IGNITION SYSTEM WITH TRANSISTOR CONTROL

Filed Dec. 18, 1959 2 Sheets-Sheet 1

FIG.1

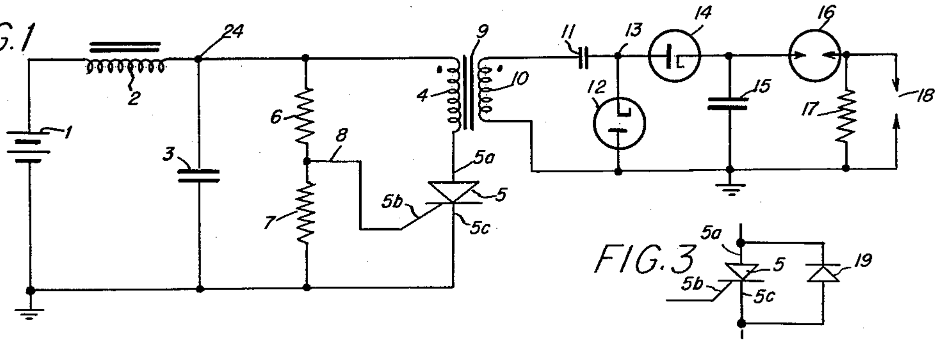


FIG.2

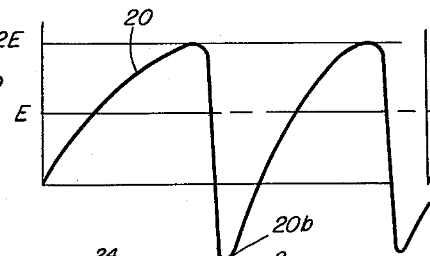


FIG.4

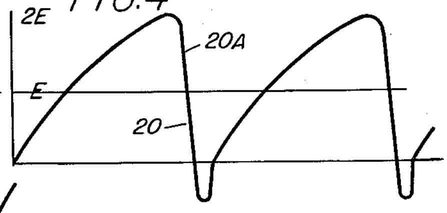


FIG.5

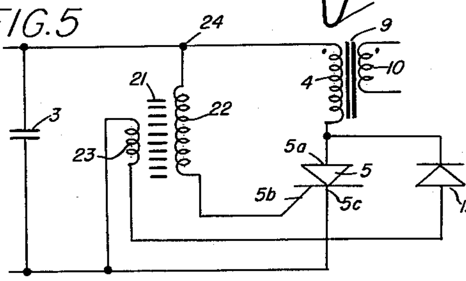
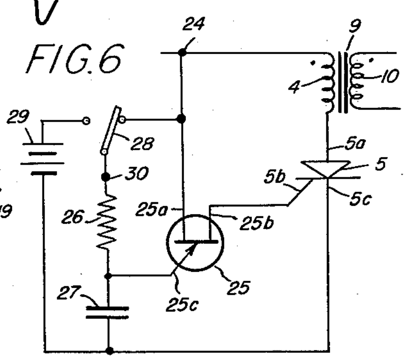


FIG.6



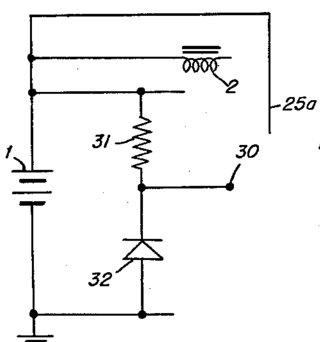


FIG.7

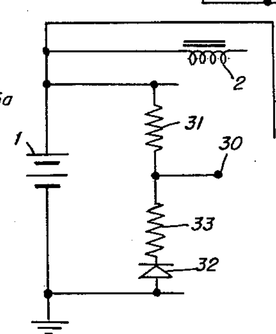


FIG.8

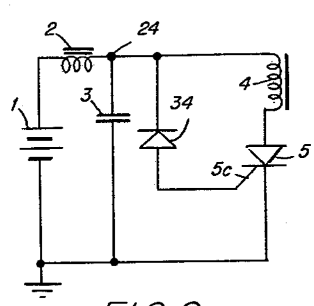


FIG.9

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IGNITION SYSTEM WITH TRANSISTOR CONTROL

