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(54) Exciter circuits and methods with protective measures for solid state switches.

(57) An exciter for an internal combustion engine igniter plug (12) comprises a continuous AC charging circuit (20) and a discharge circuit (22). The discharge circuit (22) is connectable to the plug (12) and the charging circuit (20) includes a transformer (T1) having a primary winding connectable to an AC power source (28) and a secondary winding connected to the discharge circuit. The discharge circuit includes a storage capacitor (38) connected to the transformer secondary winding such that current induced in the secondary charges the capacitor (38) at a generally constant rate. A switching device (46) is connected in series between the capacitor (38) and the plug (12). A trigger circuit (52) triggers the switching device (46) in response to charge on the capacitor (38). The charging circuit (20) and trigger circuit (52) operate to maintain a generally constant spark rate. A current multiplier (76) is also provided to substantially increase the peak currents delivered to the plug (12). A clamping diode (150) is also provided in parallel with the storage capacitor (38) to prevent reverse currents and voltages due to resonance between the capacitor (38) and stray inductance.

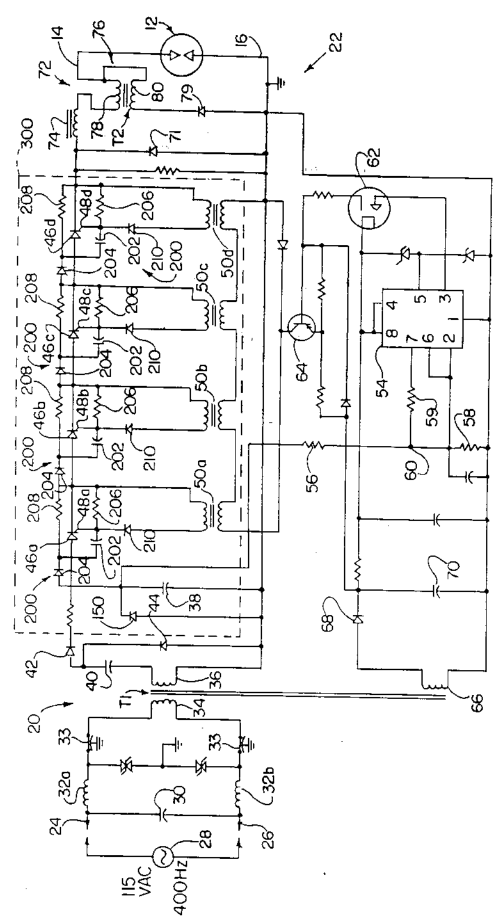

FIG. 1

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The invention relates generally to exciter circuits for ignition systems used with internal combustion engines. More particularly, the invention relates to exciter circuits that utilize solid-state switches such as, for example, thyristors, as control devices for spark rate timing, and circuits that utilize rectifiers for unidirectional current control.

A conventional ignition system for an internal combustion engine, such as, for example, a gas turbine aircraft engine, includes a charging circuit, a storage capacitor, a discharge circuit and at least one igniter plug located in the combustion chamber. The discharge circuit includes a switching device connected in series between the capacitor and the plug. For many years, such ignition systems have used spark gaps as the switching device to isolate the storage capacitor from the plug. When the voltage on the capacitor reaches the spark gap breakover voltage, the capacitor discharges through the plug and a spark is produced.

More recently, turbine engine and aircraft manufacturers have become interested in replacing the spark gap with a solid-state switch, such as an SCR or thyristor. This is due, in part, because a solid state switch typically operates longer than a spark gap tube which may exhibit electrode erosion. Also, solid state switches are produced in large volume making them less expensive than spark gaps which are individually crafted in small quantities. Furthermore, the storage capacitor's voltage at discharge remains essentially constant over the life time of the solid state switch, but can change significantly during the life of the spark gap due to electrode erosion.

However, there are also significant disadvantages to replacing a spark gap with a solid state switch. One concerns the occurrence of high frequency oscillatory reverse currents through the solid state devices as the capacitor initially discharges. These reverse currents can damage solid state switches. This damage occurs when the rectifier switch abruptly blocks reverse current during the reverse recovery period. High frequency reverse voltages can also damage rectifiers if the reverse voltages exceed the reverse junction breakdown voltage. The high energy storage capacitor commonly used with exciter circuit can also be damaged by high frequency reverse charging currents and voltages.

Conventional spark gap exciter circuits can also exhibit these high frequency reverse currents and voltages. And in fact, oscillatory discharge spark gap circuits are specifically designed to have such oscillatory reverse currents and voltages. The spark gap device are not damaged by the high frequency reverse currents because they remain in conduction during this period and conduct equally well in both directions. The spark gaps do not have sufficient time to recover their blocking state at the point of current reversal. Spark gaps are not typically damaged by voltage reversals.

However, some spark gap circuits utilize rectifying diodes in connection with the main charging capacitors. Such a circuit is illustrated in US Patent No. 3,629,652 issued to Maycock et al. The Maycock circuit includes two charging circuits and two storage capacitors that are isolated by a unidirectional current diode. This diode is susceptible to damage from reverse currents and voltages.

The need exists, therefore, for an exciter circuit that protects solid state device such as switching rectifiers and unidirectional current diodes from damage due to reverse voltages and currents that may occur during the discharge sequence of such a circuit.

According to the invention, there is provided an exciter for an igniter, comprising an AC charging circuit and a discharge circuit, said discharge circuit being connectable to a plug to cause the plug to produce sparks and said charging circuit being connectable to an AC power source characterized in that said discharge circuit comprises a storage capacitor connected to said charging circuit such that charging current charges said capacitor at a generally constant rate between sparks, a solid state switching device connected between said capacitor and the plug, and a trigger circuit for triggering said switching device in response to charge on said capacitor, said charging circuit and said trigger circuit operating to maintain a generally constant spark rate

According to the invention, there is also provided a method for producing a constant spark rate of an igniter plug in an engine, characterized by the steps of producing a half-wave rectified charging current from an AC power source; charging a capacitor with said charging current at a generally constant rate of charge between sparks; detecting the charge on said capacitor; triggering a switching device in response to charge on said capacitor to discharge said capacitor through the igniter plug; and turning the switching device off during a non-charging half-cycle of said charging current after said capacitor discharges.

According to the invention, there is further provided an exciter of the type used for supplying energy to an igniter plug and characterized by a charging circuit, a capacitor charged by said charging circuit, a discharge circuit having a switching device for controlling the discharge of energy stored in said capacitor to the plug, and a current multiplier connected between said switching device and the plug.

According to the invention, there is yet further provided an exciter of the type used for supplying energy to an igniter plug and characterized by a charging circuit, a capacitor charged by said charging circuit, a discharge circuit having two or more series-connected solid state switching devices for controlling the discharge of energy stored in said capacitor to the plug, and a snubber circuit connected to each of said switching devices, each snubber circuit comprising a capacitor connected between a gate and anode of the respective switching device.

According to the invention, there is still further provided an exciter circuit for an igniter plug, said exciter circuit comprising a storage capacitor that unidirectionally discharges through the plug to produce sparks; characterized by rectifier means in parallel with said capacitor to prevent reverse currents and voltages by preventing resonance between said capacitor and stray inductance in the exciter circuit.

