

PATENT SPECIFICATION

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COMPLETE SPECIFICATION DRAWINGS ATTACHED

Semiconductor Switching Circuits

We, TEXAS INSTRUMENTS INCORPORATED, a Corporation organized and existing under the Laws of the State of Delaware, United States of America, of 13500, N. Central Expressway, Dallas, Texas, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates generally to switching circuits, and more particularly, to switching circuits employing a four-layer semiconductor device for rapidly switching currents in inductive load circuits.

It has been recognized for some time that considerably more difficulty is experienced in terminating current flow through a direct current circuit than through an alternating current circuit. Specifically, if during a switching operation in a direct current circuit an arc is struck across the contacts of the switching device, the direct current continues to feed the arc until some external means is employed to extinguish it. In an alternating current circuit, however, the arc is normally extinguished when the voltage goes through zero.

The problem of switching in direct current circuits becomes aggravated when an inductive device is included, for termination of current flow causes the field established around the inductor to collapse, thereby increasing the voltage across the open contacts and increasing the probability of arcing. The transient voltage due to the collapse of the field about the inductor rises to whatever value is required to maintain the flow of current in the switching circuit since the rate at which the field in the inductance collapses, and therefore the voltage generated is a function of the switching rate. Thus, if no arcing initially occurs at the instant the

contacts are opened, the field about the inductive device collapses almost instantaneously and an extremely high transient voltage is generated which in most instances is sufficient to strike the arc across the opening contacts.

Numerous expedients have been employed to attempt either to prevent the striking of an arc upon opening a d.c. circuit or to minimize the intensity of the arc and render it readily extinguishable. Perhaps the most common type of arrangement for this purpose is the connection of a capacitor across the switching contacts so that the transient current is absorbed in the capacitor and the voltage across the contacts is held to a relatively low value. If the capacitor cannot prevent arcing, it at least reduces the intensity of the arc and therefore reduces the burning of the contacts which otherwise would occur.

In more sophisticated systems, arc draw-out configurations are employed with or without gas generation devices which tend to extinguish the arc. However, in all of these cases some degree of burning takes place across the contacts and tends to shorten their life. Further, in systems in which the expense incident to the provision of arc drawout and gas blast suppression devices cannot be justified or cannot be physically accommodated, the only practical alternative now being employed is the utilization of the capacitor across the contacts. As indicated above, this solution is not completely satisfactory.

As an example of a circuit in which considerable difficulty is experienced in suppressing and reducing the effects of an arc across switching contacts in a highly inductive circuit, attention is directed to the ignition circuit of the conventional automobile. In such a circuit, breaker points are connected

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in a series circuit with the primary winding of a spark coil and a condenser is connected across these points in order to suppress the arc generated by the sudden collapse of the field in the spark coil when the breaker contacts are opened. It is well known to anyone who is familiar with the automobile, that the contact points become badly pitted in a relatively short period of time, and further, the capacitor is often in need of replacement due to damage thereto or outright failure thereof.

It has been suggested in the prior art to replace the mechanical switch in series with the primary winding of the spark coil with a transistor and switching the transistor on and off by means of a switch connected in the control electrode circuit, usually the base electrode, of the transistor. The difficulty with such an arrangement is that the ordinary transistor cannot withstand the high voltages generated by collapse of the field in the spark coil upon termination of current in the circuit. Further, the voltage developed across the transistor in such a circuit is sufficiently high to permit some current to flow therethrough, thereby reducing the energy which can be transferred to the secondary circuit.

Because of the importance of a practical and economical circuit whose function is to terminate direct current flow without damaging the components thereof, it is the purpose of the present invention to provide such circuits that overcome the disadvantages of the prior art.

According to this invention, there is provided a pulse generating circuit comprising an inductor, a transformer and a semiconductor switching device connected in series across a direct current power supply, a capacitor connected with said inductor and said transformer, circuit means including said semiconductor switching device effective at one time for establishing current flow within said inductor thereby to store energy therein, circuit means including said semiconductor switching device effective at another time for discharging the energy stored in said inductor into said capacitor thereby to charge said capacitor to a voltage higher than the voltage of said direct current power supply, and circuit means including said semiconductor switching device effective at still another time for abruptly discharging said capacitor through said transformer thereby to induce an abrupt pulse of high voltage therein.