Filed Dec. 18, 1959 2 Sheets-Sheet 2

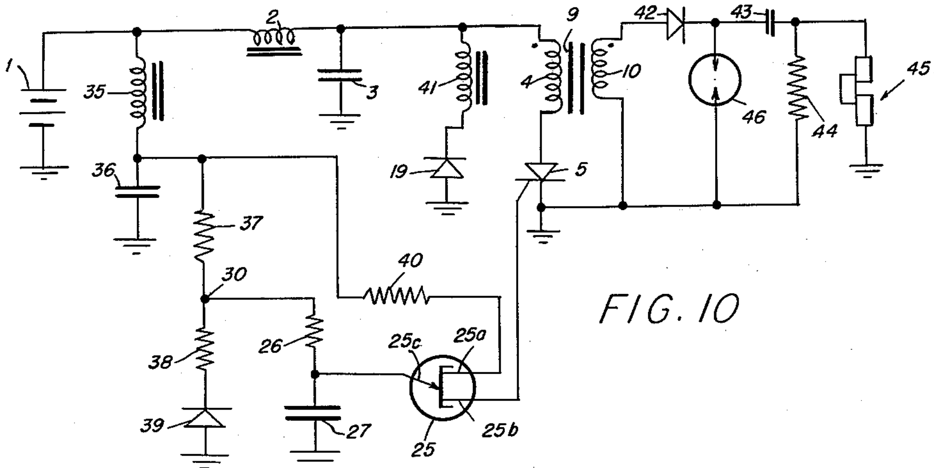

FIG. 10

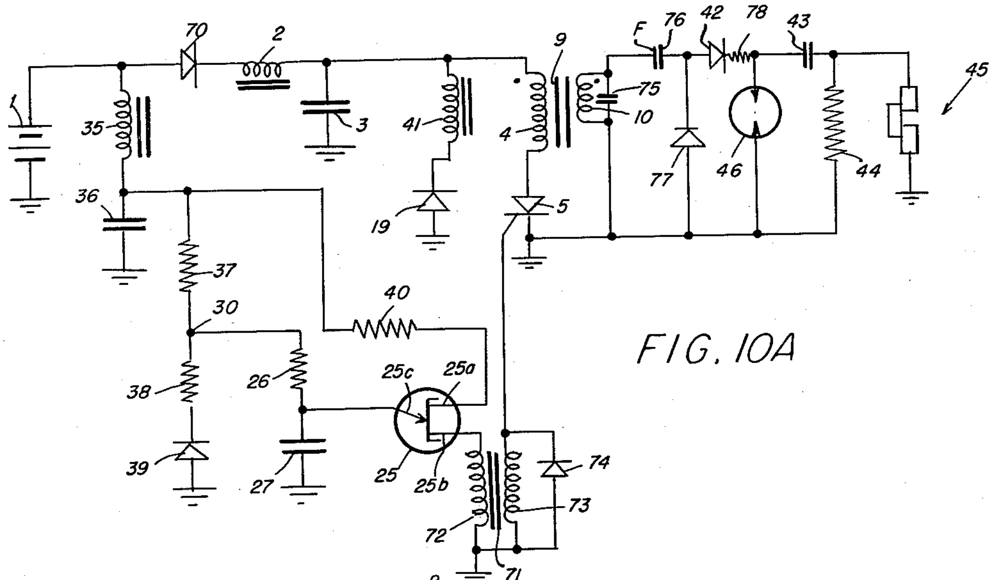

FIG. 10A

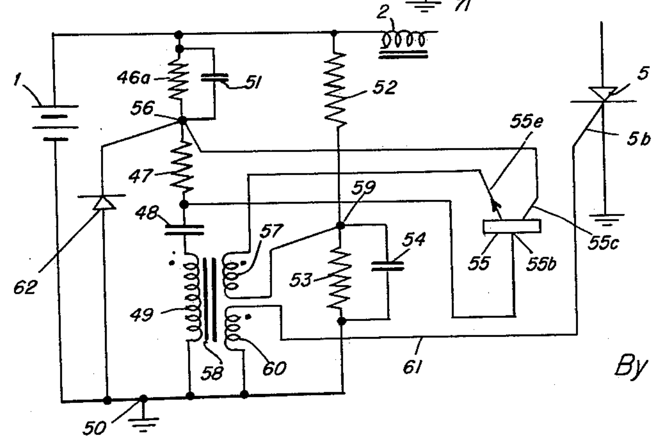

FIG. 11

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IGNITION SYSTEM WITH TRANSISTOR CONTROL

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Filed Dec. 18, 1959, Ser. No. 860,486
19 Claims. (Cl. 315—183)

This invention relates to ignition apparatus of the capacitor discharge type, such as commonly used on jet and rocket engines.

