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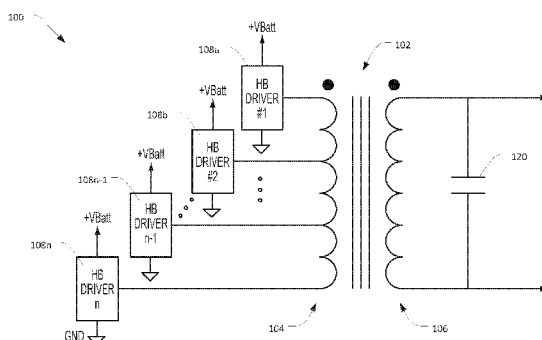


FIG. 1

(57) Abstract: The design of high-power RF amplifiers, specifically the design of the output transformer, is complicated by the relatively low voltage provided by battery packs that are practical for handheld devices meant for possibly delicate uses. Provided is an RF amplifier with one or more taps on the primary coil, wherein each tap is controlled by a half bridge driver. The output transformer primary winding may be driven between any two half bridge drivers, with the number of turns between the half bridge drivers and the fixed output winding determining the overall turns ration for the transformer.

HIGH POWER BATTERY POWERED RF AMPLIFIER TOPOLOGY

INTRODUCTION

[0001] The present disclosure relates to the design of high-power radiofrequency amplifiers for use in electrosurgical instruments that employ radiofrequency energy to cauterize or coagulate tissue.

[0002] Conventional corded electrosurgical instruments are large in size, have large power supplies and control electronics, and take up a lot of space in the operating room. Corded electrosurgical instruments are particularly cumbersome and difficult to use during a surgical procedure in part due to tethering of the hand-held electrosurgical instrument to the power supply and control electronics and the potential for cord entanglement. Some of these deficiencies have been overcome by providing battery powered hand-held electrosurgical instruments in which the power and control electronics are mounted within the instrument itself, such as within the handle of the instrument, to reduce the size of the electrosurgical instrument and make such instruments easier to use during surgical procedures.

[0003] Electrosurgical medical instruments generally include an end effector having an electrical contact, a radiofrequency (RF) generation circuit for generating an RF drive signal and to provide the RF drive signal to the at least one electrical contact where the RF generation circuit also includes a resonant circuit. The RF circuit includes circuitry to generate a cyclically varying signal, such as a square wave signal, from a direct current (DC) energy source and the resonant circuit is configured to receive the cyclically varying signal from the switching circuitry. The DC energy source is generally provided by one or more batteries that can be mounted in a handle portion of the housing of the instrument, for example.

[0004] Batteries mounted within the electrosurgical instrument have several limitations. For example, the amount of power the batteries provide must be balanced against their weight and size. Thus electrosurgical instruments employing RF energy typically include a high-power RF amplifier, for instance, one producing 5A RMS output, 300W, at 170V RMS.

[0005] The design of high-power RF amplifiers, specifically the design of the output transformer, is complicated by the relatively low voltage provided by battery packs that are practical for handheld devices meant for possibly delicate uses. Such battery packs usually provide voltage in multiples of 4.2V (i.e. Lilon cell potential). The upper practical limit for handled devices is up to five cells in series — for example, in a 2P5S (sets of two parallel cells, five sets in a series string) — due to space and weight constraints. Even with a 2P5S battery

configuration, selecting a workable turns ratio for the output transformer is at best a compromise between the maximum allowable primary current when in current limit mode and the need for a reasonable turns ratio for generating 170-250V RMS in the voltage control region of an electrosurgical device's power curve. The present disclosure provides a compact, optimally performing high power RF amplifier with significantly less compromise in the design of the output transformer. The present disclosure provides systems and methods for changing the turns ratio at will, synchronously with the carrier frequency of the energy device. Thus it is possible to adapt to the requirements of each region of an electrosurgical or ultrasonic power curve (current limit, power limit and voltage limit).

SUMMARY

[0006] In one embodiment, a current amplifier comprises a transformer, the transformer comprising one or more taps on the primary coil, wherein each tap comprises a half bridge driver, wherein the half bridge drivers configured to selectively turn on or turn off the tap.

[0007] In another embodiment, the half bridge driver comprises an upper switch element and a lower switch element, a high-side drive input connected to the input of the upper switch element, a low-side drive input connected to the input of the lower switch element, wherein the upper and lower switch elements are connected in a cascade arrangement and the output of the half bridge driver is taken from the node between the upper and lower switch elements.

[0008] In another embodiment, the upper and lower switch elements comprise solid-state switching elements. In another embodiment, the solid-state switching elements comprise MOSFETs.

[0009] In another embodiment, the upper and lower switch elements comprise IGBTs.

[0010] In another embodiment, the upper and lower switch elements comprise mechanical relays.

[0011] In another embodiment the current amplifier comprises a parallel capacitor on the secondary coil, such that the output produced by the amplifier is a sine wave.

[0012] In another embodiment, the minimum winding ratio is 4:1.

[0013] In another embodiment, the maximum winding ratio is 15:1.

[0014] In one embodiment, an electrosurgical medical instrument comprises a radio frequency (RF) generation circuit coupled to and operated by a battery and operable to generate an RF drive signal and to provide the RF drive signal to at least one electrical contact, wherein the RF generation circuit comprises: A current amplifier, comprising a transformer, the

transformer comprising one or more taps on the primary coil, wherein each tap comprises a half bridge driver.

[0015] In another embodiment, the half bridge driver comprises an upper switch element and a lower switch element, a high-side drive input connected to the input of the upper switch element, a low-side drive input connected to the input of the lower switch element, wherein the upper and lower switch elements are connected in a cascade arrangement and the output of the half bridge driver is taken from the node between the upper and lower switch elements.

[0016] In another embodiment, the upper and lower switch elements comprise solid-state switching elements. In another embodiment, the solid-state switching elements comprise MOSFETs.

[0017] In another embodiment, the upper and lower switch elements comprise IGBTs.

[0018] In another embodiment, the upper and lower switch elements comprise mechanical relays.

[0019] In another embodiment, the medical instrument comprises a parallel capacitor on the secondary coil, such that the output produced by the amplifier is a sine wave.

[0020] In another embodiment, the minimum winding ratio is 4:1.

[0021] In another embodiment, the maximum winding ratio is 15:1.

In one embodiment, a current amplifier, comprises a transformer comprising one or more taps on the primary coil, wherein each tap comprises a half bridge driver configured to selectively turn on or turn off the tap, wherein the half bridge driver comprises an upper switch element and a lower switch element, a high-side drive input connected to the input of the upper switch element, a low-side drive input connected to the input of the lower switch element, wherein the upper and lower switch elements are connected in a cascade arrangement and the output of the half bridge driver is taken from the node between the upper and lower switch elements; and a parallel capacitor on the secondary coil, such that the output produced by the amplifier is a sine wave; wherein the minimum winding ratio is 4:1; and wherein the maximum winding ratio is 15:1.

[0022] In another embodiment, the upper and lower switch elements comprise solid-state switching elements.

FIGURES

[0023] The novel features of the embodiments described herein are set forth with particularity in the appended claims. The embodiments, however, both as to organization and

methods of operation may be better understood by reference to the following description, taken in conjunction with the accompanying drawings as follows:

[0024] FIG. 1 illustrates one embodiment of an RF amplifier with one or more of taps on the primary coil, wherein each tap is controlled by a half bridge driver;

[0025] FIG. 2 illustrates one embodiment of a half bridge circuit that may be employed by the half bridge driver;

[0026] FIG. 3 illustrates an RF drive and control circuit, according to one embodiment;

[0027] FIG. 4 illustrates a perspective view of one embodiment of the transformer shown as transformer in connection with the RF drive circuit illustrated in FIG. 3;

[0028] FIG. 5 illustrates a perspective view of one embodiment of the primary coil of the transformer illustrated in FIG. 4;

[0029] FIG. 6 illustrates a perspective view of one embodiment of a secondary coil of the transformer illustrated in FIG. 4;

[0030] FIG. 7 illustrates a bottom view of the primary coil illustrated in FIG. 5;

[0031] FIG. 8 illustrates a side view of the primary coil illustrated in FIG. 5;

[0032] FIG. 9 illustrates a sectional view of the primary coil illustrated in FIG. 5 taken along section 28-28;

[0033] FIG. 10 illustrates a bottom view of the secondary coil illustrated in FIG. 6;

[0034] FIG. 11 illustrates a side view of the secondary coil illustrated in FIG. 6;

[0035] FIG. 12 illustrates a sectional view of the secondary coil illustrated in FIG. 11 taken along section 31-31;

[0036] FIG. 13 is a perspective view of one embodiment of the inductor shown as inductor L_s in connection with the RF drive circuit illustrated in FIG. 3;

[0037] FIG. 14 illustrates a bottom view of the inductor illustrated in FIG. 13;

[0038] FIG. 15 illustrates a side view of the inductor illustrated in FIG. 13;

[0039] FIG. 16 illustrates a sectional view of the inductor illustrated in FIG. 15 taken along section 35-35.

[0040] FIG. 17 illustrates the main components of the controller, according to one embodiment;

[0041] FIG. 18 is a signal plot illustrating the switching signals applied to the FETs, a sinusoidal signal representing the measured current or voltage applied to the load, and the timings when the synchronous sampling circuitry samples the sensed load voltage and load current, according to one embodiment; and

[0042] FIG. 19 illustrates a drive waveform for driving the FET gate drive circuitry, according to one embodiment.

DESCRIPTION

[0043] In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols and reference characters typically identify similar components throughout the several views, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the scope of the subject matter presented here.

[0044] The following description of certain examples of the technology should not be used to limit its scope. Other examples, features, aspects, embodiments, and advantages of the technology will become apparent to those skilled in the art from the following description, which is by way of illustration, one of the best modes contemplated for carrying out the technology. As will be realized, the technology described herein is capable of other different and obvious aspects, all without departing from the technology. Accordingly, the drawings and descriptions should be regarded as illustrative in nature and not restrictive.