Further features of the invention will be apparent from the following detailed description given, by way of example, with reference to the accompanying drawings in which:

Figure 1 is an elementary schematic diagram depicting a controlled rectifier electric-

ally connected in an energization circuit;

Figure 2 is a graph of the general voltage-current characteristics of the controlled rectifier of Figure 1;

Figure 3 is another graph depicting the voltage-current characteristics for several different gate currents for a controlled rectifier of relatively small holding current value with accompanying load line of relatively steep slope;

Figure 4 is another graph depicting the voltage-current characteristic for a gate current for a controlled rectifier of relatively large holding current value with accompanying load line much less steeply inclined than that of Figure 3;

Figure 5 is a schematic diagram of one embodiment of the invention employing a controlled rectifier and its related operation as depicted in Figure 4;

Figure 6 is a schematic diagram of another embodiment employing a controlled rectifier and its related operation as depicted in Figure 3;

Figure 7 is a schematic diagram of yet another embodiment employing a transistor;

Figure 8 is a schematic diagram of still another embodiment employing the cooperative action between two controlled rectifiers of different characteristics as depicted in Figures 3 and 4, respectively;

Figures 9 and 10 are schematic diagrams of still other embodiments employing cooperative action between two controlled rectifiers;

Although specific semiconductor controlled rectifiers, circuits and values of the circuit elements will be designated as preferred embodiments, it will be appreciated that other embodiments may be utilized within the scope of the invention.

Referring specifically to Figure 1 of the accompanying drawings there is schematically illustrated a PNP controlled rectifier, which may be utilized in circuits of the present invention, connected in a simple energization circuit. Specifically, the PNP controlled rectifier has a P region 2, hereinafter referred to as the P-emitter region, connected through a load resistor 3 to the positive terminal of a suitable source of voltage 4. The negative terminal of the source 4 is connected to an N-region 6 of the rectifier hereinafter referred to as the N-emitter region or electrode. A second P region 7, hereinafter referred to as the gate, is connected via a lead 8 to a stationary contact 9 of a switch 11. A movable contact 12 of the switch 11 is connected to the positive terminal of a bias source 13, the negative terminal of which is connected to the N-emitter region 6. The rectifier further comprises an N-region 10 referred to as the N-base region.

The general characteristics of the PNP

silicon controlled rectifier approximate, to a certain degree, those of a thyatron, and in order to illustrate the operation of the device, reference is now made to Figure 2. Figure 2 is a graph of voltage from the P-emitter region 2 to the N-emitter region 6 of the rectifier plotted as a function of the current therethrough. Initially, the curve rises sharply and toward the right so that relatively large increases in voltage are required to produce relatively small changes in current through the device. When the voltage reaches a value characteristic of the particular device and designated by the reference numeral 14, voltage across the device suddenly decreases to a point designated by the reference numeral 16 which in a practical device is about one to two volts. Thereafter, relatively small increases in voltage produce large increases in current through the device.

The numeral 17 in Figure 2 designates what is known as the holding current of the device, I_H . To turn off the device once the current of the device exceeds the holding current value 17, a voltage of sufficient value and of opposite polarity must be applied from the P-emitter 2 to N-emitter 6 in order to reduce the conduction current below the holding current value. Back-bias voltage can be applied between the gate 7 and N-emitter 6 to aid in reducing the conduction current below the holding current value.

It is a known fact concerning the PNPN semiconductor controlled rectifier that the breakdown voltage is a function of the current across the P-N junction between the N-emitter 6 and the gate region 7. Advantage may be taken of this fact to control the operation or breakdown of the device by establishing a control current across this junction.

Referring to Figures 3 and 4, there are reproduced two sets of voltage-current characteristics for semiconductor controlled rectifiers. Figure 3 represents the d-c voltage-current characteristics of a controlled rectifier of relatively small holding current 23, say 0.1 to 10 milliamperes, with the corresponding load line 20 of steep slope. In this particular case the numeral 21 represents the voltage-current characteristic for a small current across the junction between the regions 6 and 7 of Figure 1, herein referred to as the gate current. The numeral 22 represents a high gate current, with the intermediate curves representing intermediate gate currents. Figure 3 pertains to the operation of a controlled rectifier that is turned on with a high gate current 22 in conjunction with sufficient P-emitter to N-emitter voltage 24 to cause the current in the device to exceed the holding current 23. The current through and the voltage across the device then follows the load line 20 in

Figure 3. Simply cutting off the gate current 22 does not return the device to its "off" state but has little effect on its operation. This is seen by the steep slope of the load line 20. To return the device to the "off" state requires, as previously described, a back bias voltage of sufficient value to reduce the conduction current below the value of the holding current. In other words, the device has "fired" like a thyatron, and conduction will continue until it is returned to its "off" state in a manner as described.