Ignition apparatus for jet and rocket engines and the like is required to produce repeatedly spark discharges characterized by equal quantities of energy, in order that the conditions for proper ignition at the igniter plug may be consistent from one ignition to the next. Most such engines are used on aircraft and are supplied with electrical energy from a battery or other source of limited capacity. The terminal voltage available from such a source varies with the age of the battery and with the magnitude of the load represented by other electrical devices which may be energized from the battery concurrently with the ignition apparatus. Other conditions may also affect the voltage available at the source. For example, in one type of installation, the ignition system is required to maintain a substantially constant energy of the spark discharge while the potential of the source varies over a range from 14 to 30 volts.

It is an object of the present invention to provide ignition apparatus producing sparks of substantially constant energy at an igniter over a considerable range of variation in the potential of the source of electrical energy.

Another object of the invention is to provide an improved ignition apparatus of the capacitor discharge type.

A further object of the invention is to provide an improved arrangement for charging a capacitor to predetermined potential.

The foregoing and other objects of the invention are attained in the apparatus described herein, which includes a voltage doubler consisting of an inductance element and a capacitance element connected in series across a source of electrical energy; means for discharging the capacitor of the voltage doubler in pulses comprising a transformer primary winding and a thyratron semiconductor device connected in series, and means for controlling the triggering potential of the thyratron semiconductor device in response to a control potential varying concurrently with the potential across the capacitance element of the voltage doubler. The secondary winding of the transformer is connected in series with the main ignition capacitor and supplies a pulse charge to that capacitor with each triggering of the thyratron device. The energy stored on the main capacitor is delivered to the igniter whenever the potential across the main capacitor exceeds a predetermined value.

Other objects and advantages of the invention will become apparent from a consideration of the following specification and claims, taken together with the accompanying drawings.

In the drawings:

FIG. 1 is a wiring diagram of one form of ignition apparatus embodying our invention;

FIG. 2 is a graphical illustration of the variation in potential across the voltage doubler capacitor of FIG. 1;

FIG. 3 illustrates a modification of the wiring diagram of FIG. 1;

FIG. 4 is a graphical illustration showing the effect of the modification of FIG. 3 upon the potential variation across the voltage doubler capacitor;

FIGS. 5 to 9 are fragmentary wiring diagrams illustrating further modifications of the circuit of FIG. 1;

FIG. 10 is a complete wiring diagram illustrating a further embodiment of the invention;

FIG. 10A is a wiring diagram illustrating another embodiment of the invention; and

FIG. 11 is a fragmentary wiring diagram illustrating a modification of the circuit of FIG. 10.

FIGURE 1

This figure illustrates an ignition system which is supplied with electrical energy from a battery **1**. A voltage doubler comprising an inductance element **2** and a capacitance element **3** in series is connected across the terminals of the battery **1**. Across the terminals of the capacitor element **3** is connected a capacitor discharging circuit including a transformer primary winding **4** and an anode-cathode path of a thyratron semiconductor device, shown as a controlled rectifier or thyratron transistor **5**. The controlled rectifier **5** has an anode *5a*, a gate electrode or control electrode *5b* and a cathode *5c*. A control potential deriving network including resistors **6** and **7** in series is connected across the terminals of capacitance element **3**. The common junction of the resistors **6** and **7** is connected through a wire **8** to the control electrode *5b*.

The primary winding **4** is part of a transformer **9** having a secondary winding **10**. A voltage doubler capacitor **11** is connected in series with a diode **12** across the terminals of the secondary winding **10**. The diode **12** has its cathode connected to a junction **13**, which is common to the capacitor **11**. Another diode **14** has its anode connected to the junction **13**. A storage capacitor **15** is connected between the cathode of diode **14** and ground. A sealed gap **16** is connected in series with a resistor **17** across the storage capacitor **15**. An igniter gap **18** is connected across the resistor **17**.

