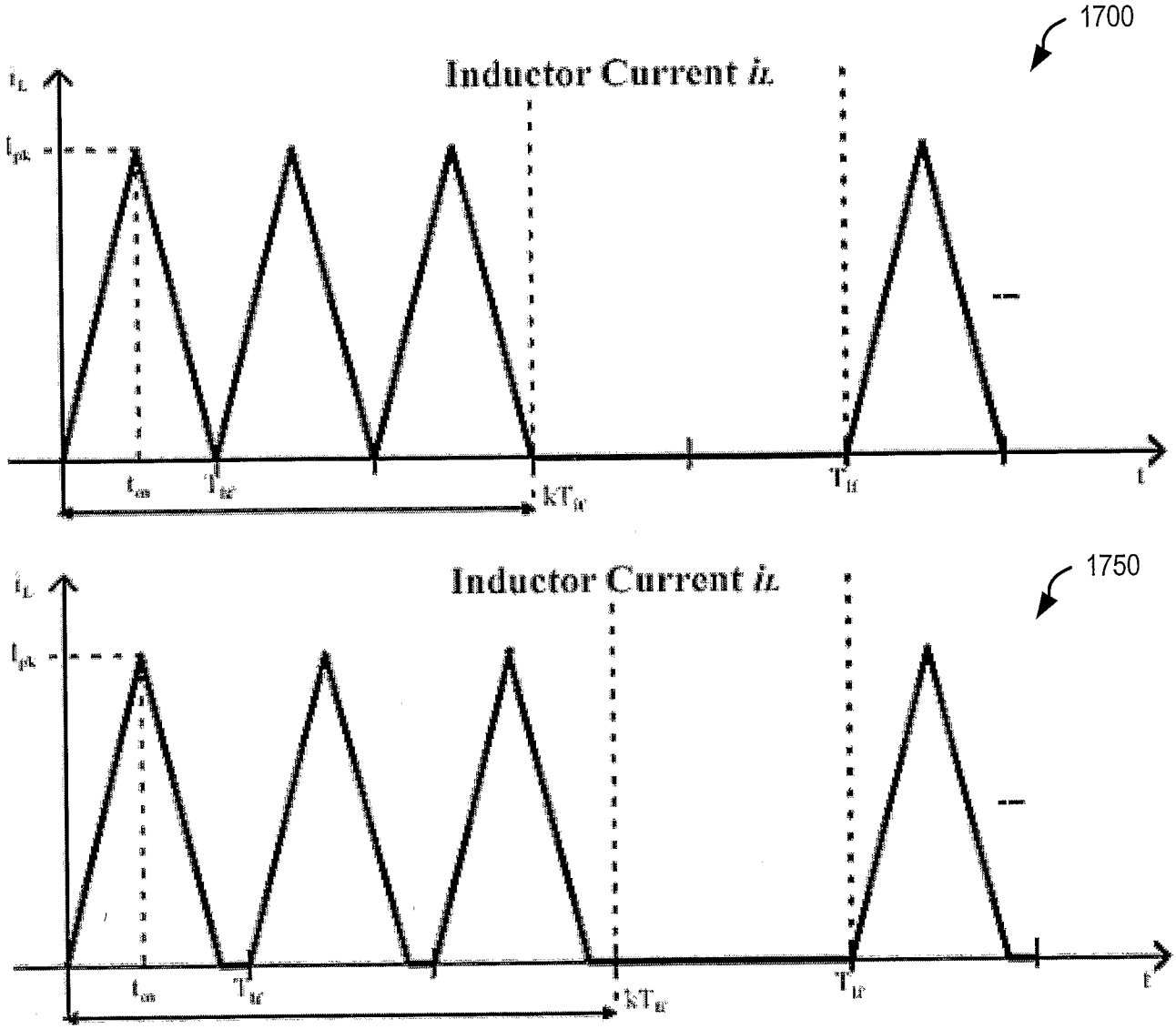


FIG. 17

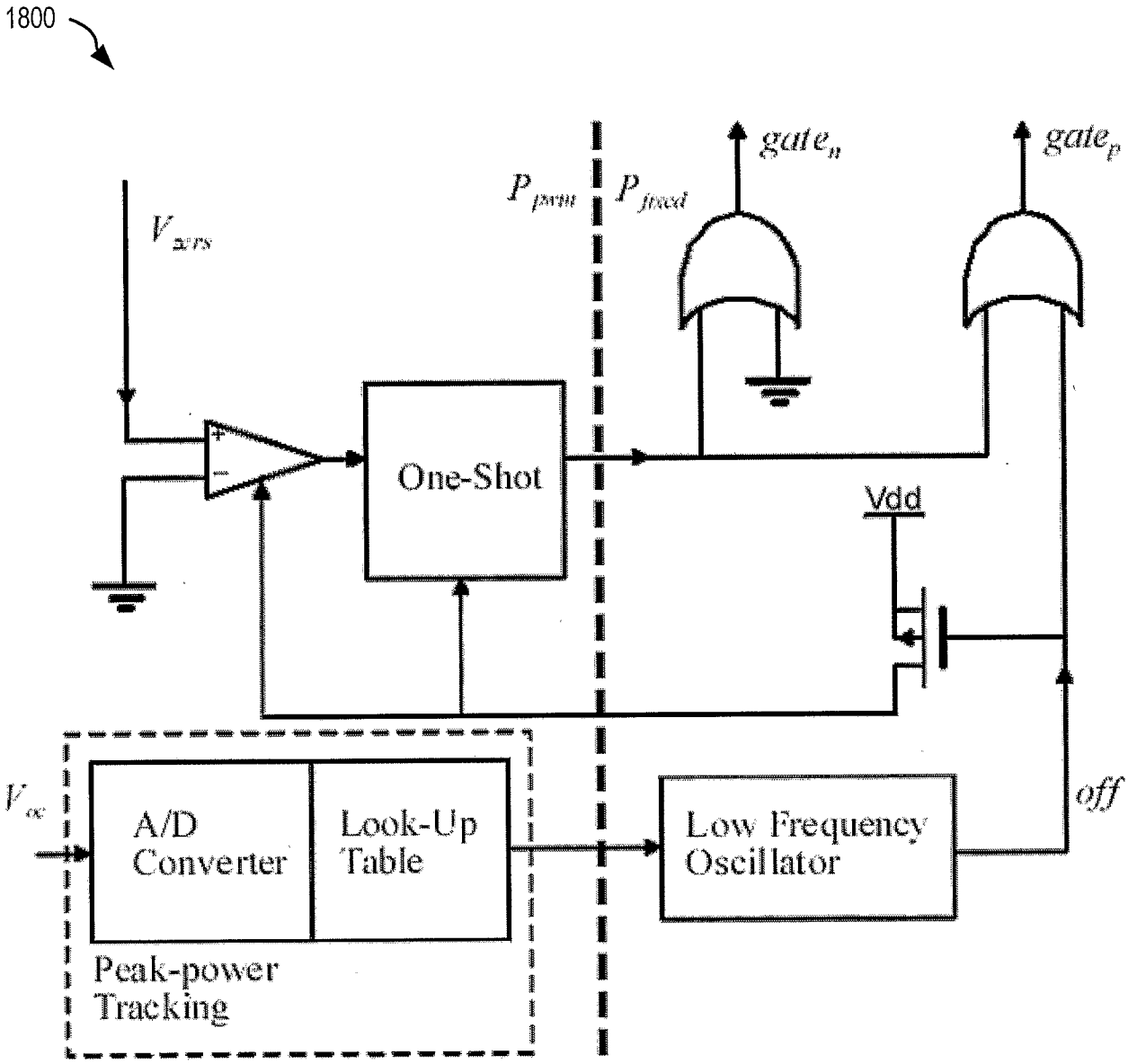

1800
V_{ref}
P_{pwm}
P_{feed}
$gate_n$
$gate_p$
One-Shot
Vdd
V_{osc}
A/D Converter
Look-Up Table
Peak-power Tracking
Low Frequency Oscillator
off