The characteristics of a controlled rectifier of relatively large holding current 31, say 30 milliamperes or greater, are reproduced in Figure 4. The slope of the accompanying load line 30 is adjusted by the load impedance presented to the device to such a value as not to allow the current of the device to attain the value of the holding current 31. A relatively small gate current 32 allows the device to conduct along the load line 30. The conduction current through the device may be any value and may exceed the holding current for a time. The only requirement for proper operation is that the conduction current through the device be less than the holding current at the time when it is desired to switch the device off. For example, a capacitor may be discharged through the device giving rise to extremely high conduction currents for short times. If the charge of the capacitor is expended before it is desired to turn off the device, i.e., the conduction current through the device is once again below the holding current value, the operation of the device in conjunction with the switch is unimpaired. To those familiar in the art, it is seen that the operation of a four layer semiconductor controlled rectifier in the conducting condition whereby the conduction current is maintained below the holding current value is similar to the operation of two transistors, a PNP and an NPN, in tandem. In this case the controlled rectifier generates a certain amount of positive feedback, thereby causing the operation of the device to be regenerative to some degree. The regenerative action gives the device the characteristic of a greater current gain than is obtainable with a device having negative or no feedback. With the controlled rectifier's conduction current maintained below the holding current value, it is seen that insufficient positive feedback is generated in order to make the device self-sustaining with regards to its conduction. On the other hand, if enough regenerative action is created by positive feedback, the device will "fire", the conduction current will exceed the holding current value and the conduction of the device will be self-sustained, that is, conduction will be maintained with or without

gate current.

The controlled rectifier device as represented by the characteristics of Figure 4 has shorted reverse characteristics as represented by the numeral 33. In other words, the device will conduct in the reverse direction and is almost equivalent to a short circuit as in contrast to the reverse characteristics of the controlled rectifier device represented by the characteristics of Figure 3. The numeral 25 of Figure 3 denotes the reverse characteristics and indicates that the device will not conduct in the reverse direction. The shorted reverse characteristic 33 of the device as shown in Figure 4 is attained during the diffusion process when fabricating the device. The shorted reverse characteristics attained during this diffusion process aid in giving the device the desired high holding current.

Figure 5 illustrates a circuit that has applicability in an automobile ignition system and employs the controlled rectifier previously described in Figure 4. The circuit depicted in Figure 5 is capable of attaining a very hot spark across the gap 61 of the secondary winding 59 of the transformer 60, and at the same time allowing both very fast and very slow switching rates. The schematic circuit depicted in Figure 5 includes: A serial combination of resistor 50 is connected between the positive battery voltage terminal 75 and diode 54, the other end of diode 54 is connected to one end of inductance 55 whose other end is connected to the primary 58 of transformer 60, and the other end of the primary 58 is connected to ground 72 through controlled rectifier 62. The serial combination just described is shunted by resistor 52 which is connected between positive battery voltage terminal 75 and ground 72 through switch 70. Capacitor 56 is connected between the terminal 71 of primary 58 of transformer 60 and ground 72.

To more fully understand the operation of the circuit depicted in Figure 5, a description will be given that includes specific values of all components, although other suitable values of these components may be used without departing from the scope of the invention. The following values of the components of the circuit as depicted in Figure 5 are known to give optimum results for the use of the circuit as an automobile ignition circuit switching at both fast and slow speeds: E_b is the battery voltage and is equal to 12 volts, resistor 50 has resistance of 3 ohms, resistor 52 has resistance of 100 ohms, diode 54 has the characteristic of low forward resistance and breakdown voltage exceeding 300 volts, inductor 55 has an inductance of about 6 millihenries and a resistance of about 1 ohm, capacitor 56 has a

ponding breakdown voltage exceeding 300 volts, controlled rectifier has the characteristic of holding-current in excess of 3 amperes, and switch 70 being the points in the distributor of an automobile ignition system. For optimum performance, transformer 60 will have characteristics specially designed for use in the circuit. Transformer 60 has a primary inductance of approximately 50-100 microhenries and a secondary to primary turns ratio of 200 and an effective capacitance shunting the primary whose value is much less than that of capacitance 56. Assuming that switch 70 is closed when the battery voltage of approximately 12 volts is initially applied to terminal 75, current will flow through resistor 52 to ground 72. Current will not pass through the other series combination of the circuit since the gate 63 of controlled rectifier 62 is at ground potential when switch 70 is closed.

When switch 70 is opened, current will flow from terminal 75 through resistor 52 and through gate 63 of controlled rectifier 62 to ground 72. This gate current turns on controlled rectifier 62 and allows a current of approximately 3 amperes to flow from terminal 75 through resistor 50, diode 54, inductance 55, primary 58 of transformer 60 to ground 72 through controlled rectifier 62. The load line of controlled rectifier 62 is such as not to allow the conduction current to exceed the holding current 31 referred to in Figure 4. Therefore, controlled rectifier 62 must be fabricated in such a way as to give it a holding current characteristic exceeding 3 amperes. During the time the current is being conducted through controlled rectifier 62, energy is stored in inductance 55 in the amount of $1/2 LI^2$. Energy, greatly in deficiency of that stored in inductance 55, is also stored in the primary 58 of transformer 60 due to the same current flow of 3 amperes. The circuit remains in this condition until switch 70 is again closed. As switch 70 is closed, gate 63 of controlled rectifier 62 is returned to ground potential. Since the conduction current of controlled rectifier 62 has not exceeded at the holding current, the device will return to its "off" state when gate 63 is returned to ground potential. Current no longer flows through controlled rectifier 62, but due to the energy stored in and the effective capacitance shunting the primary 58 of transformer 60 as the current is abruptly stopped, a damped sinusoidal oscillation, commonly known as "ring", is set up in the oscillator composed of primary 58 and the effective shunting capacity thereacross. Since the effective shunting capacitance is slight and the energy stored in primary 58 is relatively small, the resulting "ring" is of very high frequency, thereby allowing the core of transformer 60 to ab-