According to the invention, there is also provided a method of preventing reverse currents and voltages across a storage capacitor in an exciter circuit for an igniter plug used in a turbine engine, comprising the step of using a rectifier directly in parallel with the capacitor to prevent resonance between the capacitor and stray inductance in the exciter circuit.

Exciter circuits embodying the invention, and methods according to the invention of exciting ignition, will now be described, by way of example only, with reference to the accompanying drawings in which:-

Fig. 1 is an electrical schematic diagram of one of the exciter circuits;

Fig. 2 is a graph of typical operating currents produced by the circuit of Fig. 1;

Figs 3A and 3B illustrate modified ones of the exciter circuits;

Fig 4 is an idealized schematic diagram of a discharge section of one of the exciter circuits using capacitive discharge;

Fig 5 is another schematic diagram of a discharge section of one of the exciter circuits using capacitive discharge section and taking into consideration stray inductance;

Fig. 6 is a graph illustrating typical stray inductance effects in a circuit such as shown in Figs. 1 and 5; and

Fig. 7 illustrates another use of the exciter circuits.

With reference to Fig. 1, an exciter in accordance with the present invention is generally designated by the numeral 10. Such an exciter is particularly well suited for use in an ignition system for a gas turbine engine, such as, for example, in aircraft engines. However, exciters in accordance with the invention can also be used other than in the aircraft applications. One of the basic functions of the exciter 10 is to produce high energy sparks at the igniter plug gap, which is shown in a simplified schematic manner in Fig. 1 and designated with the numeral 12. An important requirement imposed by engine manufacturers is that the spark rate should be generally constant over a wide operating temperature and input voltage range of the exciter.

The plug 12, of course, is physically positioned in the combustion chamber of the engine (not shown). The exciter 10 is connected to the plug by a high tension lead wire 14 and a return 16.

The exciter 10 includes an uninterrupted charging circuit 20 and a discharge circuit 22. The charging circuit 20 is connectable by leads 24,26 to an AC power supply 28, such as, for example, a 115 VAC 400Hz supply from the engine power plant. By "uninterrupted" we mean that during normal use of the exciter to produce sparks, the AC power supply 28 energizes the charging circuit 20 to operate in a continuous manner. The AC power supply 28 connects in parallel with a capacitor 30 which may be provided for power factor correction, as is well known to those skilled in the art. A pair of current regulating inductors 32a and 32b are connected in series between the power supply 28 and a primary winding 34 of a power transformer T1. The inductors 32a,b operate to maintain a generally constant current through the primary winding of the transformer T1, and this current is generally independent of variations of input voltage as long as the ratio of input voltage to input frequency remains generally constant. A pair of capacitors 33 are provided for low pass filtering.

Current induced in the secondary winding 36 of transformer T1 is used to charge a main storage capacitor 38. Because the primary current is generally constant, the capacitor 38 charges at a constant average rate between sparks. The secondary winding 36 is connected to the capacitor 38 by means of a half-wave rectified voltage doubler constituted by a capacitor 40 and two diodes 42,44. During each negative half-cycle of the current induced in the secondary, no charging current is applied to the main capacitor 38, however, the capacitor 40 is charged to the voltage output of the secondary winding 36 through the diode 44. On the succeeding positive half-cycle, charging current is applied to the main capacitor 38 through the second diode 42 to a voltage that is approximately twice the output voltage of the transformer T1. Two important aspects of this design should be noted. First, during alternating half-cycles of the 115 VAC input, no charging current is applied to the main capacitor 38. Second, however, the average rate of charge of the capacitor 38 is generally constant between sparks because of the generally constant current supplied through the primary and secondary windings of the transformer T1.

The discharge circuit 22 further and preferably includes a cascaded set of switching devices 46a, 46b, 46c and 46d. In the preferred embodiment, the devices 46a-d are SCR thyristor devices or GTO devices. Although four devices are shown in Fig. 1, the actual number of such devices used will depend on the particular requirements of the ignition system, primarily the type of switching device used, the type of plug used, and the operating voltages, currents and temperatures. For example, a standard SCR can only withstand or block 1000-1500 VDC, therefore, if the capacitor 38 needs to be charged to 3000 VDC or more then several SCR devices need to be used. It will be appreciated that the series string of switching devices 46 can also be thought of as a single switching device connected between the main capacitor 38 and the plug 12. Those skilled in the art will readily appreciate that the voltage imposed on the capacitor 38 will depend on the type of plug being used, as well as the type of output conditioning circuit employed with the discharge circuit, as will be more fully explained herein.

The switching devices 46a-d are triggered on in response to a current pulse applied to their respective gate terminals 48a-d. These trigger pulses are applied to the gates 48a-d by a set of corresponding pulse transformers 50a-d. In order to produce the trigger pulses with the correct timing, a trigger circuit 52 monitors the charge on the main storage capacitor 38. The trigger circuit 52 includes a comparator device 54, such as, for example, part no. ICM 7555 manufactured by Maxim.

A series pair of resistors 56,58 provide a resistor divider circuit connected in parallel with the main capacitor 38. The resistor divider junction node 60 is connected to input pins 2 and 6 of the comparator device 54. When the voltage at the junction node 60 exceeds a first predeterminable threshold at pin 6, the device 54 latches a low going signal at an output pin 3 and at pin 7. The low signal at pin 7 pulls the node 60 towards a second lower threshold detected at pin 2, in essence resetting the comparator so that the output at pin 3 goes back high after a predetermined time, thus creating a pulse at pin 3. This pulse may be, for example, 30 μseconds in duration. The pulse duration can be set by selection of a discharge resistor 59 value. The output pulse from the comparator 54 pulses on an FET switch 62 which in turn pulses on a PNP switch 64. The pulsed PNP switch conducts current through the primary of the pulse transformers 50a-d thereby triggering the switching devices 46a-d on.

Power for the trigger circuit 52 can be conveniently provided using a tertiary winding 66 of the power transformer T1. The tertiary current is rectified and filtered by a diode 68 and capacitor 70 to provide a DC voltage supply for the comparator device 54. This DC supply may also be used to establish the bias voltages for the FET and PNP switches 62,64.

The switching devices 46a-d are connected in series between the main capacitor 38 and an output conditioning circuit 72. The output circuit 72 may include a current limiting saturating core inductor 74 that momentarily limits the initial current surge through the switches 46a-d when these devices are initially switched on. This may be important when conventional SCRs are used for the switching devices because the extremely high current surges could otherwise damage or degrade the SCR devices.

It should be noted at this time that in a conventional capacitive discharge ignition circuit, the current and voltage waveforms can be divided into three rather distinct time periods. During the arc inception period, in a typical low tension application for example, the storage capacitor 38 is charged to about 3000 volts, and when the switching device is closed, the high impedance gap of the plug 12 sees a voltage above the gap breakover voltage (of course, in a high tension circuit, the capacitor 38 voltage is stepped-up such as with a step-up transformer in the output circuit so as to increase the voltage across the plug gap sufficient to create the arc). As arc current rises from 0 to several amps, the plug 12 impedance falls rapidly, the plug voltage falls to about 50 volts and the capacitor 38 voltage now appears mainly across the saturable inductor 74. Thus during this period, high voltage and low current from the storage capacitor strike an arc across the high impedance plug gap.