[0045] It is further understood that any one or more of the teachings, expressions, embodiments, examples, etc. described herein may be combined with any one or more of the other teachings, expressions, embodiments, examples, etc. that are described herein. The following-described teachings, expressions, embodiments, examples, etc. should therefore not be viewed in isolation relative to each other. Various suitable ways in which the teachings herein may be combined will be readily apparent to those of ordinary skill in the art in view of the teachings herein. Such modifications and variations are intended to be included within the scope of the claims.

[0046] Before explaining the various embodiments of the high power battery powered RF amplifier technology in detail, it should be noted that the various embodiments disclosed herein are not limited in their application or use to the details of construction and arrangement of parts illustrated in the accompanying drawings and description. Rather, the disclosed embodiments may be positioned or incorporated in other embodiments, variations and modifications thereof, and may be practiced or carried out in various ways. Accordingly, embodiments of the surgical devices disclosed herein are illustrative in nature and are not meant to limit the scope or application thereof. Furthermore, unless otherwise indicated, the terms and expressions employed herein have been chosen for the purpose of describing the embodiments for the

convenience of the reader and are not to limit the scope thereof. In addition, it should be understood that any one or more of the disclosed embodiments, expressions of embodiments, and/or examples thereof, can be combined with any one or more of the other disclosed embodiments, expressions of embodiments, and/or examples thereof, without limitation.

[0047] For clarity of disclosure, the terms "proximal" and "distal" are defined herein relative to a human or robotic operator of the surgical instrument. The term "proximal" refers the position of an element closer to the human or robotic operator of the surgical instrument and further away from the surgical end effector of the surgical instrument. The term "distal" refers to the position of an element closer to the surgical end effector of the surgical instrument and further away from the human or robotic operator of the surgical instrument.

[0048] Also, in the following description, it is to be understood that terms such as front, back, inside, outside, top, bottom, upper, lower and the like are words of convenience and are not to be construed as limiting terms. Terminology used herein is not meant to be limiting insofar as devices described herein, or portions thereof, may be attached or utilized in other orientations. The various embodiments will be described in more detail with reference to the drawings.

[0049] Many surgical procedures require cutting or ligating blood vessels or other vascular tissue. With minimally invasive surgery, surgeons perform surgical operations through a small incision in the patient's body. As a result of the limited space, surgeons often have difficulty controlling bleeding by clamping and/or tying-off transected blood vessels. By utilizing electrosurgical instruments, such as electrosurgical forceps, a surgeon can cauterize, coagulate/desiccate, and/or simply reduce or slow bleeding by controlling the electrosurgical energy applied through jaw members of the electrosurgical forceps, otherwise referred to as clamp arms.

[0050] Electrosurgical instruments generally comprise an electronics system for generating and controlling electrosurgical energy. The electronics system comprises an RF generation circuit to generate an RF drive signal and to provide the RF drive signal to at least one electrical contact, where the RF generation circuit also includes a resonant circuit. The electronics system also comprises control elements such as one or more than one microprocessor (or micro-controller) and additional digital electronic elements to control the logical operation of the instrument.

[0051] The electronics elements of the power supply and RF amplifier sections should be designed to have the highest efficiency possible in order to minimize heat rejected into the housing of the instrument. Efficiency also provides the longest storage and operational battery

life possible. As described in the embodiments illustrated in FIGS. 4-16, litz wire may be wound around a bobbin core to reduce AC losses due to high frequency RF. The litz wire construction provides greater efficiency and thus also prevents heat generation in the device.

[0052] In various embodiments, efficiency of the power supply and RF drive and control circuitry sections also may minimize the size of the battery required to fulfill the mission life, or to extend the mission life for a given size battery. In one embodiment, the battery provides a low source impedance at a terminal voltage of 12.6V (unloaded) and a 1030 mA-Hour capacity. Under load, the battery voltage is a nominal 11.1V, for example.

[0053] Radio frequency drive amplifier topologies may vary according to various embodiments. In one embodiment, for example, a series resonant approach may be employed where the operating frequency is varied to change the output voltage to force the medical instrument to operate according to a pre-programmed load curve. In a series resonant approach, the impedance of a series resonant network is at a minimum at the resonant frequency, because the reactance of the capacitive and inductive elements cancel, leaving a small real resistance. The voltage maximum for a series resonant circuit also occurs at the resonant frequency (and also depends upon the circuit Q). Accordingly, to produce a high voltage on the output, the series resonant circuit should operate closer to the resonant frequency, which increases the current draw from the DC supply (e.g., battery) to feed the RF amplifier section with the required current. Although the series resonant approach may be referred to as a resonant mode boost converter, in reality, the design is rarely operated at the resonant frequency, because that is the point of maximum voltage. The benefit of a resonant mode topology is that if it is operated very close to the resonant frequency, the switching field effect transistors (FETs) can be switched "ON" or "OFF" at either a voltage or current zero crossing, which dissipates the least amount of power in the switching FETs as is possible.

[0054] Another feature of the RF drive and control circuitry section according to one embodiment, provides a relatively high turns ratio transformer which steps up the output voltage to about 85V RMS from the nominal battery voltage of about 11.1V. This provides a more compact implementation because only one transformer and one other inductor are required. In such a circuit, high currents are necessary on the transformer primary to create the desired output voltage or current. Such device, however, cannot be operated at the resonant frequency because allowances are made to take into account for the battery voltage dropping as it is expended. Accordingly, some headroom is provided to maintain the output voltage at the required level. A more detailed description of a series resonant approach is provided in commonly assigned international PCT Patent Application No. PCT/GB2011/000778, titled

"Medical Device," filed May 20, 2011, the disclosure of which is incorporated herein by reference in its entirety.

[0055] According to another embodiment, an RF instrument topology is provided for a handheld battery powered RF based generator for the electrosurgical medical instrument. Accordingly, in one embodiment, the present disclosure provides an RF instrument topology with an architecture configured such that each power section of the device operate at maximum efficiency regardless of the load resistance presented by the tissue or what voltage, current, or power level is commanded by the controller. In one embodiment, this may be implemented by employing the most efficient modalities of energy transformation presently known and by minimizing the component size to provide a small and light weight electronics package to fit within the instrument's housing, for example.

[0056] In one embodiment, the RF power electronics section of the electronics system may be partitioned as a boost mode converter, synchronous buck converter, and a parallel resonant amplifier. According to one embodiment, a resonant mode boost converter section of the medical instrument may be employed to convert the DC battery voltage to a higher DC voltage for use by the synchronous mode buck converter. One aspect to consider for achieving a predetermined efficiency of the resonant mode boost converter section is ratio between input and output voltages of the boost converter. In one embodiment, although a 10:1 ratio is achievable, the cost is that for any appreciable power on the secondary the input currents to the boost mode transformer become quite heavy, in the range of about 15-25A, depending on the load. In another embodiment a transformer turns ratio of about 5:1 is provided. It will be appreciated that transformer ratios in the range of about 5:1 to about 10:1 also may be implemented, without limitation. In a 5:1 transformer turns ratio, the design tradeoff is managing the Q of the parallel resonant output against the boost ratio. The resonant output network performs two functions. First, it filters the square, digital pulses from the Class D output amplifier and removes all but the fundamental frequency sine wave from the output. Second, it provides a passive voltage gain due to the Q of the filter network. In other words, current from the amplifier is turned into output voltage, at a gain determined by the circuit's unloaded Q and the load resistance, which affects the Q of the circuit.

[0057] Another aspect to consider for achieving a predetermined efficiency in the resonant mode boost converter section is to utilize a full bridge switcher topology, which allows half the turns ratio for the boost transformer for the same input voltage. The tradeoff is that this approach may require additional FET transistors, e.g., an additional two FETs are required over a half bridge approach, for example. Presently available switchmode FETs, however, are

relatively small, and while the gate drive power is not negligible, it provides a reasonable design tradeoff.

[0058] Yet another aspect to consider for achieving a predetermined efficiency in the resonant mode boost converter section and operating the boost converter at maximum efficiency, is to always run the circuit at the resonant frequency so that the FETs are always switching at either a voltage or current minima, whichever is selected by the designer (ZCS vs. ZVS switching), for example. This can include monitoring the resonant frequency of the converter as the load changes, and making adjustments to the switching frequency of the boost converter to allow 35 ZVS or ZCS (Zero Voltage Switching/Zero Current Switching) to occur for minimum power dissipation.

[0059] Yet another aspect to consider for achieving a predetermined efficiency in the resonant mode boost converter section is to utilize a synchronous rectifier circuit instead of a conventional full-wave diode rectifier block. Synchronous rectification employs FETs as diodes because the on-resistance of the FET is so much lower than that of even a Schottky power diode optimized for low forward voltage drop under high current conditions. A synchronous rectifier requires gate drive for the FETs and the logic to control them, but offers significant power savings over a traditional full bridge rectifier.

[0060] In accordance with various embodiments, the predetermined efficiency of a resonant mode boost converter is approximately 98-99% input to output, for example. Any suitable predetermined efficiency may be selected based on the particular implementation. Accordingly, the embodiments described herein are limited in this context.

[0061] According to one embodiment, a synchronous buck converter section of the medical instrument may be employed to reduce the DC voltage fed to the RF amplifier section to the predetermined level to maintain the commanded output power, voltage or current as dictated by the load curve, with as little loss as is possible. The buck converter is essentially an LC lowpass filter fed by a low impedance switch, along with a regulation circuit to control the switch to maintain the commanded output voltage. The operating voltage is dropped to the predetermined level commanded by the main controller, which is running the control system code to force the system to follow the assigned load curve as a function of sensed tissue resistance. In accordance with various embodiments, the predetermined efficiency of a synchronous buck regulator is approximately 99%, for example. Any suitable predetermined efficiency may be selected based on the particular implementation. Accordingly, the embodiments described herein are limited in this context.