sorb almost entirely all of the energy represented by the "ring". Practically no energy is transferred to the secondary 59 of the transformer 60 due to stopping the 3 ampere current flow in the primary 58, and therefore, preignition or sparking at gap 61 does not occur at this time. Due to the tendency of inductance 55 to maintain the current flow, capacitor 56 will be charged to a voltage greatly exceeding that of the battery potential E_b , e.g., to approximately 150 volts. At this time current ceases to flow in inductance 55. Due to the high voltage of capacitor 56 a means is necessary to prevent backward discharging through inductance 55 and resistor 50. (Since controlled rectifier 62 is in its "off" state no current can flow through this portion of the circuit). Diode 54 prevents reverse current flow, and capacitor 56 retains its charge until controlled rectifier 62 again returns to its "on" state. Controlled rectifier 62 remains in its "off" state until switch 70 again opens. At this time, capacitor 56 discharges rapidly through the primary 58 of transformer 60 to ground through controlled rectifier 62. The discharge results from the placing of capacitor 56 in electrical parallel with the primary 58 through which current can now flow to ground 72. The energy stored in capacitor 56 is much larger than was previously stored in the primary 58 when the 3 ampere current flow was stopped. The shunting capacitance due to capacitor 56 greatly exceeds that of the effective shunting capacitance inherent in transformer 60. Therefore, a damped sinusoidal oscillation of much lower frequency than previously described occurs as a result of the oscillator composed of primary 58, capacitor 56 and the energy stored therein. Because of the low frequency of oscillation, very little energy is lost in the core of transformer 60, and almost entirely all of the energy is transferred to the secondary 61 of transformer 60 as a fast transient high voltage pulse. A spark is generated at gap 61 and can be used as an ignition source.

Since the rate of energy being transferred through the primary 58 of transformer 60 determines the power dissipated across the gap 61, capacitor 56 must be allowed to discharge rapidly through this portion of the circuit. Therefore, the time period of primary 58 and capacitor 56 is adjusted so as to allow this fast discharge. It is well known in the art that the cut-on time of four layer controlled rectifier is, in general, much more rapid than the cut-off time. Since the cut-on time of controlled rectifier 62 is very rapid, the rate of discharge of capacitor 56 through primary 58 of transformer 60 is not increased thereby. Therefore, by properly adjusting the time period of pri-

mary 58 and capacitor 56, very large energy per unit time can be transferred to the secondary 59 of transformer 60 to produce the necessary spark at gap 61.

During the discharge of capacitor 56, the primary 58 of transformer 60 and controlled rectifier 62 will withstand a large current for a very short period of time say, approximately 40 amperes. As soon as capacitor 56 is discharged, normal current will flow, say approximately 3 amperes, through inductance 55 and transformer primary 58. Again, energy is stored in inductance 55, and the cycle starts over. By operating the switch 70 in the desired sequence, the spark in gap 61 may be obtained at desired intervals.

Figure 6 depicts a circuit that is very similar to that of Figure 5 with the exception that controlled rectifier 80 is characterized by a much smaller holding current value than that of controlled rectifier 62 previously described. The holding current value of controlled rectifier 80 is only a few milliamperes and when the controlled rectifier is cut on, the conduction current from P-emitter to N-emitter exceeds that of the holding current value. Therefore, the operation of controlled rectifier 80 in this circuit is similar to that as described in Figure 3, and simply returning the gate 83 to ground potential does not return the device to its "off" condition. Other techniques must therefore be used to make the circuit operate successfully when using a controlled rectifier of such small holding current. Figure 6 is an example of such a circuit that will work successfully. However, it employs an additional capacitor and diode.

Capacitor 56 is connected between primary 58 of transformer 60 and switch 70 to serve the dual purpose of aiding in turning off controlled rectifier 80 and also supplying the current pulse that produces the spark at gap 61. The additional capacitor 57 is connected between gate 83 of controlled rectifier 80 and switch 70 to serve the purpose of aiding in cutting off controlled rectifier 80. The other addition, diode 85, bypasses switch 70 in order to provide a current path for discharge of capacitor 56.