The next time period of interest occurs as the capacitor 38 energy is transferred to the saturable inductor 74 as the capacitor discharges to zero volts and the inductor 74 current, in essence the loop current through the plug 12, increases to about 2000 amps. During this energy transfer period of time, energy is now transferred from the high voltage source of the capacitor 38 to the high current source of the inductor 74 to supply energy to the low impedance spark gap.

Then, during the arc period, the energy stored in the inductor 74, which may be nearly 95% of the energy initially stored on the capacitor 38, is transferred to the arc of the plug 12. The inductor 74 circulates current around the loop consisting of the inductor 74, the plug 12, and the clamp rectifier 71. The current then decays from a peak of about 2000 amps to zero during this time.

The requirement that the switching devices 46 block high voltage during the capacitor 38 charging time and conduct fast rising high peak currents during the energy transfer period is difficult to realize using a conventional thyristor device. This is due to the current limitations of these devices as explained hereinabove. In accordance with the invention, a current multiplier is used in the output circuit 72 to circumvent this current limitation.

Thus, the output circuit 72 includes a current multiplier 76 connectable in series with the igniter plug 12. The current multiplier 76 may be realized conveniently in the form of an autotransformer T2 having windings 78 and 80 on a common core, with a rectifier 79 being series connected between winding 80 and the return line 16. The primary winding of T2 consists of both windings 78,80 in series after the arc is established; and the secondary is winding 80 which means that winding 80 is shared by the primary and secondary. The windings 78 and 80 may have the same number of turns. When the switching devices 46 close, the rectifier 79 blocks magnetizing current through the common winding 80, which prevents the autotransformer 76 from initially operating which would otherwise limit open circuit voltage to the plug 12; and the inductance of inductor 74 and the winding 78 impedes the arc inception current to the plug 12 thus protecting the switching devices. As the plug 12 impedance drops rapidly to a point at which the plug voltage is approximately the capacitor 38 voltage divided by the autotransformer 76 turns ratio, the autotransformer begins operating such that current now flows through windings 78,80 and the plug 12. After the arc is struck and as the voltage across the plug gap drops rapidly to 50 volts, the winding 80 conducts high current to the plug gap to give high peak currents and high transition currents without degrading switch 46 performance. Magnetizing current provided in the primary 78,80 of T2 during discharge of the main capacitor 38 induces a load current in the secondary 80, which current is added to the main capacitor discharge current to substantially increase the power delivered to the plug when a spark is created. Fig. 2 illustrates typical current characteristics for current through the switching devices 46a-d (REF 1) and current through the plug 12 (REF 2) using a current multiplier 76.

It should be noted that the current multiplier 76 can be used to provide the plug 12 with discharge current peaks and transition rates similar to those provided by a spark gap and at the same time reduce current peaks and transition rates conducted by the solid state switch to levels consistent with their capability. In this case, inductor 74 need not be of the saturable type.

In operation, AC power applied to transformer T1 continuously energizes the charging circuit 20 which charges the main capacitor 38 at a generally constant average rate. However, during each half-cycle of the AC supply, no charging current is applied to the capacitor 38 due to operation of the half wave doubler circuit connected between the charging circuit 20 and the storage capacitor 38. When the capacitor is sufficiently charged to a voltage level adequate to produce a spark at the plug 12, the comparator 54 generates a trigger pulse that gates the switching devices 46a-d on. The capacitor 38 is thus shorted across the plug 12 and transformer T2. The main capacitor 38 discharges through the current multiplier 76 and a high energy spark is created. After the capacitor discharges, the switching devices 46 are able to turn off because the current through the devices falls below the sustaining level needed to keep the devices on when the succeeding half cycle of charging current is blocked. Thus the circuit is self-commutated without the need for a controlled switch or a controlled reactance to interrupt the supply of charging current or the need for a forced commutation circuit to by-pass charging current around the switching devices. As soon as the switching devices 46a-d turn off, the capacitor 38 immediately begins charging again at the same generally constant average rate between sparks and the process repeats continuously as long as AC power is provided to the charging circuit 20.

In a typical exciter, the capacitor 38 is charged to about 3000 VDC. The capacitor discharges in 100 μseconds or less and can produce discharge currents as high as 2000 amps. Because the AC supply is preferably operating at 400 Hz, there is at least a 1.25 millisecond commutation period during which no charging current is applied to the capacitor 38. This is more than adequate time to insure that the switching devices 46a-d turn off within one cycle of the discharge time.

An important aspect of this invention is that an exciter is provided that operates in a continuous and uninterrupted charging mode without the need for timing circuits to achieve a constant spark rate. By designing the AC charging circuit 20 to continuously charge the capacitor 38 at a generally constant average rate between sparks, the AC charging power need not be interrupted and can be continuously applied to the capacitor 38. Because the comparator 54 always trips at the same reference level, a constant spark rate can be maintained without using any timer circuits. This is particularly useful with GTO devices used for the switches 46a-d. A GTO thyristor exhibits very low leakage currents even at high operating temperatures. Thus, a continuous mode exciter according to the invention will provide a constant spark rate over a wide range of temperatures. Also, GTO devices have high sustaining currents compared to conventional SCR devices. Therefore, GTO devices can be used with the continuous mode charging circuitry of the present invention without the need for the half wave rectifier. This is because the higher sustaining currents of the GTO allow the device to turn off as the capacitor 38 discharges, without the need for the half-wave commutation period needed by SCR devices.

The continuous mode technique is a significant improvement over the pulse width modulated exciter designs that rely on timer circuits to maintain a constant spark rate. Those skilled in the art will also appreciate that conventional SCRs exhibit high leakage currents at elevated operating temperatures. These leakage currents can affect the spark rate timing due to their load on the charging of the main capacitor 38. Leakage may cause, for example, charging power loss of 1 to 2 watts with conventional SCRs. However, in some applications the total power delivered by the charging circuit far exceeds the total power loss due to leaky SCRs even at elevated temperatures. In such circumstances, the continuous mode exciter as described herein can be used to achieve a spark rate that is sufficiently constant for engine specifications. The use of the half-wave doubler circuit permits the self-commutation to occur thus obviating the need to interrupt power to the discharge circuit.

The efficiency of the exciter 10 can be further improved by physically placing the current multiplier 76 at the plug 12. This substantially lowers the currents through the discharge circuit 22 and the high tension lead 14. The current multiplier concept can be applied to any exciter, including those of the spark gap switching device type, to realize this improvement in output efficiency. Also, the current multiplier is particularly advantageous with solid-state switches such as SCRs and GTOs because the exciter can achieve the same peak output power characteristics of a spark gap exciter while reducing the di/dt and peak currents in the switching devices to safe operating values. Use of the current multiplier also reduces the peak currents discharged from the main storage capacitor 38, which can be expected to improve the operating life of the main capacitor.