[0062] According to one embodiment, a resonant mode RF amplifier section comprising a parallel resonant network on the RF amplifier section output is provided. In one embodiment, a predetermined efficiency may be achieved by a providing a parallel resonant network on the RF amplifier section output. The RF amplifier section may be driven at the resonant frequency of the output network, which accomplishes three things. First, the high Q network allows some passive voltage gain on the output, reducing the boost required from the boost regulator in order to produce high voltage output levels. Second, the square pulses produced by the RF amplifier section are filtered and only the fundamental frequency is allowed to pass to the output. Third, a full-bridge amplifier is switched at the resonant frequency of the output filter, which is to say at either the voltage zero crossings or the current zero crossings in order to dissipate minimum power. Accordingly, a predetermined efficiency of the RF amplifier section is approximately 98%. Gate drive losses may limit the efficiency to this figure or slightly lower. Any suitable predetermined efficiency may be selected based on the particular implementation. Accordingly, the embodiments described herein are limited in this context.

[0063] In view of the RF instrument topology and architecture described above, an overall system efficiency of approximately $0.99 \times 0.99 \times 0.98$, which is approximately 96%, may be achieved. Accordingly, to deliver approximately 45W, approximately 1.8W would be dissipated by the electronics exclusive of the power required to run the main and housekeeping microprocessors, and the support circuits such as the ADC and analog amplifiers and filters. To deliver approximately 135W, approximately 5.4W would be dissipated. This is the amount of power that would be required to implement a large jaw class generator in a hand held electrosurgical medical instrument. Overall system efficiency would likely only be a weak function of load resistance, instead of a relatively strong one as it may be the case in some conventional instruments.

[0064] In various other embodiments of the electrosurgical medical instrument, a series resonant topology may be employed to achieve certain predetermined efficiency increase by employing a full bridge amplifier for the primary circuit and isolate the full bridge amplifier from ground to get more voltage on the primary. This provides a larger primary inductance and lower flux density due to the larger number of turns on the primary.

[0065] FIG. 3 illustrates an RF drive and control circuit 800, according to one embodiment. FIG. 3 is a part schematic part block diagram illustrating the RF drive and control circuitry 800 used in this embodiment to generate and control the RF electrical energy supplied to the electrosurgical instrument. As will be explained in more detail below, in this embodiment, the drive circuitry 800 is a resonant mode RF amplifier comprising a parallel resonant network on

the RF amplifier output and the control circuitry operates to control the operating frequency of the drive signal so that it is maintained at the resonant frequency of the drive circuit, which in turn controls the amount of power supplied to the instrument. The way that this is achieved will become apparent from the following description.

[0066] As shown in FIG. 3, the RF drive and control circuit 800 comprises a battery 300 arranged to supply, in this example, about 0V and about 12V rails. An input capacitor (C_{in}) 802 is connected between the 0V and the 12V for providing a low source impedance. A pair of FET switches 803-1 and 803-2 (both of which are N-channel in this embodiment to reduce power losses) is connected in series between the 0V rail and the 30 12V rail. FET gate drive circuitry 805 is provided that generates two drive signals — one for driving each of the two FETs 803. The FET gate drive circuitry 805 generates drive signals that causes the upper FET (803-1) to be on when the lower FET (803-2) is off and vice versa. This causes the node 807 to be alternately connected to the 12V rail (when the FET 803-1 is switched on) and the 0V rail (when the FET 803-2 is switched on). FIG. 3 also shows the internal parasitic diodes 808-1 and 808-2 of the corresponding FETs 803, which conduct during any periods that the FETs 803 are open.

[0067] As shown in FIG. 3, the node 807 is connected to an inductor-inductor resonant circuit 810 formed by an inductor L_s 812 and an inductor L_m 814, which is the primary coil of a transformer 815. The FET gate driving circuitry 805 is arranged to generate drive signals at a drive frequency (f_d) that opens and crosses the FET switches 803 at the resonant frequency of the parallel resonant circuit 810. As a result of the resonant characteristic of the resonant circuit 810, the square wave voltage at node 807 will cause a substantially sinusoidal current at the drive frequency (f_d) to flow within the resonant circuit 810. As illustrated in FIG. 9, the inductor L_m 814 is the primary coil of a transformer 815, the secondary coil of which is formed by inductor L_{sec} 816. The inductor L_{sec} 816 of the transformer 815 secondary is connected to a resonant circuit 817 formed by inductor L_2 , capacitor C_4 820, capacitor C_2 822, and capacitor C_3 825. The transformer 815 up-converts the drive voltage (V_d) across the inductor L_m 814 to the voltage that is applied to the output parallel resonant circuit 817. The load voltage (V_L) is output by the parallel resonant circuit 817 and is applied to the load (represented by the load resistance R_{load} 819 in FIG. 3) corresponding to the impedance of the forceps' jaws and any tissue or vessel gripped by the forceps 108. As shown in FIG. 3, a pair of DC blocking capacitors C_{bl1} 840-1 and C_{bl2} 840-2 is provided to prevent any DC signal being applied to the load 819.

[0068] In one embodiment, the transformer 815 may be implemented with a Core Diameter (mm), Wire Diameter (mm), and Gap between secondary windings in accordance with the following specifications:

Core Diameter, D (mm)

$$D = 19.9 \times 10^{-3}$$

Wire diameter, W (mm) for 22 AWG wire

$$W = 7.366 \times 10^{-4}$$

Gap between secondary windings, in gap= 0.125

$$G = \text{gap}/25.4$$

[0069] In this embodiment, the amount of electrical power supplied to the electrosurgical instrument is controlled by varying the frequency of the switching signals used to switch the FETs 803. This works because the resonant circuit 810 acts as a frequency dependent (loss less) attenuator. The closer the drive signal is to the resonant frequency of the resonant circuit 810, the less the drive signal is attenuated. Similarly, as the frequency of the drive signal is moved away from the resonant frequency of the circuit 810, the more the drive signal is attenuated and so the power supplied to the load reduces. In this embodiment, the frequency of the switching signals generated by the FET gate drive circuitry 805 is controlled by a controller 841 based on a desired power to be delivered to the load 819 and measurements of the load voltage (V_L) and of the load current (I_L) obtained by conventional voltage sensing circuitry 843 and current sensing circuitry 845. The way that the controller 841 operates will be described in more detail below.

[0070] In one embodiment, the voltage sensing circuitry 843 and the current sensing circuitry 845 may be implemented with high bandwidth, high speed rail-to-rail amplifiers (e.g., LMH6643 by National Semiconductor). Such amplifiers, however, consume a relatively high current when they are operational. Accordingly, a power save circuit may be provided to reduce the supply voltage of the amplifiers when they are not being used in the voltage sensing circuitry 843 and the current sensing circuitry 845. In one-embodiment, a step-down regulator (e.g., LT3502 by Linear Technologies) may be employed by the power save circuit to reduce the supply voltage of the rail-to-rail amplifiers and thus extend the life of the battery 300.

[0071] In one embodiment, the transformer 815 and/or the inductor L_s 812 may be implemented with a configuration of litz wire conductors to minimize the eddy-current effects in the windings of high-frequency inductive components. These effects include skin-effect losses and proximity effect losses. Both effects can be controlled by the use of litz wire, which are conductors made up of multiple individually insulated strands of wire twisted or woven together. Although the term litz wire is frequently reserved for conductors constructed according to a carefully prescribed pattern, in accordance with the present disclosure, any wire strands that are

simply twisted or grouped together may be referred to as litz wire. Accordingly, as used herein, the term litz wire refers to any insulated twisted or grouped strands of wires.

[0072] By way of background, litz wire can reduce the severe eddy-current losses that otherwise limit the performance of high-frequency magnetic components, such as the transformer 815 and/or the inductor L_s 812 used in the RF drive and control circuit 800 of FIG. 3. Although litz wire can be very expensive, certain design methodologies provide significant cost reduction without significant increases in loss, or more generally, enable the selection of a minimum loss design at any given cost. Losses in litz-wire transformer windings have been calculated by many authors, but relatively little work addresses the design problem of how to choose the number and diameter of strands for a particular application. Cost-constrained litz wire configurations are described in C. R. Sullivan, "Cost-Constrained Selection of Strand Wire and Number in a Litz-Wire Transformer Winding," *IEEE Transactions on Power Electronics*, vol. 16, no. 2, pp. 281-288, which is incorporated herein by reference. The choice of the degree of stranding in litz wire for a transformer winding is described in C. R. Sullivan, "Optimal Choice for Number of Strands in a Litz-Wire Transformer Winding," *IEEE Transactions on Power Electronics*, vol. 14, no. 2, pp. 283-291, which is incorporated herein by reference.

[0073] In one embodiment, the transformer 815 and/or the inductor L_s 812 may be implemented with litz wire by HM Wire International, Inc., of Canton, OH or New England Wire Technologies of Lisbon, NH, which has a slightly different construction in terms of the number of strands in the intermediate windings, but has the same total number of strands of either 44 gauge or 46 gauge wire by HM Wire International, Inc. Accordingly, the disclosure now turns to FIGS. 4-16, which illustrate one embodiment of the transformer 815 and the inductor L_s 81 implemented with litz wire.

[0074] FIG. 4 illustrates a perspective view of one embodiment of the transformer shown as transformer 815 in connection with the RF drive circuit 800 illustrated in FIG. 3. As shown in FIG. 4, in one embodiment, the transformer 404 comprises a bobbin 804, a ferrite core 806, a primary coil 821 (e.g., inductor L_m 814 in FIG. 3), and a secondary coil 823 (e.g., inductor L_{sec} 816 in FIG. 3). In one embodiment, the bobbin 804 may be a 10-pin surface mounted device (SMD) provided by Ferroxcube International Holding B.V. In one embodiment, the ferrite core 806 may be an EFD 20/107 N49. In one embodiment, the transformer 815 has a power transfer of ~45W, a maximum secondary current of ~1.5A RMS, maximum secondary voltage of ~90V RMS, maximum primary current of ~15.5A RMS, and a turns ratio of 20:2 (secondary turns:primary turns), for example. The operating frequency range of the transformer 404 is from ~370kHz to ~550kHz, and a preferred frequency of ~430kHz. It will be appreciated that these

specification are provided as examples and should not be construed to be limiting of the scope of the appended claims.