FIG. 18

1900

$$P_{in} = V_g \cdot I_{avg} = V_g \cdot \frac{I_{pk}}{2} k = \frac{V_g^2 \cdot t_{on}}{2L} k \quad (1)$$

1950

$$I_{pk} = \frac{V_g \cdot t_{on}}{L} \Rightarrow R_{emulated} = \frac{2L}{t_{on} \cdot k} \quad (2)$$

FIG. 19

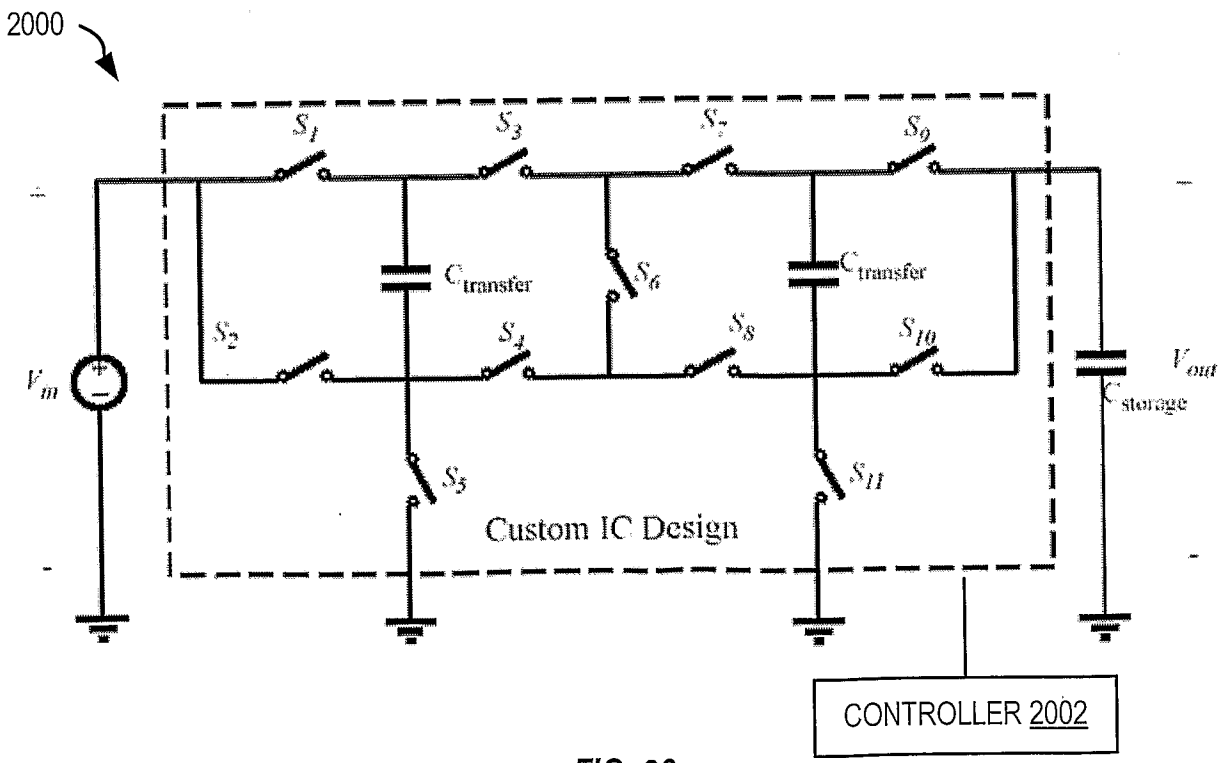


FIG. 20