The circuit illustrated in Fig. 1 may generally be referred to as a unidirectional discharge. This is evident from Fig. 4, which illustrates in simplified form the basic elements of a capacitive discharge circuit. Those elements are the energy storage capacitor, C, a switching device such as a spark gap or alternatively a solid state switching means, S, a freewheeling diode Dx, an arc current inductor, L, and the plug, P. The capacitor is charged to a suitable voltage at which time the switch is closed, allowing the capacitor voltage to instantaneously appear across the plug to strike an arc. In an ideal analysis, the diode Dx is initially reverse biased by the voltage on the capacitor so that all current flows through the capacitor, inductor and the plug, as indicated by the current loop I_1. Energy is transferred, of course, to the inductor as current flows therethrough. As the capacitor fully discharges, the current through the inductor reaches its peak and is instantaneously commutated to the outer current loop indicated by I_2. This outer loop current decays exponentially to zero as it circulates in one direction through loop I_2. The diode Dx causes the unidirectional current flow through the plug after the current is commutated. The current in loop I_1 during the rising period as the capacitor discharges, as well as the current in loop I_2 during the discharge period as the current decays to zero is unidirectional and non-oscillatory because there is no resonant circuit due to the operation of the diode Dx.

As stated, however, the circuit of Fig. 4 is idealized because it neglects stray inductance. A significant problem that can occur with capacitive discharge circuits is the presence of stray inductance (primarily lead length inductance of internal wiring and inductance associated with the storage capacitor's electrode winding). As shown in Fig. 5, the discharge circuit actually includes a third or inner current loop (designated by I_3) consisting of the capacitor, the switching device and the free wheeling diode, back to the return line. These stray inductances are represented by the inductors L_S. Although stray inductance exists in both loops I_2 and I_3, it is only shown in the inner loop I_3 because the energy transfer inductor, L, dominates any effects that might be caused by stray inductance in the outer loop, I_2. For example, the stray inductance may be on the order of 1 micro Henry, while the energy transfer inductor may have a value such as 5 to 20 micro Henry.

The effects of stray inductance, L_S, in the inner current loop I_3 through the capacitor and the switching device is illustrated in a representative manner in Fig. 6. The most significant difference is the presence of an oscillatory current in loop I_3 that begins when current I_1 commutates at time t_1 and ends shortly after time t_2. This oscillatory current flows through the capacitor and switching device presenting them with high frequency current reversals that can damage solid state switches and shorten the life of energy storage capacitors. The current I_3 flows concurrently through the diode Dx with current I_2, creating a peak current that may be over 50% higher than the ideal waveform. It is important to note that this oscillatory current flows through the diode in the reverse direction, although the total current through the diode, I_{Dx}, always flows in the forward direction. It should further be noted that the current in the outer loop I_2 is unaffected by this oscillatory current. Thus, the freewheeling diode, although it appears in effect in parallel with the storage capacitor, is actually ineffective to prevent these reverse voltages and currents.

The presence of the oscillatory current in the inner current loop I_3 can be explained as follows. As the current in loop I_1 begins its sine wave ascent (it is sinusoidal due to the effective LC network present in loop I_1 prior to time t_1), it is commutated at time t_1 when the capacitor is discharged and most, but not all the capacitor energy, has been transferred to the inductor L. Some of the energy, albeit small, is trapped in the stray inductance L_S in loop I_3. At the time t_1, there is a single energy source L in loop I_2 and a single energy source L_S in loop I_3. Because loop I_3 contains the capacitor C, there is a resonant circuit consisting of capacitor C and the stray inductance L_S. The value L_S is small so that the inner loop current oscillates at a high frequency defined approximately by $1/\sqrt{(L_sC)}$. This oscillatory current decays exponentially by time t_2 due to circuit impedance in the inner loop I_3 such as the diode Dx resistance.

In the past, when the switching device was a solid state switch such as a thyristor or SCR, it has been common to place a clamping diode in reverse parallel with each device. The clamping diode is intended to turn on in response to reverse voltages appearing across the respective SCR and thus protect the device. We have discovered, however, that this approach can be ineffective in many cases because the turn on time of the clamping diodes may not be fast enough to respond to the high frequency reverse voltage surges from stray inductance. Consequently, excess reverse voltage can still appear across the SCR and cause degradation or failure. This was particularly noted with GTO type thyristors which are very sensitive to reverse voltages. The reverse voltage and current oscillations are also damaging to conventional energy storage capacitors commonly used for the main storage capacitor in the exciter circuits.

In order to prevent these damaging current oscillations in the inner loop I_3, in accordance with the invention, we provide a clamp diode across the storage capacitor with a polarity that allows normal charging of the capacitor but which by-passes the capacitor in the opposite direction so that the capacitor cannot resonate with the stray inductance L_S in the inner loop. This clamp diode effectively eliminates the reverse oscillatory voltages and currents that would otherwise damage the switching devices and the storage capacitor, as well as eliminates the reverse currents through the freewheeling diode Dx. Referring again to Fig. 6, we show a typical curve for the diode Dx current (identified with the reference I'_{Dx}) when a clamp diode is placed directly in parallel with the storage capacitor so as to prevent oscillations between the capacitor and the stray inductance L_S.

In the preferred circuit of Fig. 1, for example, in accordance with the invention, the reverse parallel diodes are removed and a clamp diode rectifier 150 such as part no. BYM56E available from Philips is placed directly in parallel with the main storage capacitor 38. This effectively shunts the capacitor 38 to prevent reverse currents or voltages appearing due to the stray inductance. It will be noted that the free wheeling diode 71, which is also in the outer current loop of the discharge circuit (consisting of the inductor 74, the current multiplier 76, the plug 12 and the diode 71), is ineffective against the stray inductances of the inner loop because that diode 71 is effectively in parallel with the capacitor 38 and the stray inductance L_S. Furthermore, because the clamping diode 150 is in series with the switching devices 46 which are in parallel with the free wheeling diode 71, the clamping diode 150 should be chosen to have a higher internal resistance so as not to divert arc current from diode 71 through the switches 46 when energy is transferred from the inductor 74 to the plug 12. This higher impedance does not adversely affect circuit efficiency because the clamp diode 150 only conducts a small fraction of the current conducted by the free wheeling diode 71. Typically, diode strings will be used for both the free wheeling diode 71 and the clamp diode 150 in order to meet system voltage requirements. The relative impedance of the clamp diode 150 can be increased, for example, by also using a series non-inductive resistor, selecting the clamp diode to have a smaller die size, or using more diodes in the diode string, to name just a few options available to the designer.

The rectifier 150 thus prevents reverse voltages and charging currents from occurring due to the inner loop stray inductances, thus protecting the switching devices 46. The invention as explained however, also achieves benefits with spark gap circuits because the clamp diode limits oscillatory currents through the main storage capacitor and the free wheeling diode used for unidirectional discharge circuits.