[0075] In one embodiment, the transformer 404 comprises a ferrite core material having particular characteristics. The core used for both the inductor 406 and the transformer 404, albeit with a different gap to yield the required A_L for each component. A_L has units of Henrys/turns², so the inductance of a winding may be found by using $N\text{TURN}^2 \cdot A_L$. In one embodiment, an A_L of 37 is used for the inductor 406, and an A_L of 55 is used for the transformer 406. This corresponds to a gap of approximately 0.8mm and 2.0mm respectively, although the A_L or the inductance is the parameter to which the manufacturing process controls, with the A_L being an intermediate quantity that we are not measuring directly.

[0076] In one embodiment, the inductance of the inductor 406 and transformer 404 winding may be measured directly with "golden bobbins," which are squarely in the middle of the tolerance bands for the winding statistical distributions. Cores that are ground are then tested using the "golden bobbin" to assess whether the grind is good on the cores. Better results were yielded than the industry standard method, which is to fill a bobbin with as many windings as they can fit on the bobbin, and then back calculating the A_L of the core, and controlling A_L instead of the inductance. It was found that using a "golden bobbin" in the manufacturing process yielded better results. The bobbin is what the copper windings are secured to, and the ferrite E cores slip through a hole in the bobbin, and are secured with clips.

[0077] FIG. 5 illustrates a perspective view of one embodiment of the primary coil 821 (e.g., inductor L_m 814 in FIG. 3) of the transformer 404 illustrated in FIG. 4. In one embodiment, the primary coil 821 windings may be constructed using 300 strand/46 gauge litz wire as indicated in TABLE 1 below, among other suitable configurations. In one embodiment, primary coil 821 has an inductance of ~270nH, an AC resistance < 46mΩ, and a DC resistance of ≤ 5mΩ, for example.

TABLE 1

Primary Coil 821 (L_m 814) 46 Gauge Litz Wire
300 Strands 46 AWG- 24 turns per foot (TPF)
Single Build MW80 155°C
Single Nylon Served
Construction: 5 x 3 x 20 / 46 AWG

Ft per lb: 412 Nominal
OD: 0.039" Nominal

[0078] FIG. 7 illustrates a bottom view of the primary coil 821 (e.g., inductor L_m 814 in FIG. 3) illustrated in FIG. 5. FIG. 8 illustrates a side view of the primary coil 821 illustrated in FIG. 5. FIG. 9 illustrates a sectional view of the primary coil 821 illustrated in FIG. 5 taken along section 28-28.

[0079] FIG. 6 illustrates a perspective view of one embodiment of a secondary coil 823 (e.g., inductor L_{sec} 816 in FIG. 3) of the transformer 404 illustrated in FIG. 4. In one embodiment, the secondary coil 823 windings may be constructed using 105 strand/44 gauge litz wire as indicated in TABLE 2 below, among other suitable configurations. In one embodiment, the secondary coil 823 has an inductance of $22\mu H \pm 5\%$ @430kHz, an AC resistance $< 2.5\Omega$, and a DC resistance $\leq 80m\Omega$, for example.

TABLE 2

Secondary Coil 823 (L_{sec} 816) 44 Gauge Litz Wire
105 Strands 44 AWG 24 TPF
Single Build MW80 155°C
Single Nylon Served
Construction: 5 x 21 / 44 AWG
Ft per lb: 1214 Nominal
OD: 0.023" Nominal

[0080] FIG. 10 illustrates a bottom view of the secondary coil 823 (e.g., inductor L_{sec} 816 in FIG. 3) illustrated in FIG. 6. FIG. 11 illustrates a side view of the secondary coil 823 illustrated in FIG. 6. FIG. 12 illustrates a sectional view of the secondary coil 823 illustrated in FIG. 11 taken along section 31-31.

[0081] FIG. 13 is a perspective view of one embodiment of the inductor 406 shown as inductor L_s 812 in connection with the RF drive circuit 800 illustrated in FIG. 3. As shown in FIG. 13, in one embodiment, the inductor 406 comprises a bobbin 809, a ferrite core 811, and a coil 813. In one embodiment, the bobbin 809 may be a 10-pin surface mounted device (SMD)

provided by Ferroxcube International Holding B.V. In one embodiment, the ferrite core 811 may be an EFD 20/107 N49. In one embodiment, the coil 813 windings may be constructed using 300 strand/46 gauge litz wire wound at 24 TPF. In one embodiment, the inductor L_s 812 may have an inductance of $\sim 345\text{nH} \pm 6\%$ @430kHz, an AC resistance $< 50\text{m}\Omega$, and a DC resistance $\leq 7\text{m}\Omega$, for example. The operating frequency range of the inductor L_s 812 is from $\sim 370\text{kHz}$ to $\sim 550\text{kHz}$, and a preferred frequency of $\sim 430\text{kHz}$, and an operating current of $\sim 15.5\text{A RMS}$. It will be appreciated that these specification are provided as examples and should not be construed to be limiting of the scope of the appended claims.

[0082] FIG. 14 illustrates a bottom view of the inductor 406 (e.g., inductor L_s 812 in FIG. 3) illustrated in FIG. 13. FIG. 15 illustrates a side view of the inductor 406 illustrated in FIG. 13. FIG. 16 illustrates a sectional view of the inductor 406 illustrated in FIG. 15 taken along section 35-35.

[0083] Accordingly, as described above in connection with FIGS. 4-16, in one embodiment, the transformer 404 (e.g., transformer 815) and/or the inductor 406 (e.g., inductor 812) used in the RF drive and control circuit 800 of FIG. 3 may be implemented with litz wire. One litz wire configuration may be produced by twisting 21 strands of 44 AWG SPN wire at 18 twists per foot (left direction twisting). Another litz wire configuration may be produced by twisting 5 x 21/44 AWG (105/44 AWG SPN), also at 18 twists per foot (left direction twisting). Other litz wire configurations include 300/46 AWG litz wire as well as 46 AWG or finer gauge size wire.

[0084] FIG. 17 illustrates the main components of the controller 841, according to one embodiment. In the embodiment illustrated in FIG. 17, the controller 841 is a microprocessor based controller and so most of the components illustrated in FIG. 3 are software based components. Nevertheless, a hardware based controller 841 may be used instead. As shown, the controller 841 includes synchronous I, Q sampling circuitry 851 that receives the sensed voltage and current signals from the sensing circuitry 843 and 845 and obtains corresponding samples which are passed to a power, V_{rms} and I_{rms} calculation module 853. The calculation module 853 uses the received samples to calculate the RMS voltage and RMS current applied to the load 819 and, from the voltage and current, the power that is presently being supplied to the load 839. The determined values are then passed to a frequency control module 855 and a medical device control module 857. The medical device control module 857 uses the values to determine the present impedance of the load 819 and based on this determined impedance and a pre-defined algorithm, determines what set point power (P_{set}) should be applied to the frequency control module 855. The medical device control module 857 is in turn controlled by signals received from a user input module 859 that receives inputs from the user and also

controls output devices (lights, a display, speaker or the like) on the handle of the instrument via a user output module 861.

[0085] The frequency control module 855 uses the values obtained from the calculation module 853 and the power set point (P_{set}) obtained from the medical device control module 857 and predefined system limits (to be explained below), to determine whether or not to increase or decrease the applied frequency. The result of this decision is then passed to a square wave generation module 863 which, in this embodiment, increments or decrements the frequency of a square wave signal that it generates by 1 kHz, depending on the received decision. As those skilled in the art will appreciate, in an alternative embodiment, the frequency control module 855 may determine not only whether to increase or decrease the frequency, but also the amount of frequency change required. In this case, the square wave generation module 863 would generate the corresponding square wave signal with the desired frequency shift. In this embodiment, the square wave signal generated by the square wave generation module 863 is output to the FET gate drive circuitry 805, which amplifies the signal and then applies it to the FET 803-1. The FET gate drive circuitry 805 also inverts the signal applied to the FET 803-1 and applies the inverted signal to the FET 803-2.

[0086] FIG. 18 is a signal plot illustrating the switching signals applied to the FETs 803, a sinusoidal signal representing the measured current or voltage applied to the load 819, and the timings when the synchronous sampling circuitry 851 samples the sensed load voltage and load current, according to one embodiment. In particular, FIG. 18 shows the switching signal (labeled PWM1 H) applied to upper FET 803-1 and the switching signal (labeled PWM1 L) applied to lower FET 803-2. Although not illustrated for simplicity, there is a dead time between PWM1 H and PWM1 L to ensure that that both FETs 803 are not on at the same time. FIG. 18 also shows the measured load voltage/current (labeled OUTPUT). Both the load voltage and the load current will be a sinusoidal waveform, although they may be out of phase, depending on the impedance of the load 819. As shown, the load current and load voltage are at the same drive frequency (f_o) as the switching Signals (PWM1 H and PWM1 L) used to switch the FETs 803. Normally, when sampling a sinusoidal signal, it is necessary to sample the signal at a rate corresponding to at least twice the frequency of the signal being sampled — i.e. two samples per period. However, as the controller 841 knows the frequency of the switching signals, the synchronous sampling circuit 851 can sample the measured voltage/current signal at a lower rate. In this embodiment, the synchronous sampling circuit 851 samples the measured signal once per period, but at different phases in adjacent periods. In FIG. 18, this is illustrated by the "I" sample and the "Q" sample. The timing that the synchronous sampling circuit 851 makes

these samples is controlled, in this embodiment, by the two control signals PWM2 and PWM3, which have a fixed phase relative to the switching signals (PWM1 H and PWM1 L) and are out of phase with each other (preferably by quarter of the period as this makes the subsequent calculations easier). As shown, the synchronous sampling circuit 851 obtains an "I" sample on every other rising edge of the PWM2 signal and the synchronous sampling circuit 851 obtains a "Q" sample on every other rising edge of the PWM3 signal. The synchronous sampling circuit 851 generates the PWM2 and PWM3 control signals from the square wave signal output by the square wave generator 863 (which is at the same frequency as the switching signals PWM1 H and PWM1 L). Thus control signals PWM2 and PWM3 also change (whilst their relative phases stay the same). In this way, the sampling circuitry 851 continuously changes the timing at which it samples the sensed voltage and current signals as the frequency of the drive signal is changed so that the samples are always taken at the same time points within the period of the drive signal. Therefore, the sampling circuit 851 is performing a "synchronous" sampling operation instead of a more conventional sampling operation that just samples the input signal at a fixed sampling rate defined by a fixed sampling clock.