Assuming that switch 70 is initially closed when the battery voltage E_b is applied to terminal 75, current will flow through resistor 52 to ground. Controlled rectifier 80 will not conduct as yet since no gate current has been provided to turn it on. When switch 70 is opened, current flows through the serial combination of resistor 52, capacitor 57 and resistor 53 to ground 72, thereby raising the voltage at gate 83 and cutting on controlled rectifier 80. Current then flows from terminal 75 through resistor 50, diode 54, inductance 55,

and primary 58 of transformer 60 to ground 72 through controlled rectifier 80. The voltage of terminal 71 between inductance 55 and primary 58 of transformer 60 drops above ground potential due to the conduction of controlled rectifier 80. Once the voltage of terminal 71 is dropped to a low value, current flows from terminal 75 through resistor 52 and capacitor 56, thereby charging it to a value of approximately E_b minus the one or two volts drop across controlled rectifier 80. During this time, capacitor 57 is charged to its full value, and current no longer flows through the gate 83 of controlled rectifier 80. Although gate 83 of controlled rectifier 80 is now returned to ground potential, the device continues to conduct since it has exceeded its holding current value. Also, during the conduction time of controlled rectifier 80, energy is stored in inductance 55 in the amount of $1/2 LI^2$. The circuit now remains in this state until switch 70 is again closed. When switch 70 is closed the voltage at terminal 71 and the voltage at gate 83 of controlled rectifier 80 drop to about eleven volts below ground potential due to the charge on capacitors 56 and 57, respectively. The negative voltages applied across both P-emitter 81/N-emitter 82 and gate 83/N-emitter 82 reduce the conduction current below the holding current value, thereby causing the device to return to its off state. Transformer 60 with its related primary and effective capacitance features are essentially the same as those described in conjunction with Figure 5 and no preignition occurs at this time.

As previously described in conjunction with Figure 5, inductance 55 tends to sustain the current flow in the circuit. Since controlled rectifier 80 is now cut off and current cannot flow in this path, inductance 55 charges capacitor 56 to a large value to approximately 150-200 volts. Diode 54 again serves the purpose to prevent this charge from leaking off. As switch 70 is again opened, charging current for capacitor 57 flows to gate 83 and thence, to ground, thereby causing the controlled rectifier 80 to return to its "on" state. A high current discharge through primary 58 of transformer 60 in the amount of approximately 40 amperes is produced due to the high voltage charge on capacitor 56. Diode 85 provides the path for which this discharge can take place since switch 70 is now open. Once the discharge of capacitor 56 through the primary 58 of transformer 60 is completed, the cycle starts over.

It is seen that the circuit as depicted in Figure 6 produces the same results as that of Figure 5 while the same time utilizing a controlled rectifier device that has a much smaller holding current value.

Illustrated in Figure 7 is a circuit very similar to that of Figure 5 with the exception that controlled rectifier 62 is replaced by a transistor 90 of special characteristics. Transistor 90 must have the characteristics of withstanding a current flow of approximately 3 amperes from collector to emitter. In addition, it must be able to withstand the current surge of approximately 40 amperes as capacitor 56 discharges through primary 58 of transformer 60 to produce the spark at gap 61. By replacing controlled rectifier 62 with transistor 90, the concern with holding current is eliminated, for transistor 90 may be cut off rapidly by simply returning the base 93 to ground potential. The simple operation of opening and closing switch 70 cuts the transistor 90 on and off.

The operations of the circuits as illustrated in Figures 5 and 7 are identical with the exception that a transistor is interchanged with a controlled rectifier device. Those familiar in the art will realize that a controlled rectifier device will much more readily sustain the high current pulses necessary for the operation of this circuit. Therefore, the circuit as illustrated in Figure 5 is more desirable from this standpoint than that illustrated in Figure 7. It should be noted, however, that in both circuits successful operation can be effected by simply opening and closing a switch 70. Figure 6 represents a circuit in which the featured type of operation is possible due to the characteristics of the controlled rectifier device employed. However, as previously explained, successful operation is effected by the action of capacitors 56 and 57 which aid in cutting off the controlled rectifier device when necessary. In addition, it should be pointed out with regard to Figure 6 that the switch 70, or what will normally be the points in an automobile ignition system, carries a high current during one portion of the cycle as the stored energy in inductance 55 charges capacitor 56 to the high voltage necessary to produce the high current pulse. Switch 70 is closed at this time and must carry approximately 3 amperes of current. However, no burning or pitting of the switch or points is encountered due to this high current flow since the switch remains closed during this interval. The ordinary automobile points or switch are sufficiently large in cross-sectional area to withstand a 3 ampere current flow without great damage to the critical parts. This is in contrast to the old automobile ignition circuit in which high voltage is generated across the points or switch when they are opened. Such high voltage increases tend to produce a spark across the points thereby pitting them and burning them.