Turning next to Fig. 7, another advantageous use of the present invention is shown in the form of a dual charger exciter circuit 500. Although this circuit is shown with a spark gap switching device 502, this is merely for convenience and should not be construed in a limiting sense. A solid state switching device could also be used with the provision for a trigger circuit, such as shown in Fig. 1 herein. The dual charger is realized in a conventional manner and includes, in this example, an AC charging circuit 504, and a DC invertor charging circuit 506. The dual circuit 500 is typically used, for example, for ignition circuits in which a high energy spark is required for starting an engine, and then a lower energy spark is used for maintaining engine operation. Accordingly, the exciter 500 includes two storage capacitors 508 and 510. During engine start, the DC invertor receives a DC system input voltage 512 and charges both capacitors 508, 510. This provides high energy storage for the parallel capacitors such that when the spark gap triggers a high energy spark is created. After ignition, the DC invertor is turned off by disconnection of the DC input, and system AC power 514 is applied to the AC charger 504. The AC charger charges only the smaller capacitor 508 due to the presence of the blocking diode 520. Most of the circuit of Fig 7. is conventional spark gap technology and well known to those skilled in the art. The dual charging circuit is fully described in US Patent No. 3,629,652 issued to Maycock et al., the entire disclosure of which is fully incorporated herein by reference. In that patent, two AC charging circuits are used rather than an AC charger and a DC charger, but the present invention can be used with either embodiment as well as others.

The blocking diode 520, as used in the Maycock et al. patent for example, is subject to reverse and damaging oscillatory currents and voltages due to the presence of the stray inductance L_S which we have previously described herein. The unidirectional or free wheeling diode 522 is ineffective to prevent these reverse phenomena. In accordance with the invention, clamping diodes 530 and 532 are provided directly in parallel with the storage capacitors 508, 510 respectively to prevent these reverse currents and voltages by shunting the capacitors in the reverse charging direction thus eliminating the resonant circuit that would otherwise be present if the parallel clamping diodes were not used.

We have further found that when a series string of switching devices 46 is used, the devices may have different transition times for turning on when the gate terminals are triggered. This can result in excessive voltages across the anode/cathode junction of the slower devices. For example, in Fig. 1, if devices 46a and 46b begin to conduct current at an appreciably faster rate than device 46c, excessive anode/cathode voltages may appear across the slower device 46c. To reduce this effect, we have provided snubber circuits 200 for each switching device 46. Each snubber circuit 200 operates in substantially the same manner, therefore, only one will be described.

Each snubber circuit 200 includes a capacitor 202, a diode 204, and a gate return resistor 206. A series string of static balancing resistors 208 are also provided. The snubber capacitor 202 is connected between the diode 204 and the corresponding gate terminal 48 of the switching device 46. For purposes of explaining operation of the snubber circuits 200, assume that switching device 46a and 46b begin to turn on before device 46c. Without the snubber circuits, voltage would rapidly build across the anode/cathode junction of the slower device. However, with the snubber circuit 200 in place, this excess charge is shunted away from the switching device and charges the snubber capacitor 202 through the snubber diode 204. Because the snubber capacitor is also connected to the gate terminal of the slower switching 46c, the charging of the capacitor adds a boost to the gate drive signal from pulse transformer 50c in order to drive the slower device harder. The effect of this is to help turn on the switching device 46c faster. The static balancing resistor 208 in each snubber circuit serves at least two purposes. First, these resistors operate in a conventional manner to provide static balance across the switching devices so that no single device 46 sees an excessive anode/cathode potential while the main capacitor 38 is charging. The balancing resistors 208 also serve to discharge the snubber capacitors after each spark discharge period of the exciter 10.

We have found that the snubber circuit 200 is particularly useful when the switching device is a GTO type thyristor. This is because these devices are particularly susceptible to excess anode/cathode voltages due to slower and less predictable turn on time delays from the time that the gate current is applied to the time that the device operates in the thyristor region. When conventional SCRs are used for the switching devices, however, the devices exhibit fairly consistent and predictable turn on delays that are short enough that additional drive to the gate terminals is not needed. Therefore, a snubber circuit for conventional SCR devices can be used that has the snubber capacitor connected between the snubber diode and the cathode of the SCR. This snubber design simply shunts any charge build up due to devices 46 turning on at different rates around the slower devices.

It will also be noted that each snubber circuit 200 includes a diode 210 connected between the gate terminal 48 and the corresponding pulse transformer 50. This diode is provided to block current from the snubber capacitor 202 from being shunted away from the gate terminal 48 due to the low impedance of the pulse transformer secondary winding. This diode is not needed in an SCR snubber circuit because the latter returns the snubber capacitor current to the SCR cathode, not the gate terminal.

With reference now to Fig. 3A, an alternative embodiment is shown for a high tension discharge circuit. In some engine designs, the plug 12 requires a high voltage level to generate the spark across the plug electrodes. This voltage may be on the order of 15 kV or higher. Because solid-state switches cannot withstand such high voltages, a voltage step-up transformer is used in the output circuit 72. The use of voltage step-up transformers for high tension exciters has been well known since the 1960s. A typical design includes a transformer T3 having a primary winding connected in series with the main capacitor 38 (not shown in Fig. 3A) and an excitation capacitor 90. The transformer T3 secondary 92 is connected in series with the plug 12. When the switching devices 46a-d are triggered on, discharge current from the capacitor 38 initially flows through the primary of T3 until the capacitor 90 charges. During this time a high voltage spike is induced in the secondary 92 that appears across the plug 12 to create a spark. After the capacitor 90 charges, the primary of T3 no longer conducts current, and the capacitor 38 completes discharge through the secondary 92 and the current multiplier. As shown in Fig. 3A, the step-up transformer T3 can be used in parallel with the current multiplier 76 of the present invention to first provide high voltage at low current to the plug 12 in order to initiate the spark and then provide low voltage and high current to the plug 12. Fig. 3B shows yet another variation in which the current multiplier 76 and voltage step-up transformer can be realized using a single transformer T4. In this embodiment, discharge current from the capacitor 38 initially flows through the primary 94 and excitation capacitor 96. This creates a high voltage spike in the center tapped secondary winding 98 and a high current spike in the other secondary winding 100. After the capacitor 96 charges, the main capacitor 38 completes its discharge through the secondaries 98,100.

It will also be appreciated that the exemplary configuration shown in Fig. 1 can be easily modified with respect to polarities of the charging current, capacitor 38 and the switching devices 46. In other words, for example, the switching devices could be reversed and the capacitor 38 negatively charged by the charging circuit 20. The switching circuit, generally outlined by the box 300, could also be interchanged positionally with the main capacitor 38. Thus, the particular topology of the circuit shown and described with respect to Fig. 1 is not critical to realize the advantages of the invention, and can be easily changed to suit the needs of the specific application.

While the invention has been shown and described with respect to specific embodiments thereof, this is for the purpose of illustration rather than limitation, and other variations and modifications of the specific embodiments herein shown and described will be apparent to those skilled in the art within the intended spirit and scope of the invention as set forth in the appended claims.

Claims

1. An exciter for an igniter, comprising an AC charging circuit (20) and a discharge circuit (22), said discharge circuit (22) being connectable to a plug (12) to cause the plug (12) to produce sparks and said charging circuit (20) being connectable to an AC power source (28), characterized in that said discharge circuit (22) comprises a storage capacitor (38) connected to said charging circuit (20) such that charging current charges said capacitor (38) at a generally constant rate between sparks, a solid state switching device (46) connected between said capacitor and the plug (12), and a trigger circuit (52) for triggering said switching device (46) in response to charge on said capacitor (38), said charging circuit (20) and said trigger circuit (52) operating to maintain a generally constant spark rate

2. An exciter according to claim 1, characterized by a half-wave rectifier (42,44) connected between said charging circuit (20) and said capacitor (38) such that alternating half-cycles of charging current are blocked thereby providing a commutation period for said switching device (46) after discharge.