OPERATION OF FIG. 1

Considering the condition in the circuit beginning at an instant when the capacitor **3** is completely discharged, current flowing through inductance **2** and capacitor **3** will cause a potential to build up on the capacitor **3** to substantially twice the potential of the source **1**. This phenomenon is well known and is commonly described as a "voltage doubler" action. The potential across capacitor **3** is applied across the terminals of the primary winding **4** and the anode-cathode path of the thyratron device **5** in series.

The thyratron device **5** is shown herein as a semi-conductor device of the type commonly referred to as a controlled rectifier or as a thyratron transistor. Such a device has a characteristic that its forward impedance, i.e., the impedance to current flowing from anode-to-cathode, is very high until one of two conditions occur. One of the two conditions is the occurrence of an anode-to-cathode current greater than a predetermined breakdown value. The other condition is the occurrence of a current greater than breakdown value between the control electrode and the cathode. Upon the occurrence of either of these two breakdown conditions, the forward impedance of the thyratron device **5** drops to a very low value and stays at that low value until the anode-to-cathode current falls to a second value substantially lower than the sustaining value. In the circuit of FIG. 1, device **5** is tripped from its high impedance condition to its low impedance condition when the current between control electrode *5b* and cathode *5c* exceeds a predtermined value. The forward impedance of the device **5** remains at its low value until the anode-to-cathode current is reduced to zero.

Resistors **6** and **7** form a voltage divider to derive from the potential across the capacitor **3** a proportion of that potential which is applied through wire **8** to control electrode *5b* as the control potential. The resistors **6** and **7** are chosen so that the thyratron device **5** is triggered to its low impedance value when the potential across capacitance **3** approaches a value 2E, as shown in FIG. 2, E being the potential of the battery **1**.

When the thyratron devie **5** is triggered, a pulse of current flows from capacitance **3** through the primary winding **4**, a corresponding pulse being thereby induced in secondary winding **10**. The latter pulse charges the capacitor **11**. The polarity of the windings **4** and **10** is indicated by the dots in the drawing. The pulse produced in the winding **10** has its positive polarity at the upper terminal of that winding. This pulse flows through capacitor **11**, diode **14** and capacitor **15** and tends to charge the capacitors **11** and **15**. The pulse does not flow through diode **12**, since diode **12** has its high impedance opposed to the pulse.

On the half-waves when the upper terminal of the secondary winding **10** is negative, current flows from that winding through the diode **12** and charges the capacitor **11** with its right-hand terminal positive. The winding **10** and capacitor **11** together act as a voltage doubler, to develop across the capacitor **11** a transient inverse potential equal to twice the applied potential. On the opposite half-waves, current flow through the diode **12** is blocked but current can flow from winding **10** and capacitor **11**, which now act as potential sources in series aiding, through diode **14** and capacitor **15**, thereby charging capaciotr **15**. When the charge on capacitor **15** exceeds a value determined by the breakdown potential of gap **16**, that gap breaks down. Thereupon, substantially the full potential of capacitor **15** appears across the resistor **17** and gap **18** in parallel. The gap **18** in turn breaks down, whereupon the capacitor **15** discharges through it.

The discharging of the capacitor **5** is repeated each time that the charge on it builds up sufficiently to break down the gap **16**.

The circuit goes through a series of pulse producing cycles as described above. Fig. 2 shows at **20** the variation of potential across capacitor **3** during such cycles. During the capacitor discharging phase of each cycle, the inductance in the circuit tends to maintain the flow of current even after the capacitor is discharged, with the result that the capacitor begins to charge in the reverse direction, resulting in the negative excursion of potential appearing at **20*b*** in FIG. 2. Eventually this reverse potential blocks the current flow through the thyratron device **5**, which thereupon returns to its high impedance condition and the cycle begins again. During each of these cycles, a pulse of current charges the capacitors **11** and **15**. Capacitor **11** cooperates with winding **10** to form a voltage doubler, so that capacitor **15** is charged at a higher potential. As the series of pulse cycles continues, the potential across the capacitor **15** builds up in a seires of steps. The potential across storage capacitor **15** is applied across the sealed gap **16**. There being then no current flow through resistor **17**, susbtantially the full potential across capacitor **15** is applied across the sealed gap **16**. The breakdown potential of the gap **16** is made somewhat higher than the breakdown potential of the igniter gap **18**. When the potential of the charge on capacitor **15** exceeds the breakdown potential of the gap **16**, the charge on capacitor **15** is discharged through the trigger gap **16** and the igniter gap **18**. The gap **18** has a substantially lower impedance than the resistor **17** and takes substantially all the current flowing from the capacitor **15**. The breaking down of the gaps **16** and **18** produces a low impedance path to the charge stored on the capacitor **11**, and that charge now also flows through the gaps **16** and **18**.