[0087] The samples obtained by the synchronous sampling circuitry 851 are then passed to the power, V_{rms} and I_{rms} calculation module 853 which can determine the magnitude and phase of the measured signal from just one "I" sample and one "Q" sample of the load current and load voltage. However, in this embodiment, to achieve some averaging, the calculation module 853 averages consecutive "I" samples to provide an average "I" value and consecutive "Q" samples to provide an average "Q" value; and then uses the average I and Q values to determine the magnitude and phase of the measured signal (in a conventional manner). As those skilled in the art will appreciate, with a drive frequency of about 400kHz and sampling once per period means that the synchronous sampling circuit 851 will have a sampling rate of 400kHz and the calculation module 853 will produce a voltage measure and a current measure every 0.01 ms. The operation of the synchronous sampling circuit 851 offers an improvement over existing products, where measurements can not be made at the same rate and where only magnitude information is available (the phase information being lost).

[0088] In one embodiment, the RF amplifier and drive circuitry for the electrosurgical medical instrument employs a resonant mode step-up switching regulator, running at the desired RF electrosurgical frequency to produce the required tissue effect. The waveform illustrated in FIG. 18 can be employed to boost system efficiency and to relax the tolerances required on several custom components in the electronics system 400. In one embodiment, a first generator control algorithm may be employed by a resonant mode switching topology to

produce the high frequency, high voltage output signal necessary for the medical instrument. The first generator control algorithm shifts the operating frequency of the resonant mode converter to be nearer or farther from the resonance point in order to control the voltage on the output of the device, which in turn controls the current and power on the output of the device. The drive waveform to the resonant mode converter has heretofore been a constant, fixed duty cycle, with frequency (and not amplitude) of the drive waveform being the only means of control.

[0089] FIG. 19 illustrates a drive waveform for driving the FET gate drive circuitry 805, according to one embodiment. Accordingly, in another embodiment, a second generator control algorithm may be employed by a resonant mode switching topology to produce the high frequency, high voltage output signal necessary for the medical instrument. The second generator control algorithm provides an additional means of control over the amplifier in order to reduce power output in order for the control system to track the power curve while maintaining the operational efficiency of the converter. As shown in FIG. 19, according to one embodiment, the second generator control algorithm is configured to not only modulate the drive frequency that the converter is operating at, but to also control the duty cycle of the drive waveform by duty cycle modulation. Accordingly, the drive waveform 890 illustrated in FIG. 19 exhibits two degrees of freedom. Advantages of utilizing the drive waveform 890 modulation include flexibility, improved overall system efficiency, and reduced power dissipation and temperature rise in the amplifier's electronics and passive inductive components, as well as increased battery life due to increased system efficiency.

[0090] RF AMPLIFIER TOPOLOGY

[0091] FIG. 1 illustrates one embodiment of an RF amplifier 100 with one or more of taps on the primary coil 104, wherein each tap is controlled by a half bridge driver 108. As discussed below, each half bridge driver 108 may comprise transistors, MOSFETs, insulated-gate bipolar transistors (IGBTs) or any other suitable switching devices configured in a half bridge drive configuration. The output transformer primary winding 104 may be driven between any two of the half bridge drivers 108, with the number of turns between the half bridge drivers 108 and the fixed output winding 106 determining the overall turns ratio for the transformer 102.

[0092] This topology allows for a lower turns ratio for high current output on the secondary coil 106 while limiting the primary current to a value that is compatible with currently available lithium-ion (Li-Ion) batteries. For example, a primary current in the range of 20-30A implies a turns ratio of about 4:1. Conversely, when generating a relatively high voltage on the secondary coil 106, for example in the range of 170-250V RMS, it is desirable to have a relatively higher turns ratio between the primary coil 104 and the secondary coil 106, for

example a ratio of about 15:1. This can be accomplished by reducing the number of turns in the primary coil 104 relative to a secondary coil 106 with a fixed number of turns.

[0093] This topology provides the ability to dynamically vary the turns ratio, in real time and in sync the output waveform being generated. This is in keeping with a zero-voltage switching (ZVS) or zero current switching (ZCS) methodology for driving the amplifier at its resonant frequency for maximum efficiency and minimum power dissipation in the switching transistors, MOSFETs, IGBTs or other switching devices.

[0094] With this topology, the amplifier 100 can also be dynamically driven in a half bridge or a full bridge mode on a output-cycle-by-cycle basis, within a resonant mode drive scheme. This allows for better output regulation.

[0095] This topology also provides the ability to match the turns ratio to the region of tissue resistance. This optimizes the losses in the transformer windings by preventing excessive currents in the primary coil 104. It also optimizes the battery voltage required to produce a high voltage on the secondary coil 106 for large-jaw devices and the types of anatomical structures such devices are typically called upon to seal and cut. Multiple turns ratio values may be provided in order to optimize each region or sub-region of the electrosurgical power curve, as necessary.

[0096] With this topology the efficiency of the amplifier may be kept arbitrarily close to the optimal value by selection of taps on the primary coil 104.

[0097] An arbitrary number of half bridge driver 108 circuits and transformer taps may be provided, tailored to the performance requirements of the particular RF amplifier 100.

[0098] FIG. 2 illustrates one embodiment of a half bridge circuit 110 that may be employed by the half bridge driver 108. The half bridge circuit 110 comprises an upper switch 112 and a lower switch 114, here illustrated as MOSFETs, wherein the upper 112 and lower 114 switches are connected in a cascade arrangement. The half bridge circuit 110 further comprises an input voltage +VBatt that is provided by the instrument's onboard batteries and a ground return. The half bridge circuit 110 further comprises a high-side gate drive input 116 and a low-side gate drive input 118. The output from the half bridge circuit 110 is at the node between the upper 112 and lower 114 switches. In operation, the switches 112, 114 are turned on and off complementary to each other, with non-overlapping dead time, by applying the correct voltage waveforms at each of the gate drive inputs. This half bridge circuit 110 topology provides for four-quadrant switching, zero-voltage switching (ZVS), zero-current switching (ZCS), high-frequency operation, low EMI, and high efficiency.

[0099] While FIG. 2 illustrates a half bridge circuit 110 comprising MOSFET switches, any switch may be used, such as for example transistors, IGBTs or any other suitable switching device.

[0100] Furthermore, the design of half bridge circuits is well understood, and any half bridge circuit may be employed in the amplifier topology described above.

[0101] Various embodiments of the amplifier 100 as described above may comprise alternate topologies. For example, some embodiments may use solid-state switching elements, such as MOSFETs or other semiconductors that can be similarly controlled. Other embodiments may use physical relays, though physical relays have limitations, including relatively long switching times and arcing that occurs at the contacts when they are switched, caused because it is not possible to switch mechanical relays at a current or voltage zero crossing at the primary coil 104 or secondary coil 106. Arcing is an issue for designs that are intended to be reprocessed and reused.

[0102] FIG. 1 illustrates an embodiment of an amplifier 100 with a parallel resonant output section, comprising a parallel capacitor 120. Such an amplifier 100 is intended to produce a relatively pure sine wave as an output. The parallel capacitor 120 that forms the other half of the resonant tank circuit, with the transformer secondary inductance and leakage inductance, may be omitted, to produce a square wave approximate output waveform. When a peak-detector type of circuit is used for output voltage and current sensing, then issues with higher Nyquist rate sampling on the output may be avoided: the output pseudo-square wave will contain significant energy at the third, fifth, seventh and ninth harmonics, which will distort the output measurements if the A/D converter in the design does not have adequate bandwidth to sample these harmonics and keep them from aliasing. A lowpass anti-aliasing filter and software linearization (correction) for measured quantities could also be contemplated as solutions to reduce the Nyquist rate sampling rate required to avoid aliasing.

[0103] It is worthy to note that any reference to "one aspect," "an aspect," "one embodiment," or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the aspect is included in at least one aspect. Thus, appearances of the phrases "in one aspect," "in an aspect," "in one embodiment," or "in an embodiment" in various places throughout the specification are not necessarily all referring to the same aspect. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more aspects.

[0104] Although various embodiments have been described herein, many modifications, variations, substitutions, changes, and equivalents to those embodiments may be implemented

and will occur to those skilled in the art. Also, where materials are disclosed for certain components, other materials may be used. It is therefore to be understood that the foregoing description and the appended claims are intended to cover all such modifications and variations as falling within the scope of the disclosed embodiments. The following claims are intended to cover all such modification and variations.

[0105] Although various embodiments have been described herein, many modifications, variations, substitutions, changes, and equivalents to those embodiments may be implemented and will occur to those skilled in the art. Also, where materials are disclosed for certain components, other materials may be used. It is therefore to be understood that the foregoing description and the appended claims are intended to cover all such modifications and variations as falling within the scope of the disclosed embodiments. The following claims are intended to cover all such modification and variations.