3. An exciter according to claim 1, characterized in that said switching device (46) is a thyristor, GTO, or SCR.

4. An exciter according to any previous claim, characterized by a current multiplier (76) connected between said switching device (46) and the plug (12) to substantially increase current through the plug (12) to when said capacitor (38) discharges.

5. An exciter according to claim 4, characterized in that said current multiplier (76) is structurally positioned near the plug (12) to reduce power loss during discharge of said capacitor (38).

6. An exciter according to claim 4 or 5, characterized in that said current multiplier (76) comprises an autotransformer (T2) having a first winding in series between said switching device (46) and the plug (12), and a second winding connected to the plug (12) so that current applied to the plug (12) during discharge is substantially greater than current discharged from said capacitor (38).

7. An exciter according to claim 6, characterized in that said current multiplier (76) is connected to a voltage step-up circuit (T34,90).

8. An exciter according to claim 7, characterized in that said current multiplier (76) and voltage step-up circuit comprise a single core transformer having a first winding connected in series with said switching device (46) and capacitor (38), a second winding (92) connected across said plug (12) to substantially increase the voltage across the plug before an arc is struck, and a third winding connected to the plug to substantially increase current to the plug after an arc is struck.

9. An exciter according to claim 8, characterized by a diode in series between said secondary and the plug.

10. An exciter according to any previous claim, characterized in that said trigger circuit (52) comprises a comparator (54) for comparing said capacitor voltage with a reference voltage, said comparator producing a trigger signal in response to a predetermined relationship between said capacitor voltage and said reference.

11. A method for producing a constant spark rate of an ingiter plug (12) in an engine, characterized by the steps of producing a half-wave rectified charging current from an AC power source (28); charging a capacitor (38) with said charging current at a generally constant rate of charge between sparks; detecting the charge on said capacitor (38); triggering a switching device (46) in response to charge on said capacitor (58) to discharge said capacitor (38) through the igniter plug (12); and turning the switching device (46) off during a non-charging half-cycle of said charging current after said capacitor (38) discharges.

12. A method according to claim 11, characterized by the step of substantially increasing current delivered to the ingiter plug (12) during discharge of the capacitor (38) using a current multiplier (76).

13. A method according to claim 12, characterized in that the step of substantially increasing the current delivered to the igniter plug (12) follows a step of substantially increasing the voltage applied to the plug (12) during discharge of said capacitor (38).

14. An exciter of the type used for supplying energy to an igniter plug and characterized by a charging circuit (20), a capacitor (38) charged by said charging circuit (20), a discharge circuit (22) having a switching device (46) for controlling the discharge of energy stored in said capacitor (38) to the plug (12), and a current multiplier (76) connected between said switching device (46) and the plug (12).

15. An exciter of the type used for supplying energy to an igniter plug (12) and characterized by a charging circuit (20), a capacitor (38) charged by said charging circuit (20), a discharge circuit (22) having two or more series-connected solid state switching devices (46) for controlling the discharge of energy stored in said capacitor (38) to the plug (12), and a snubber circuit (200) connected to each of said switching devices (46), each snubber circuit (200) comprising a capacitor (202) connected between a gate and anode of the respective switching device (46).

16. An exciter circuit for an igniter plug (12), said exciter circuit comprising a storage capacitor (38) that unidirectionally discharges through the plug (12) to produce sparks; characterized by rectifier means (150) in parallel with said capacitor (38) to prevent reverse currents and voltages by preventing resonance between said capacitor (38) and stray inductance in the exciter circuit.

17. A circuit according to claim 16, characterized in that it exhibits stray inductance primarily from internal lead length inductance and/or inductance in the capacitor.

18. A circuit according to claim 16 or 17, characterized by a second charging circuit (506), and a second rectifier means in parallel with said second capacitor for preventing respectively reverse currents and voltages across said capacitors.

19. A circuit according to claim 18, characterized in that said rectifier means (530,532) are in direct parallel relationship to the said capacitors (508,510) thereby preventing resonant circuits between said capacitors and stray inductance in the exciter circuit.

20. A method of preventing reverse currents and voltages across a storage capacitor (38) in an exciter circuit for an igniter plug (12) used in a turbine engine, comprising the step of using a rectifier (150) directly in parallel with the capacitor (38) to prevent resonance between the capacitor (38) and stray inductance in the exciter circuit.