It may be seen that the circuit of FIG. 1 provides a series of spark discharges at the igniter **18**. Each of those spark discharges is built up by a series of pulses of substantially equal energy applied to the capacitors **11** and **15**, so that each spark discharge at the igniter gap **18** has substantially the same energy. Although the potential of the source **1** may vary, the characteristics of the thyratron device **5** do not vary. The breakdown control potential on electrode **5*b***, at which the thyratron device **5** shifts from its high impedance to its low impedance condition, is always the same, being determined by the characteristics of the device **5** and not by the charge stored on capacitor **3**. The magnitude of the current pulses which charge the capacitors **11** and **15** is thereby made independent of the potential of the source. The trigger gap **16** consequently always breaks down after the same number of charging pulses and the charge built up on the capacitors **11** and **15** and discharged through the igniter gap **18** alawys has susbtantially the same energy.

FIGURES 3 AND 4

FIG. 3 illustrates a modification of the circuit of FIG. 1. In accordance with this modification a diode **19** has its anode connected to the cathode of the thyratron device **5**, while its cathode is connected to the anode of the thyratron device **5**. The presence of the diode **19** limits the reverse polarity potential across the controlled rectifier **5** to the forward impedance drop across diode **19**. The operation as modified by diode **19** is illustrated by the curve **20A** in FIG. 4. The diode **19** makes the potential from which the capacitor **3** starts to charge more positive. The current for recharging the capacitor **3** from the reverse potential value shown at **20*b*** to a positive value must be supplied by battery **1**. When the diode **19** is added as in FIG. 3, this reverse potential is smaller, so that the recharging current is smaller, and hence the circuit losses are lower. The efficiency of the circuit is thereby improved.

The presence of diode **19** also prevents any tendency to build up a potential on the capacitor **3** gradually over several cycles, because of incomplete discharge of the capacitor on each cycle.

FIGURE 5

This circuit is modified from that of FIG. 1 by the substitution of a saturable core transformer **21** in the control potential deriving network, in place of the resistors **6** and **7** of FIG. 1. Transformer **21** has a primary winding **22** and a secondary winding **23**. Primary winding **22** is connected between the ungrounded terminal **24** of capacitor **3** and the control electrode **5*b***. Secondary winding **23** is connected between the anode of the diode **19** and ground.

OPERATION OF FIG. 5

During charging of the capacitor **3** the secondary winding **23** is substantially open circuited, due to the diode **19**, which has its high impedance in series with winding **23**. The current flowing through winding **22** and control electrode **5*b*** increases as the charge on capacitor **3** increases, finally saturating the core of transformer **21**, whereupon a pulse of current flows through control electrode **5*b***, setting off a discharge of capacitor **3** through the thyratron device **5**. When the thyratron device **5** breaks down to its low impedance value, the capacitor **3** is discharged and the potential across it reverses as the magnetic field of the inductance **2** collapses. This reverse potential sends a high current through the secondary winding **23** and diode **19**, resetting the core of transformer **21** by saturating it in the opposite sense, thereby restoring primary winding **22** to its high impedance condition.

FIGURE 6

In this modification of the invention, the potential of the control electrode **5*b*** is derived by the use of a semiconductor device **25** of the type known as a double-base diode. The double-base diode **25** has two base electrodes **25*a*** and **25*b*** and a control electrode **25*c***. Base electrode **25*a*** is connected to junction **24**. Base electrode **25*b*** is connected to control electrode **5*b***. Control electrode **25*c*** is connected to the common terminal of a time constant network including a resistor **26** and a capacitor **27**. A switch **28** connects the time constant network in series between the junction **24** and ground. The switch **28** is movable from the position shown to a second position in which the time constant network is connected across a battery **29**.