CLAIMS

What is claimed is:

1. A current amplifier, comprising a transformer, the transformer comprising one or more taps on the primary coil, wherein each tap comprises a half bridge driver, wherein the half bridge drivers configured to selectively turn on or turn off the tap.
2. The current amplifier of claim 1, wherein the half bridge driver comprises an upper switch element and a lower switch element, a high-side drive input connected to the input of the upper switch element, a low-side drive input connected to the input of the lower switch element, wherein the upper and lower switch elements are connected in a cascade arrangement and the output of the half bridge driver is taken from the node between the upper and lower switch elements.
3. The current amplifier of claim 2, wherein the upper and lower switch elements comprise solid-state switching elements.
4. The current amplifier of claim 3, wherein the solid-state switching elements comprise MOSFETs.
5. The current amplifier of claim 2, wherein the upper and lower switch elements comprise IGBTs.
6. The current amplifier of claim 2, wherein the upper and lower switch elements comprise mechanical relays.
7. The current amplifier of claim 1, comprising a parallel capacitor on the secondary coil, such that the output produced by the amplifier is a sine wave.
8. The current amplifier of claim 1, wherein the minimum winding ratio is 4:1.
9. The current amplifier of claim 1, wherein the maximum winding ratio is 15:1.
10. An electrosurgical medical instrument comprising:
a radio frequency (RF) generation circuit coupled to and operated by a battery and operable to generate an RF drive signal and to provide the RF drive signal to at least one electrical contact, wherein the RF generation circuit comprises:

A current amplifier, comprising a transformer, the transformer comprising one or more taps on the primary coil, wherein each tap comprises a half bridge driver.

11. The medical instrument of claim 10, wherein the half bridge driver comprises an upper switch element and a lower switch element, a high-side drive input connected to the input of the upper switch element, a low-side drive input connected to the input of the lower switch element, wherein the upper and lower switch elements are connected in a cascade arrangement and the output of the half bridge driver is taken from the node between the upper and lower switch elements.

12. The medical instrument of claim 11, wherein the upper and lower switch elements comprise solid-state switching elements.

13. The medical instrument of claim 12, wherein the solid-state switching elements comprise MOSFETs.

14. The medical instrument of claim 11, wherein the upper and lower switch elements comprise IGBTs.

15. The medical instrument of claim 11, wherein the upper and lower switch elements comprise mechanical relays.

16. The medical instrument of claim 10, comprising a parallel capacitor on the secondary coil, such that the output produced by the amplifier is a sine wave.

17. The medical instrument of claim 10, wherein the minimum winding ratio is 4:1.

18. The medical instrument of claim 10, wherein the maximum winding ratio is 15:1.

19. A current amplifier, comprising:
a transformer comprising one or more taps on the primary coil, wherein each tap comprises a half bridge driver configured to selectively turn on or turn off the tap, wherein the half bridge driver comprises an upper switch element and a lower switch element, a high-side drive input connected to the input of the upper switch element, a low-side drive input connected to the input of the lower switch element, wherein the upper and lower switch elements are connected in a cascade arrangement and the output of the half bridge driver is taken from the node between the upper and lower switch elements; and

a parallel capacitor on the secondary coil, such that the output produced by the amplifier is a sine wave;

wherein the minimum winding ratio is 4:1; and

wherein the maximum winding ratio is 15:1.

20. The current amplifier of claim 19, wherein the upper and lower switch elements comprise solid-state switching elements.