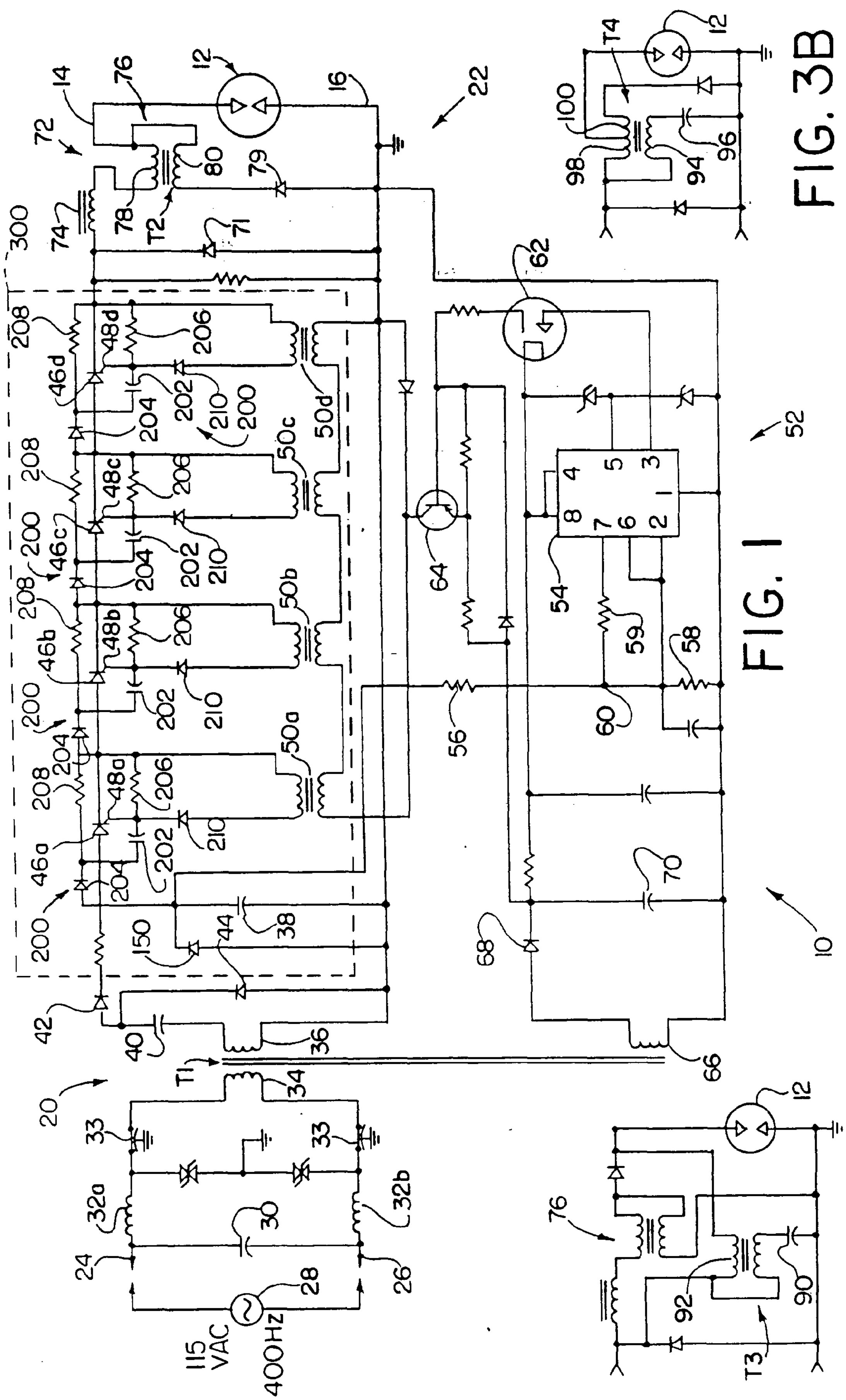

FIG. 1

FIG. 3A

FIG. 3B

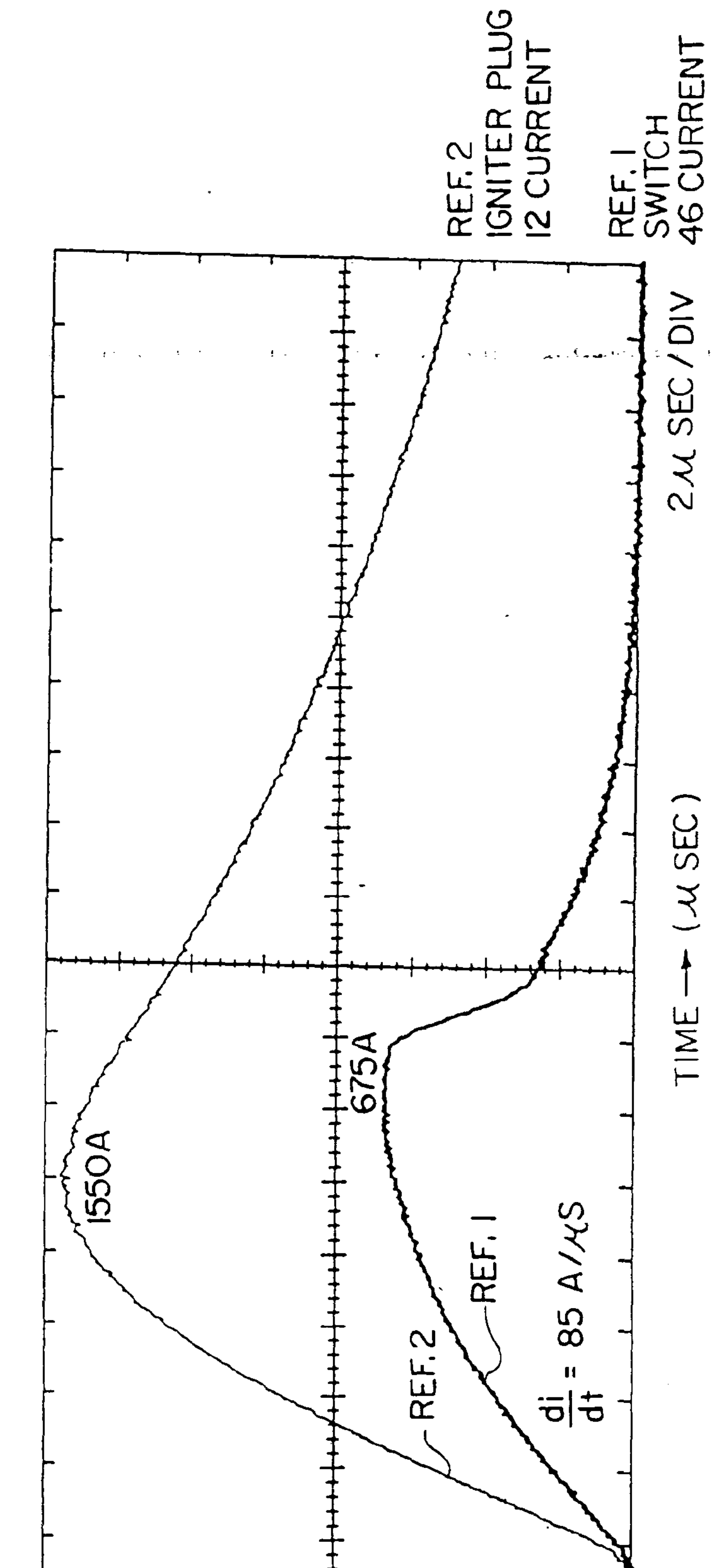
REF. 2
IGNITER PLUG
12 CURRENT
REF. 1
SWITCH
46 CURRENT
2 μ SEC / DIV
TIME → (μ SEC)
1550A
675A
REF. 2
REF. 1
di/dt = 85 A/μS
+25°C
200 A / DIV
CURRENT (AMPS)