OPERATION OF FIG. 6

The timing between the start of a cycle at zero potential across capacitor **3** and the breaking down of the thyratron device **5** is controlled in FIG. 6 by the time characteristics of the network **26**, **27** rather than by the time characteristics of the capacitor **3** itself. When the switch **28** is in its right hand position, as shown, the time characteristics of the network **26**, **27** are superimposed on the time characteristics of the voltage doubler, i.e., the potential applied to the network **26**, **27** is supplied from the capacitor **3**. When the switch **28** is thrown to its left-hand position, the triggering time of the thyratron device **5** is determined only by the time characteristics of the network **26**, **27** and the potential of the battery **29**. If this battery is provided to supply this network only, then its characteristics may be much more closely controlled and remain much more stable than the characteristics of the main battery **1** which supplies energy for the trigger gap and perhaps for other load devices.

The characteristics of the double base diode **25** are such that its impedance is high until such time as a predetermined potential is applied to control electrode **25***c*, at which time the impedance between the control electrode **25***c* and base **25***b* drops to a very low value. Capacitor **27** then discharges through this low impedance, producing an output pulse.

FIGURE 7

This figure illustrates a modification of the circuit of FIG. 6 and shows a different arrangement for supplying potential to the terminals of the time constant network **26**, **27**. In FIG. 7, the battery **1** is used to supply current through a resistor **31** and a reverse biased diode **32**. The diode **32** is of the Zener voltage type and has a high impedance in its reverse direction until a predetermined potential is exceeded. The impedance then becomes very low and effectively fixes the potential at that predetermined value. The potential across the diode **32** and hence across the time constant network is thereby fixed at a very definite value.

The ideal operation in circuits of the type disclosed herein is to maintain the power delivered to capacitor **15** substantially constant, regardless of changes in the potential of the battery **1**. An increase in the potential of battery **1** tends to increase the energy output per pulse of the capacitor **3**. A compensating effect may be provided by arranging the triggering system which times the pulses from the capacitor **3** so that an increase in the battery potential tends to decrease the pulse rate. If the decrease in the pulse rate exactly balances the increase in the energy per pulse, then a substantially constant power output may be produced, even though the battery potential changes.

In the circuit of FIG. 7, the battery potential is applied across the base electrodes **25***a* and **25***b* of the double base diode **25**. An increase in this potential requires a higher potential on the control electrode **25***c* to trip the double base diode to its low impedance value. The potential of control electrode **25***c* is determined by the time constant network **26**, **27**, which is now supplied by the constant potential across diode **32**. Capacitor **27** therefore charges at the same rate, regardless of changes in the potential of battery **1**. However, since an increase in the battery potential requires a higher potential at electrode **25***c* to trip the double base diode, a longer charging time for capacitor **27** is required before the diode **25** trips.

The pulse rate is thereby reduced to compensate for the increased energy per pulse due to the increased battery potential.

FIGURE 8

This figure shows a modification of the circuit of FIG. 7, in which a resistor **33** is added between the Zener diode **32** and the terminals of the time constant network. This circuit, by virtue of the potential drop due to current flowing in resistor **33**, varies the potential applied to the time constant network as a function of the battery potential. In other words, an increase in the battery potential increases the potential applied to the time constant network and consequently makes the capacitor **27** charge to its tripping value in a shorter time.

It has been found that the circuit of FIG. 7 tends to overcompensate for an increase in battery potential. In other words, as the battery potential increases, it slows down the pulse rate so much that the power output is actually decreased. In order to correct that unbalance, the resistor **33** has been added in the circuit of FIG. 8. Because of the resistor **33**, the potential across the time constant network **26**, **27** is not fixed, but increases with an increase in the potential of battery **1**, due to the potential drop across resistor **33**. By properly balancing the potential drop across resistor **33** with respect to the potential across battery **1**, the circuit of FIG. 8 may be made to compensate for the changes in the battery potential, so as to maintain a close control of the power output, at least over limited ranges of variation in the potential of battery **1**.

As a further alternative, the voltage dividers of FIGS. 7 and 8 may be connected across capacitor **3** instead of across battery **1**.

FIGURE 9

This circuit illustrates a modification of the circuit of FIG. 1, in which the voltage divider network **6**, **7** is replaced by a Zener voltage diode **34**, connected between the control electrode **5***c* and junction **24**. The operation is the same as the circuit of FIG. 1, except that the application of the breakdown control current to electrode **25***c* is determined by the characteristics of the Zener diode **34**.