For successful operation of the circuit as

illustrated in Figure 5, the controlled rectifier must have characteristics such that it will stand a normal P-emitter to N-emitter current flow of approximately 3 amperes and have a high holding current, that is, in excess of three amperes. There are many controlled rectifier devices that are produced that do not possess both of these desirable features. In many instances a controlled rectifier device can be fabricated in such a way as to give it a characteristic of high holding current but cannot withstand the high P-emitter to N-emitter current flow. In other cases where a controlled rectifier device is fabricated such that the device will withstand a high P-emitter and N-emitter current flow, the holding current is usually of a low value. When such is the case, two controlled rectifiers of different characteristics are utilized as illustrated in Figure 8 to perform the desired function as an automobile ignition system. In Figure 8, the points or switch 70 are operatively isolated from all possible high energy parts of the circuit, as distinguished from the circuits of Figure 6. Referring to Figure 8, the switch 70 never carries a current greater than a few milliamperes. Controlled rectifier 100 has a characteristic of sustaining a high current flow from P-emitter to N-emitter but has the disadvantage of a low holding current. Controlled rectifier 104 does not have to withstand such high current flow but does have a high holding current. Controlled rectifiers 100 and 104, respectively, act in cooperation with one another such that the desired switching from one to the other may be effected.

The schematic circuit in Figure 8 includes: Two controlled rectifiers 100 and 104 acting in cooperation with each other, controlled rectifier 104 performing the function of cooperating with switch 70 to switch the controlled rectifier 100 to the "on" state or the "off" state, whichever the case may be; the P-emitter 106 of the controlled rectifier 104 being connected to the positive battery terminal 75 through the series resistance 51, and N-emitter 107 of the controlled rectifier 104 being connected directly to ground 72. Resistor 52 is connected from the positive battery terminal 75 to gate 105 of the controlled rectifier 104 in shunt across the serial combination of resistor 51 and controlled rectifier 104, and the gate 105 is also electrically connected to the switch 70, the other side of switch 70 being connected directly to ground 72. One end of resistor 50 is connected to the positive battery terminal 75, the other end of resistor 50 is connected to the anode of diode 54; the cathode of diode 54 is connected to one end of the inductance 55, the other end of the inductance 55 being con-

nected to one end of the primary 58 of transformer 60; the other end of the primary 58 is connected to the P-emitter 102 of controlled rectifier 100, and the N-emitter 103 is connected directly to ground 72. Capacitor 56 interconnects the P-emitter 106 of controlled rectifier 104 with the junction between inductance 55 and primary 58 of transformer 60; and capacitor 57 interconnects the P-emitter 106 with gate 101 of controlled rectifier 100, the gate 101 being connected to ground 72 by resistor 53.

To more fully clarify the operation of the circuit referred to in Figure 8 assume that both controlled rectifiers 100 and 104 are initially in their "off" state and that switch 70 is closed. If a d.c. voltage E_b is applied at terminal 75, current will flow from terminal 75 through resistor 52 to ground 72, thereby preventing controlled rectifier 104 from conducting by putting the gate 105 at ground potential 72. Current also flows through the series path of resistor 51, capacitor 57 and resistor 53 to ground 72. During the time that capacitor 57 is charging, some current flows through gate 101 of controlled rectifier 100 to ground 72, thereby causing controlled rectifier 100 to conduct. Reference to Figure 3 shows that controlled rectifier 100 is "cut on" by a relatively small gate current, say 10 milliamperes, and the conduction of current from the P-emitter 102 to N-emitter 103 exceeds that of the holding current, where the holding current is less than, say 20 milliamperes. The voltage of the P-emitter 102 drops from the original E_b value to approximately one volt above ground potential due to conduction of controlled rectifier 100, thereby allowing capacitor 56 to charge through resistor 51. At the same time, current flows through the series combination of resistor 50, diode 54 and inductance 55, thereby storing energy in inductance 55. Also during this time, capacitor 57 is charged up, and no more current flows through resistor 53. This returns gate 101 to ground potential but does not stop the controlled rectifier 100 from conducting due to the characteristics as explained in connection with Figure 3.

After capacitor 56 is charged, the circuit remains in a steady-state condition until switch 70 is opened. The capacitors 56 and 57 are charged to a voltage of approximately E_b . When switch 70 is opened, current flows through gate 105 of controlled rectifier 104 and causes current to conduct from P-emitter 106 to N-emitter 107 but not in excess of the holding current. The gate current required to turn on this device is approximately 10 milliamperes. The characteristics of this device are as described in Figure 4 and this operation should be distinguished from that of controlled rectifier 100.

As controlled rectifier 104 conducts, the

voltage of the P-emitter 106 drops from approximately E_b to about one volt or less above ground potential. The voltages at connection 71 and gate 101 drop to approximately a value of E_b below ground potential due to the voltages on capacitors 56 and 57, thereby back-biasing both the P-emitter/N-emitter and gate/N-emitter of controlled rectifier 100, cutting it off. As previously indicated, no spark or large energy release at gap 61 of transformer 60 occurs at this time due to the relative values of the circuit components.

Inductance 55 will tend to sustain the current flow even though controlled rectifier 100 acts as an open circuit. Therefore, inductance 55 will force current from terminal 75 through capacitor 56 and controlled rectifier 104 to ground 72. The large amount of energy stored in inductance 55 will be transferred to capacitor 56 as a large voltage, say 150-200 volts. Diode 54 prevents the energy represented by this voltage from draining off until the proper current path is provided.