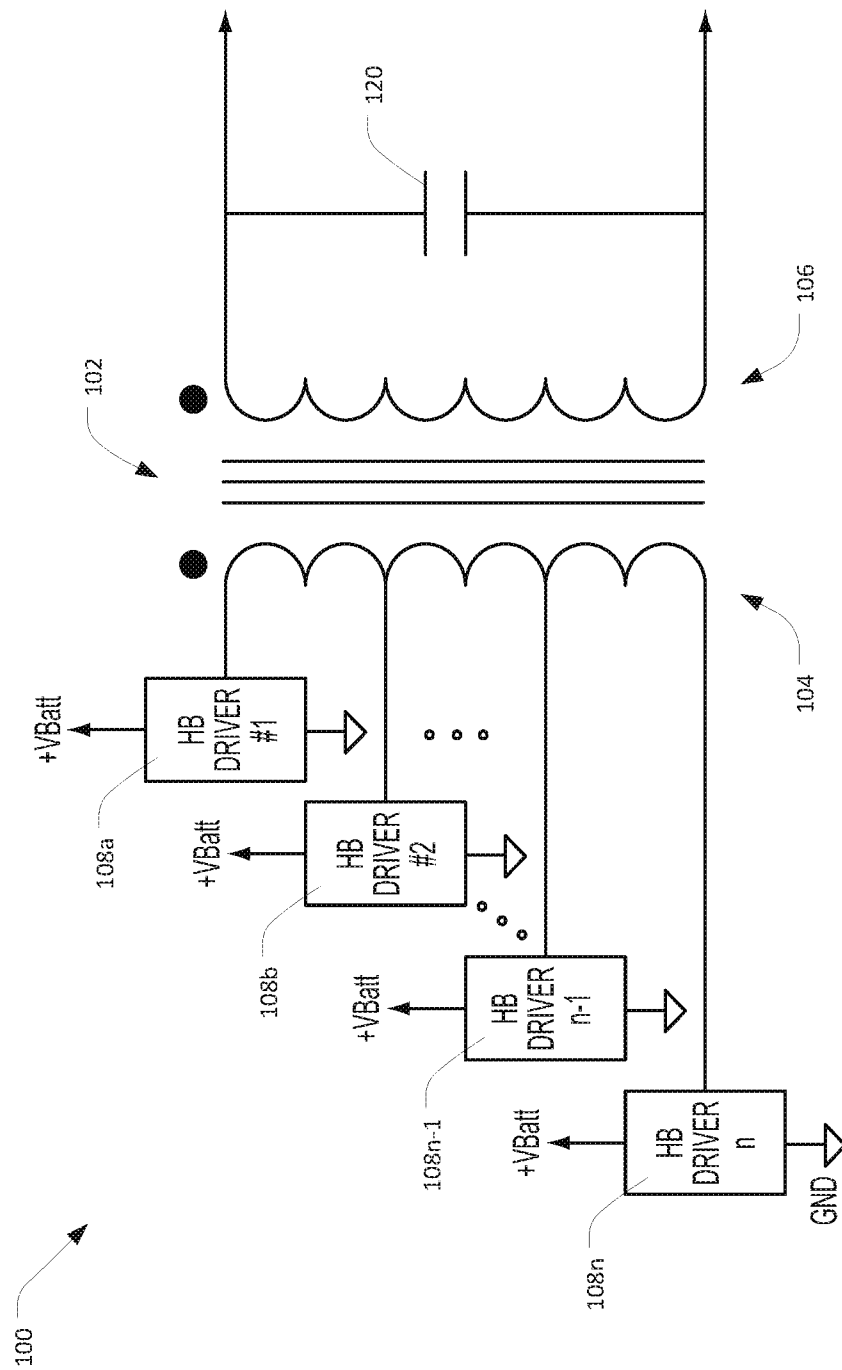


FIG. 1

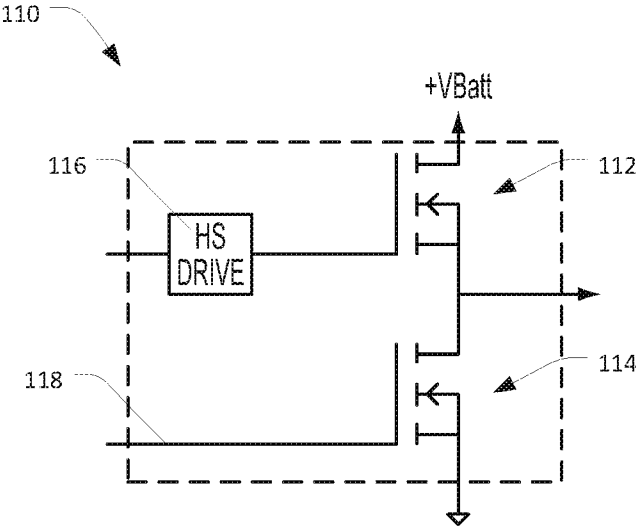


FIG. 2

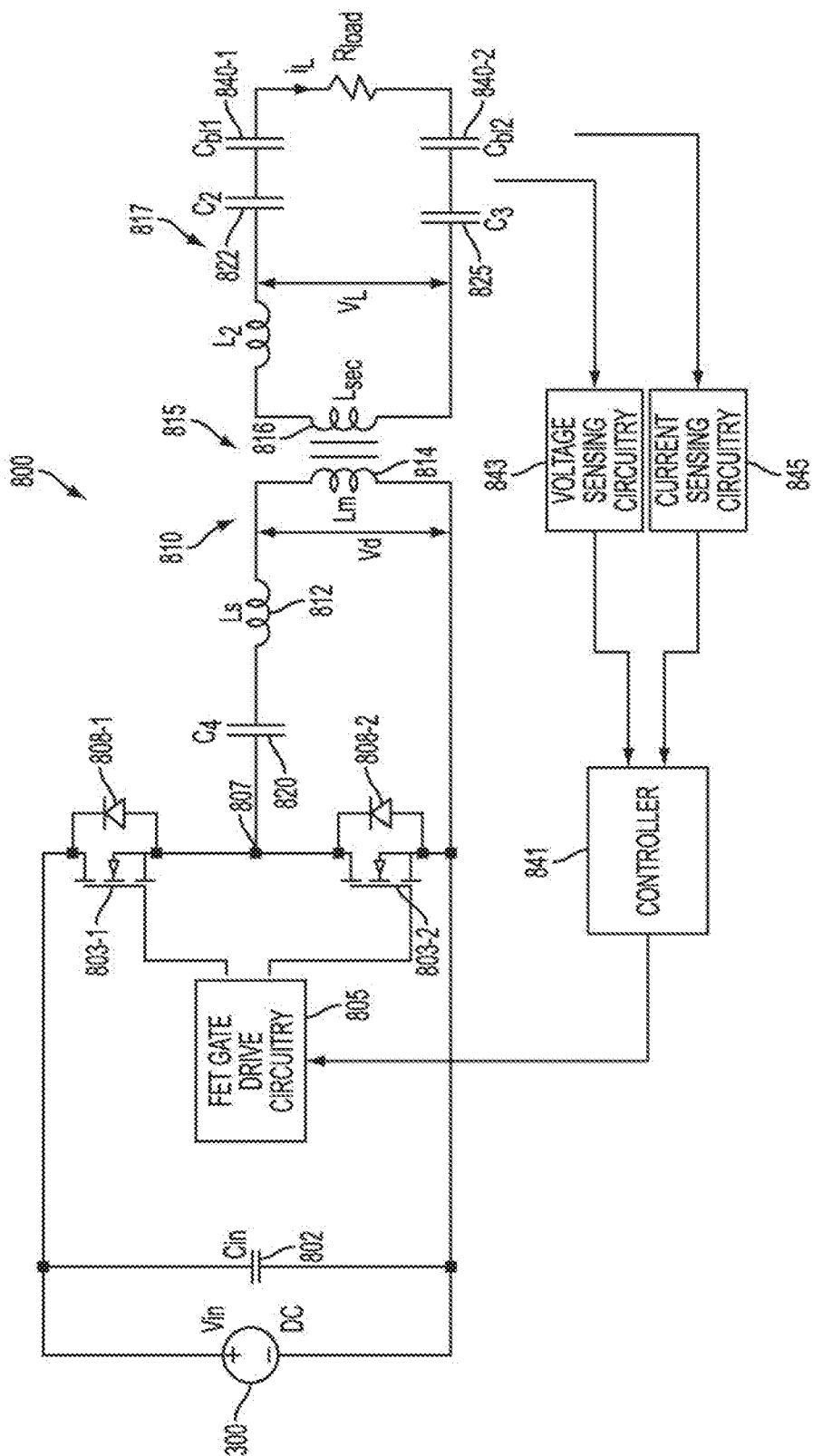


FIG. 3

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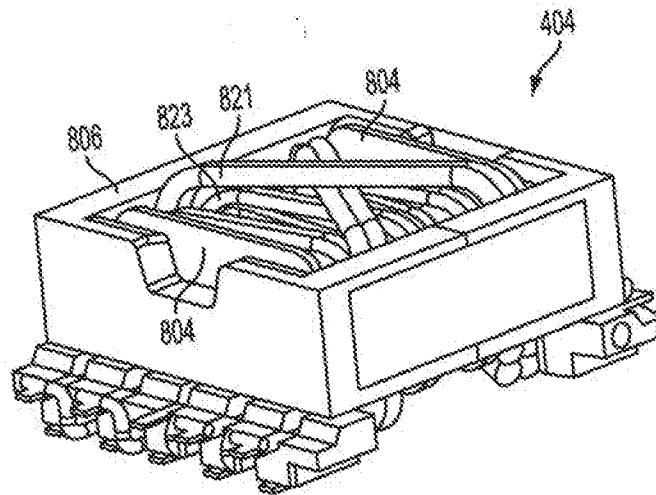


FIG. 4

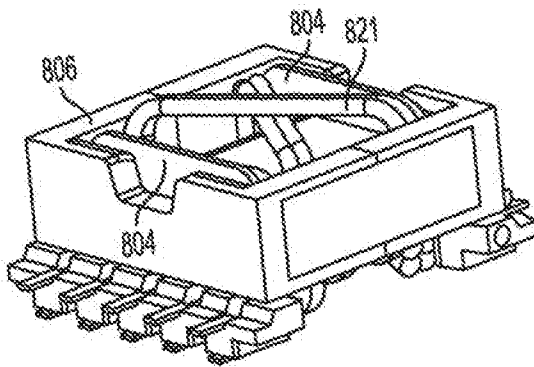


FIG. 5

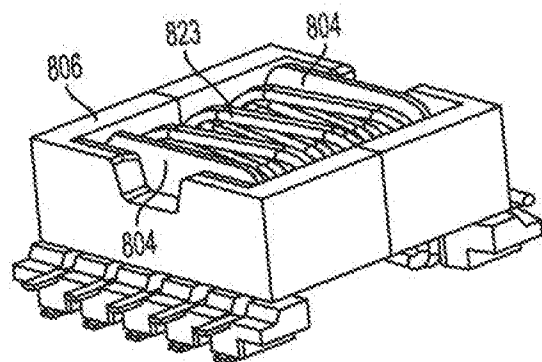


FIG. 6

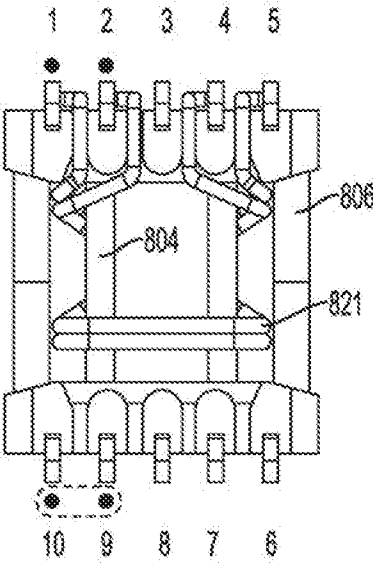


FIG. 7

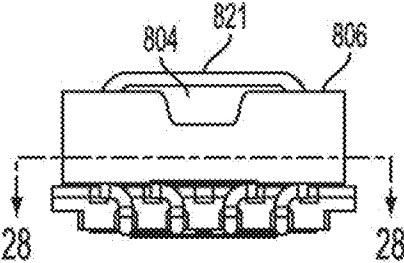


FIG. 8

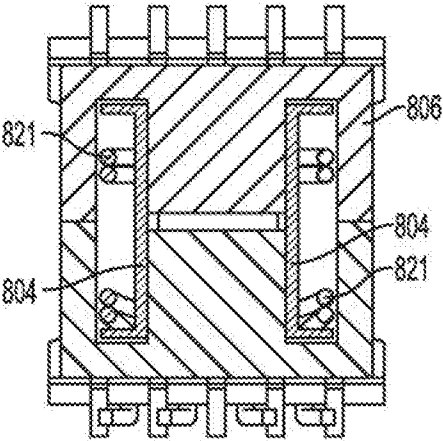


FIG. 9

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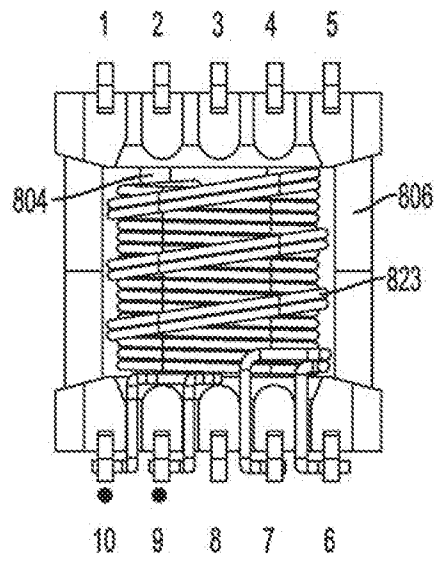


FIG. 10

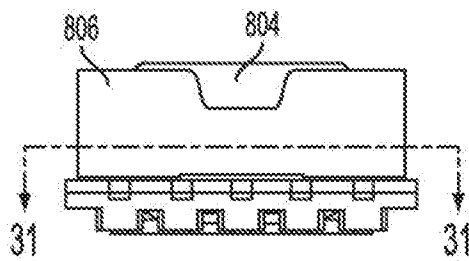


FIG. 11

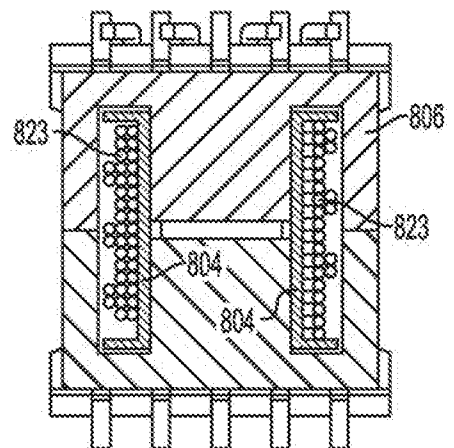


FIG. 12

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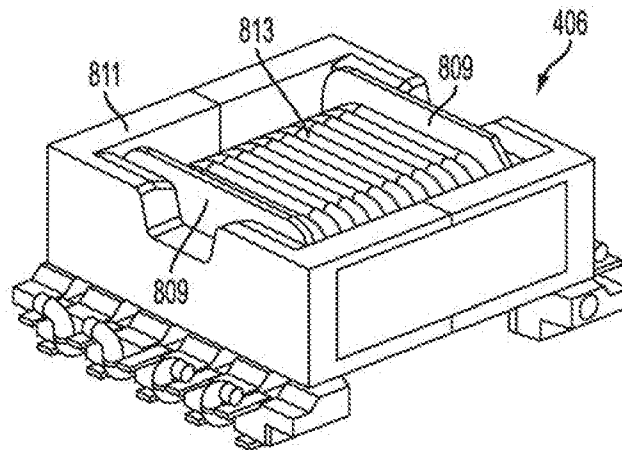