FIG. 2

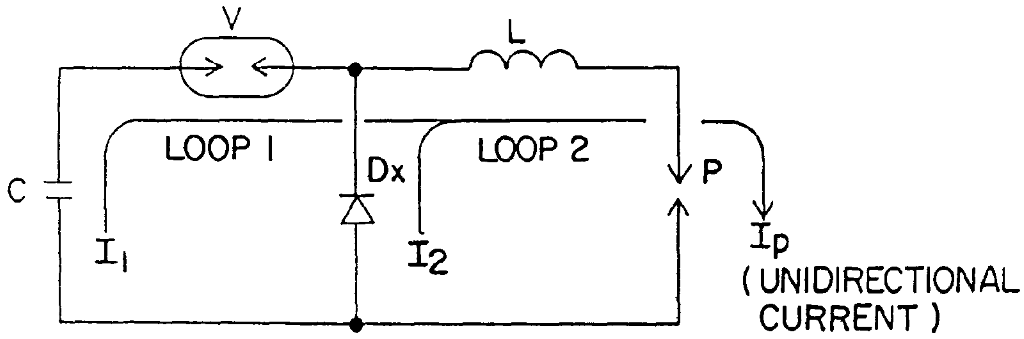

FIG. 4

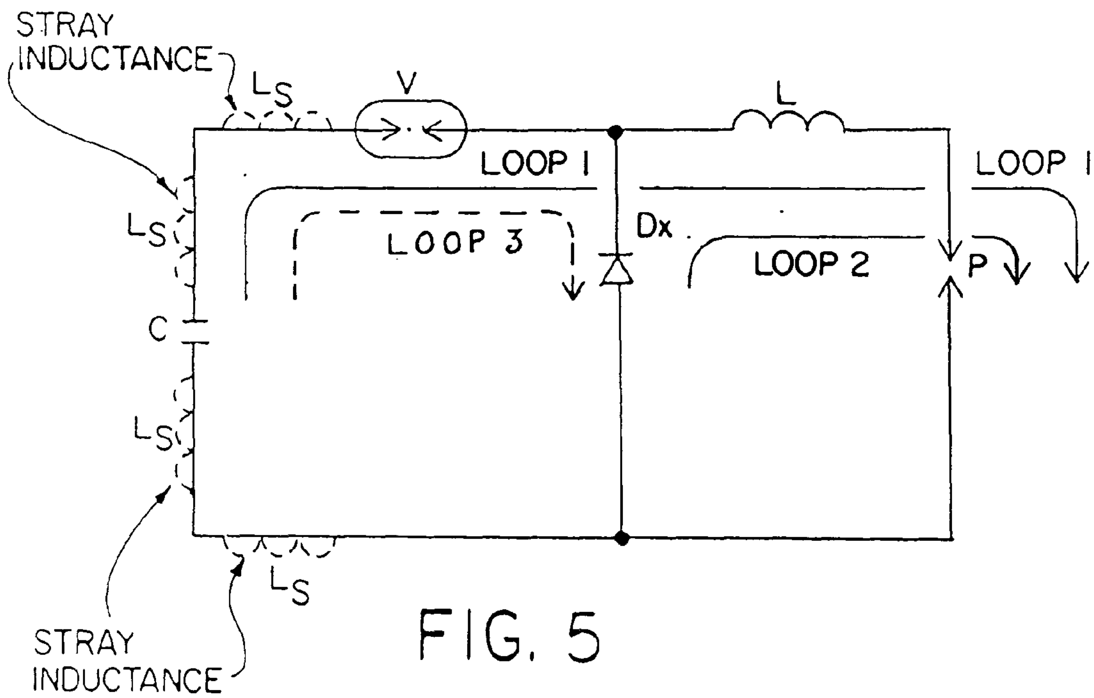

FIG. 5

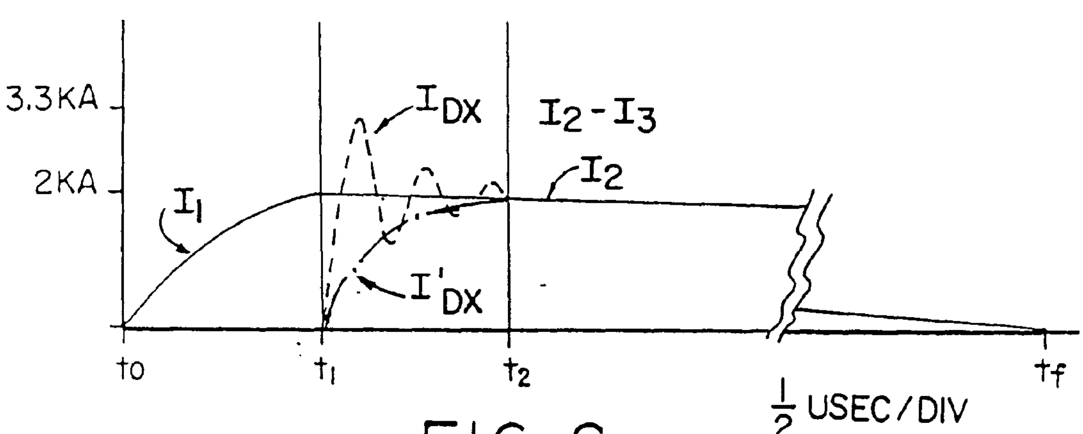

FIG. 6

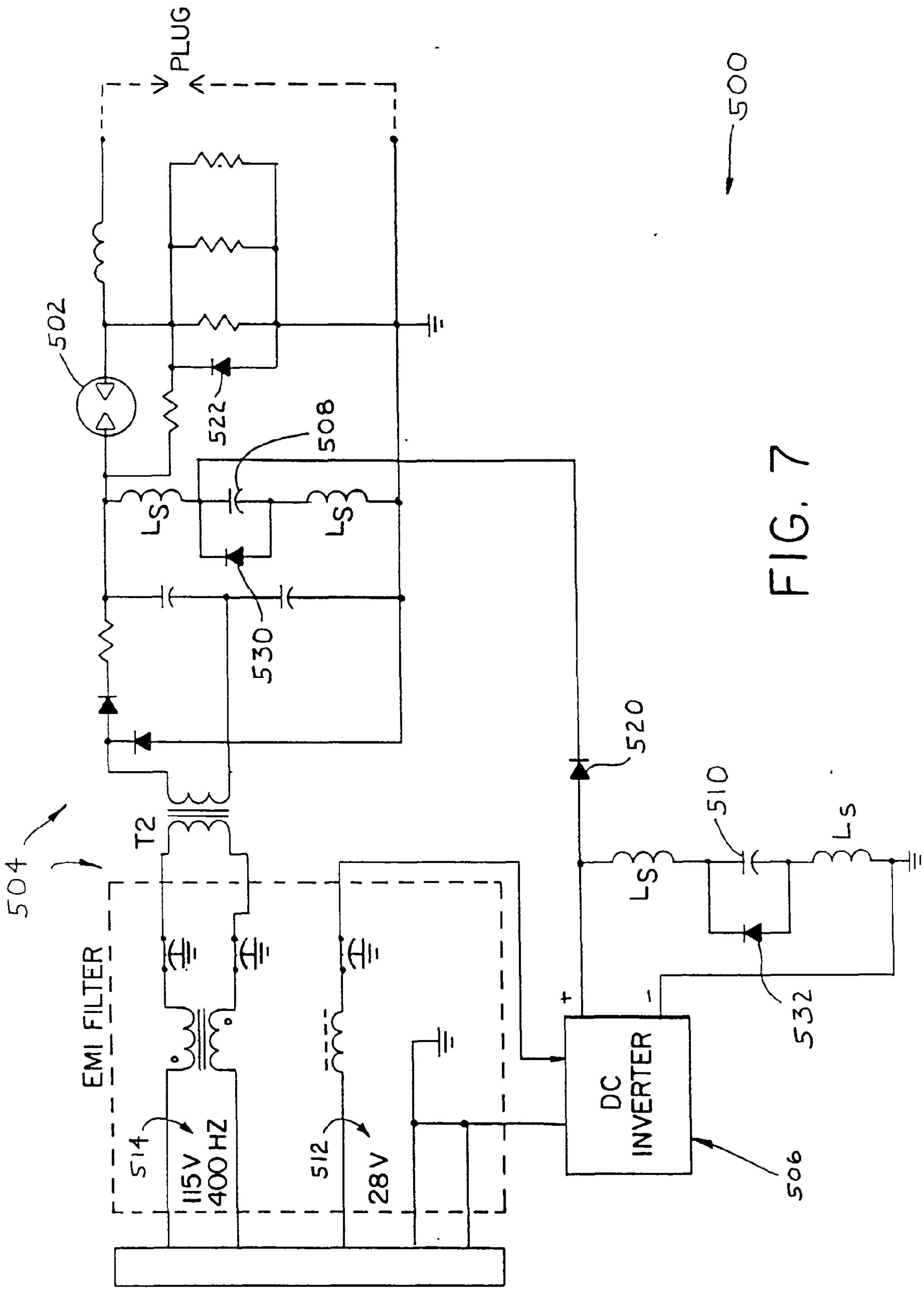
PLUG
500
502
522
508
LS
LS
530
520
510
LS
Ls
532
+
-
DC
INVERTER
506
504
T2
EMI FILTER
514
115V
400 HZ
512
28V

FIG. 7