As switch 70 is again closed, thereby grounding gate 105 of controlled rectifier 104 and consequently returning it to its "off" state, current flows through resistor 51, charging up capacitor 57 through both resistor 53 and gate 101 of controlled rectifier 100. This action again turns on controlled rectifier 100, thereby returning it to its "on" state. At the instant controlled rectifier 100 turns on, the large voltage stored in capacitor 56 discharges through the primary 58 of transformer 60 as a high current transient pulse. The conduction path for this current pulse is through primary 58, controlled rectifier 100 to ground and back through controlled rectifier 104 in the reverse direction. As stated previously the shorted reverse characteristics of controlled rectifier 104 act as a short circuit thereby allowing current to flow through it in the reverse direction. As the high energy current pulse passes through primary 58 of transformer 60, a high energy voltage pulse is transferred to the secondary 59, thereby causing a spark to be generated across gap 61.

As previously mentioned, the cut-on time of controlled rectifier 100 is much more rapid than the cut-off time. In order to exploit this relationship advantageously, the circuits are arranged so that the high energy current pulse creating the spark across gap 61 passes through primary 58 of transformer 60 during the cut-on time of controlled rectifier 100. Because of the extremely fast cut-on time of controlled rectifier 100, this allows the high energy current pulse to have an extremely fast transient time. This, of course, means that the current pulse delivers a large amount of power to the secondary of transformer 60 since the power is directly proportional to the rate of change of energy

with respect to time.

Again, capacitors 56 and 57 charge to approximately E_b as before and the cycle starts over. It is a distinct feature of this circuit that because of the well adjusted load line characteristics of both controlled rectifiers 100 and 104 and the transfer of the energy to the primary of transformer 60 during the cut-on time of controlled rectifier 100, high repetition rates can be attained and at the same time ample energy can be transferred to the gap 61 of transformer 60. The importance of the action of capacitors 56 and 57 in back-biasing controlled rectifier 100 to aid in cutting it off, and the transferring of the high energy current pulse by capacitor 56 through the primary 58 of transformer 60 should be noted.

In certain instances it would be desirable to have more voltage across capacitors 56 and 57 than represented by E_b during the time that these capacitors are back-biasing controlled rectifier 100. Figure 9 represents an arrangement which accomplishes this. It depicts a circuit very similar to that of Figure 8 except for a series combination of diode 108 and inductance 109 which have been added between resistor 51 and P-emitter 106 of controlled rectifier 104.

The operation of the circuit in Figure 9 is the same as that of Figure 8 with the exception that the serial combination of diode 108 and inductance 109 increase the voltage on capacitors 56 and 57 during their initial charging time. Assume that the circuit is switching from the operation of one controlled rectifier to the other due to the opening and closing of switch 70. If switch 70 is closed, controlled rectifier 104 will be off, controlled rectifier 100 will be conducting, and capacitors 56 and 57 will be charged to a voltage of approximately E_b . If switch 70 is opened, controlled rectifier 104 will conduct due to gate current from gate 105 to ground 72. A larger current then flows through the serial combination of resistor 51, diode 108 and inductance 109 due to the conduction of controlled rectifier 104, thereby storing energy in inductance 109. None of this current flows through capacitors 56 and 57 due to the voltage across them in the amount of E_b . Because of the conduction of controlled rectifier 104, controlled rectifier 100 is back biased by capacitors 56 and 57 as before. Inductance 55 charges capacitor 56 to a large voltage as before. The voltage across capacitor 56 remains there until switch 70 is closed, and then discharges through the primary 58 of transformer 60, producing the spark at gap 61. During the operation of closing switch 70, thereby cutting off controlled rectifier 104, inductance 109 tends to sustain the current flow. Due to this stored energy and the battery voltage of E_b capacitors 56 and 57 are charged to a

voltage of approximately $2E_b$ or greater. These greater voltages allow capacitors 56 and 57 to more forcefully backbias controlled rectifier 100 at the appropriate time. Since capacitors 56 and 57 are charged to a voltage greater than E_b , the excess charge would leak-off were it not for the presence of diode 108.

It is possible to operate circuits similar to those of Figures 8 and 9 without the special shorted reverse current characteristic described for controlled rectifier 104. For instance, Figure 10 depicts a switching circuit with controlled rectifier 120 having reverse current characteristics essentially the same as those of controlled rectifier 100 as described in conjunction with Figure 3. However, the forward current characteristics of controlled rectifier 120 are essentially the same as those of controlled rectifier 104 shown in Figures 8 and 9 and described for in Figure 4. In such case, controlled rectifier 120 is bypassed by the diode 124 such that current will flow in the reverse direction as capacitor 56 discharges through transformer 60 to create the spark at gap 61. Diode 124 only conducts in one direction and does not effect the operation of the circuit in any other manner.