FIG. 13

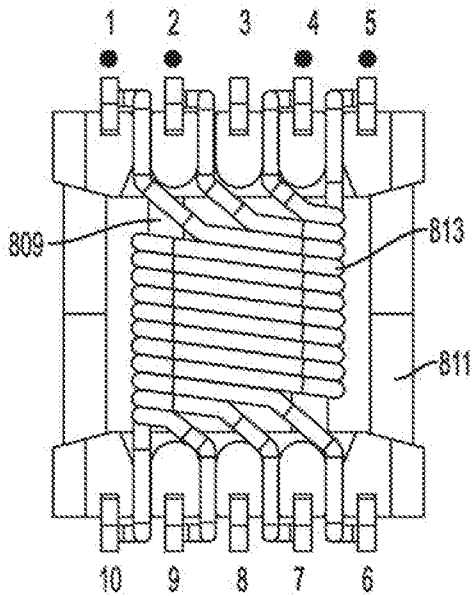


FIG. 14

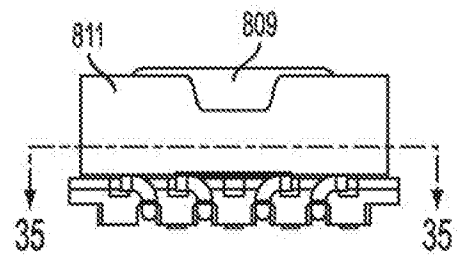


FIG. 15

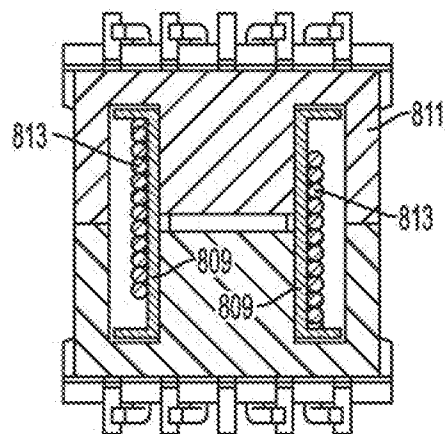


FIG. 16

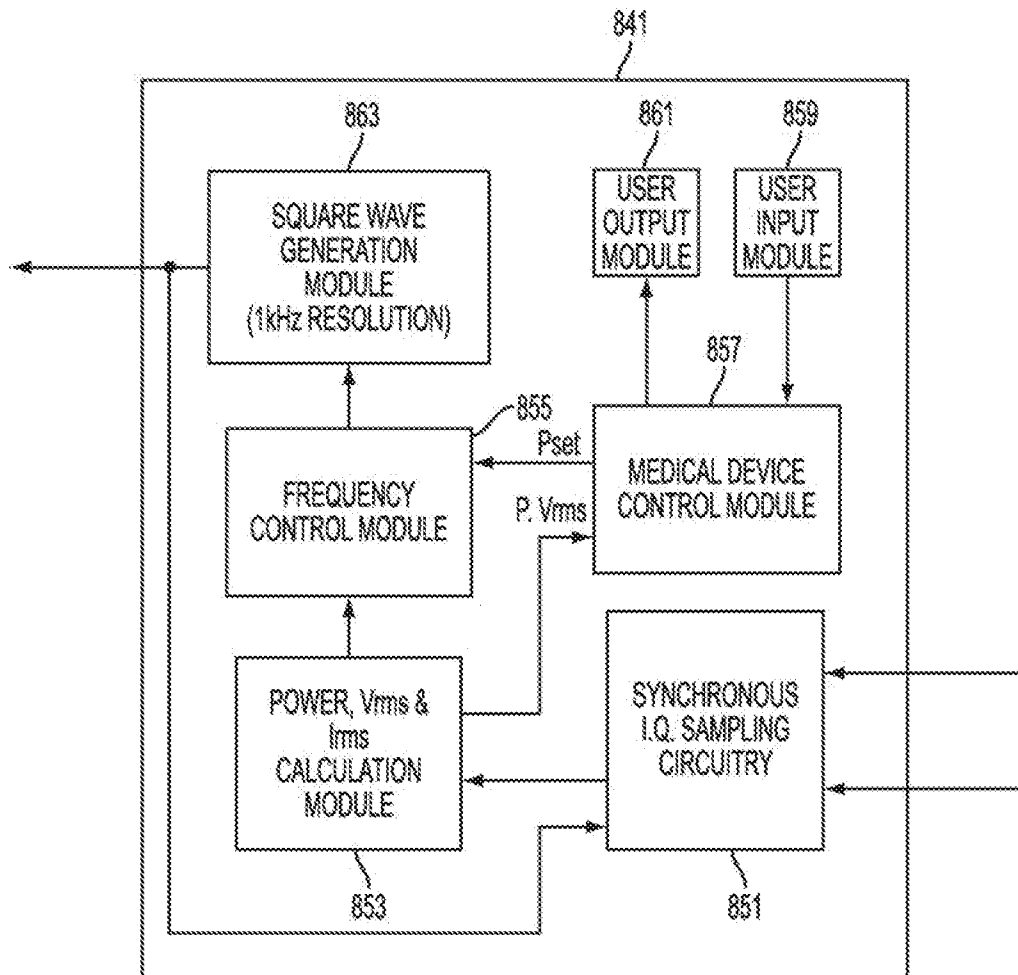


FIG. 17

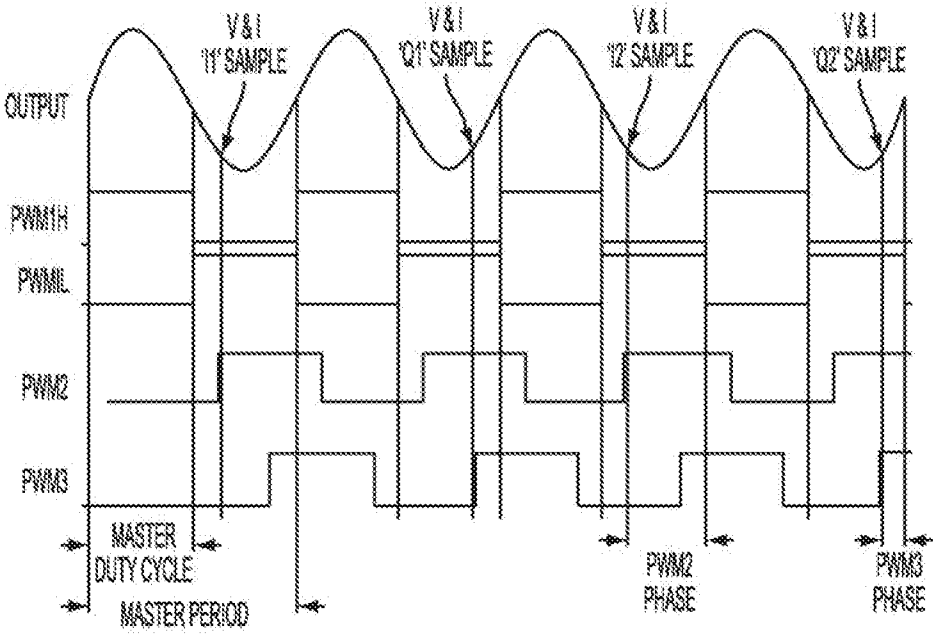


FIG. 18

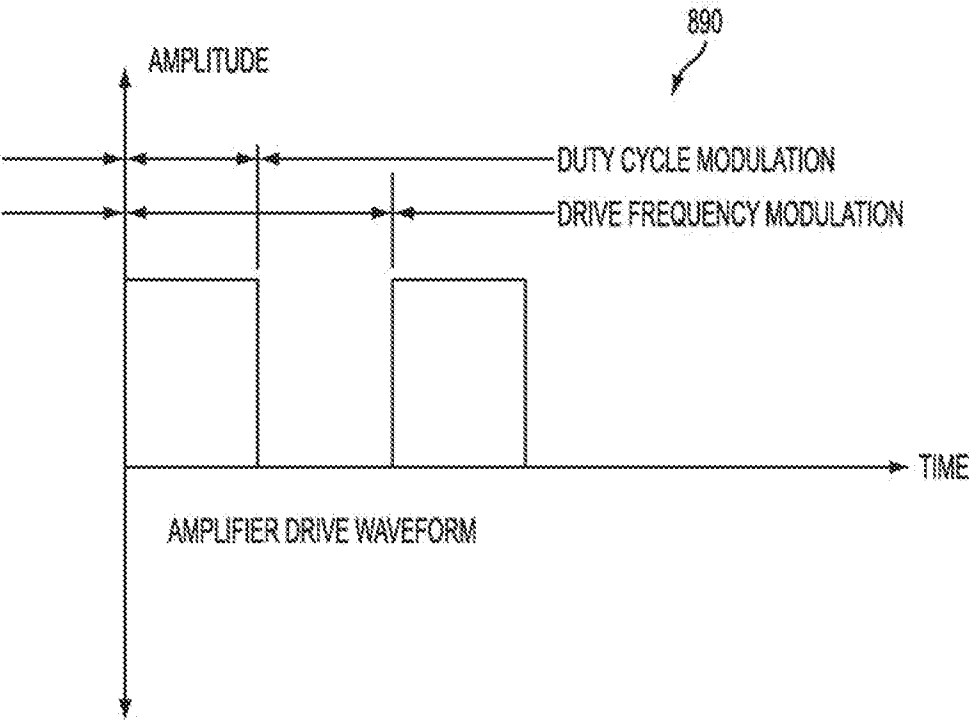


FIG. 19

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/065509

A. CLASSIFICATION OF SUBJECT MATTER
INV. H03F1/02
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H03F H02M A61B H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2010/228246 A1 (MARION DUANE W [US]) 9 September 2010 (2010-09-09) abstract paragraphs [0049] - [0063]; figure 6 -----	1-20
X	US 2011/172660 A1 (BALES JR THOMAS O [US] ET AL) 14 July 2011 (2011-07-14) abstract paragraphs [0005] - [0014], [0020] - [0023], [0027] - [0030], [0061] - [0067], [0078] - [0086]; claims 1-17 -----	1-20
A	US 2009/318915 A1 (HOSIER JOHN ROLAND [GB] ET AL) 24 December 2009 (2009-12-24) abstract figure 3 paragraph [0061] ----- -/-	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

17 March 2016

Date of mailing of the international search report

30/03/2016

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Authorized officer

Mouanda, Thierry

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2015/065509

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2013/103023 A1 (MONSON GAVIN M [US] ET AL) 25 April 2013 (2013-04-25) abstract paragraphs [0123] - [0149] figures 22-35 -----	1-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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