Although the invention has been illustrated by particular embodiments thereof, it is not limited to the specific circuits herein disclosed. Various applications, modifications, and arrangements of the invention will readily occur to those skilled in the art. For example, in certain embodiments, a mechanical switch may be advantageously employed for alternately closing and opening the electrical path through the spark coil or transformer. In addition, in other embodiments, transistors could be variously employed to effect the desired switching operations. In still other embodiments, different transducing elements could be employed as, for example, gas-discharge lamps for producing high energy flashes of light.

The terms and expressions hereinbefore employed in reference to the invention are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding equivalence of the features shown and described or parts thereof, but on the contrary it is intended to include herein any

and all equivalence, modifications and adaptations which may be employed without departing from the scope of the claimed invention.

WHAT WE CLAIM IS:—

1. A pulse generating circuit comprising an inductor, a transformer and a semiconductor switching device connected in series across a direct current power supply, a capacitor connected with said inductor and said transformer, circuit means including said semiconductor switching device effective at one time for establishing current flow within said inductor thereby to store energy therein, circuit means including said semiconductor switching device effective at another time for discharging the energy stored in said inductor into said capacitor thereby to charge said capacitor to a voltage higher than the voltage of said direct current power supply, and circuit means including said semiconductor switching device effective at still another time for abruptly discharging said capacitor through said transformer thereby to induce an abrupt pulse of high voltage therein.

2. A circuit according to claim 1 wherein the said capacitor is connected in parallel with the transformer and the switching device.

3. A circuit as claimed in either claim 1 or claim 2 in which the switching device is a controlled semiconducting rectifier.

4. A circuit as claimed in either claim 2 or claims 2 and 3 in which the said capacitor is connected in series with a rectifier and in which the capacitor and the rectifier are connected in parallel with the transformer and the switching device.

5. A circuit as claimed in any one of the preceding claims in which the series connected inductor and switching device are connected in series with a diode.

6. A circuit substantially as described with reference to and as shown by any one of Figures 5 to 10 of the accompanying drawings.

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voltage of approximately $2E_b$ or greater. These greater voltages allow capacitors 56 and 57 to more forcefully backbias controlled rectifier 100 at the appropriate time. Since capacitors 56 and 57 are charged to a voltage greater than E_b , the excess charge would leak-off were it not for the presence of diode 108.

It is possible to operate circuits similar to those of Figures 8 and 9 without the special shorted reverse current characteristic described for controlled rectifier 104. For instance, Figure 10 depicts a switching circuit with controlled rectifier 120 having reverse current characteristics essentially the same as those of controlled rectifier 100 as described in conjunction with Figure 3. However, the forward current characteristics of controlled rectifier 120 are essentially the same as those of controlled rectifier 104 shown in Figures 8 and 9 and described for in Figure 4. In such case, controlled rectifier 120 is bypassed by the diode 124 such that current will flow in the reverse direction as capacitor 56 discharges through transformer 60 to create the spark at gap 61. Diode 124 only conducts in one direction and does not effect the operation of the circuit in any other manner.

Although the invention has been illustrated by particular embodiments thereof, it is not limited to the specific circuits herein disclosed. Various applications, modifications, and arrangements of the invention will readily occur to those skilled in the art. For example, in certain embodiments, a mechanical switch may be advantageously employed for alternately closing and opening the electrical path through the spark coil or transformer. In addition, in other embodiments, transistors could be variously employed to effect the desired switching operations. In still other embodiments, different transducing elements could be employed as, for example, gas-discharge lamps for producing high energy flashes of light.

The terms and expressions hereinbefore employed in reference to the invention are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding equivalence of the features shown and described or parts thereof, but on the contrary it is intended to include herein any

and all equivalence, modifications and adaptations which may be employed without departing from the scope of the claimed invention.

WHAT WE CLAIM IS:—

1. A pulse generating circuit comprising an inductor, a transformer and a semiconductor switching device connected in series across a direct current power supply, a capacitor connected with said inductor and said transformer, circuit means including said semiconductor switching device effective at one time for establishing current flow within said inductor thereby to store energy therein, circuit means including said semiconductor switching device effective at another time for discharging the energy stored in said inductor into said capacitor thereby to charge said capacitor to a voltage higher than the voltage of said direct current power supply, and circuit means including said semiconductor switching device effective at still another time for abruptly discharging said capacitor through said transformer thereby to induce an abrupt pulse of high voltage therein.

2. A circuit according to claim 1 wherein the said capacitor is connected in parallel with the transformer and the switching device.

3. A circuit as claimed in either claim 1 or claim 2 in which the switching device is a controlled semiconducting rectifier.

4. A circuit as claimed in either claim 2 or claims 2 and 3 in which the said capacitor is connected in series with a rectifier and in which the capacitor and the rectifier are connected in parallel with the transformer and the switching device.

5. A circuit as claimed in any one of the preceding claims in which the series connected inductor and switching device are connected in series with a diode.

6. A circuit substantially as described with reference to and as shown by any one of Figures 5 to 10 of the accompanying drawings.

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