FIGURE 10

This circuit is considerably modified from the previous circuits, particularly in the potential supply for the time constant network which controls the discharge times, the connections of the diode **19**, and in the circuitry connected to the secondary winding **10**.

The potential supply for the time constant network **26**, **27** is obtained through a filter including an inductance element **35** and a capacitance element **36** connected in parallel with the voltage doubler **2**, **3** but otherwise independent of it. The potential appearing across capacitor **36** is applied to a voltage divider network including resistor **37** and resistor **38** and a Zener voltage diode **39** similar to the network shown in FIG. 8 above. The voltage divider network **37**, **38**, **39** is utilized to control the variation of output power with changes in the battery voltage. The variation may be controlled over a wide range, using the principles discussed above in connection with FIG. 8. The potential across the resistor **38** and diode **39** in series is applied across the time constant network **26**, **27**. The junction between inductance **35** and capacitor **36** is also connected through a resistor **40** to the base **25***a* of the double base diode **25**. By virtue of these arrangements, the time intervals at which the thyratron device **5** is triggered are determined by the time constant network and are not affected by transient conditions existing in the main spark energy supply circuit. The elements used in the control voltage deriving network, may, therefore, be more precisely selected and controlled as to their impedance values, since they do not have to carry the heavier currents required in the main energy supply circuit.

Diode **19**, instead of being connected directly in parallel with the anode cathode path of the thyratron device **5**, is connected in series with a high Q, low loss inductance 41. The branch circuit including diode 19 and inductance 41 is connected in parallel with the branch circuit including the anode-cathode path of thyratron device 5 and the primary winding 4. By virtue of this arrangement, a very low impedance path is provided to discharge the reverse potential on capacitor 3, so that the losses in the circuit are decreased. The utilization of the energy from the capacitor 3 is thereby made considerably more efficient.

The circuit through the secondary winding 10 includes a diode 42, a capacitor 43 and a resistor 44 in series. Diode 42 acts as a half-wave rectifier, to determine the polarity of the charge on capacitor 43. An igniter gap 45 of the semiconductor type is connected across the resistor 44. A trigger gap 46 is connected between ground and the common junction of diode 42 and capacitor 43.

The energy to be discharged at the gap 45 is stored on the capacitor 43. When the potential on capacitor 43 exceeds the breakdown potential of the sealed gap 46, the energy on the capacitor 43 is discharged through a circuit consisting only of that capacitor and the gaps 45 and 46.

FIGURE 10A

The circuit shown in this figure is based on that in FIG. 10, but has been improved by the addition of several elements. This is the presently preferred embodiment of the invention.

The elements added in this figure include a diode 70, a transformer 71 having a primary winding 72 and a secondary winding 73, a diode 74, a capacitor 75, a capacitor 76, a diode 77, and a resistor 78.

Diode 70 is effective to hold the charge on capacitor 3 if it reaches full charge before the triggering pulse is applied to the thyratron device 5.

Transformer 71 is a step-up transformer, and is effective at lower voltages to improve the tripping or starting characteristics. That is to say, it permits the circuit to trigger the transistor at a lower voltage of battery 1.

Diode 74 prevents reverse potential due to overshoot in transformer 71 from reaching the control electrode 5*b* of thyratron device 5.

Capacitor 75 provides a minimum capacitive load for thyratron device 5, and thereby prevents certain undesirable conditions which might otherwise occur in the case of an open circuit or high resistance load on the secondary winding 10. Such an open circuit condition would increase the impedance of primary winding 4 to the capacitor discharge current to a very high value, which would tend to delay the capacitor discharge and spread out the charging pulse. The capacitor 65 establishes a maximum impedance limit on the primary winding 4, and ensures that capacitor 3 will discharge on each pulse.

Capacitor 76 and diode 77 cooperate with secondary winding 10 to form a voltage doubler, functioning in a manner generally similar to the capacitor 11 and diode 12 of FIG. 1.

Resistor 78 is provided to protect diodes 77 and 42 from overcurrents in the forward direction which might occur during oscillatory discharges through the gap 45.

FIGURE 11

The circuit illustrated in FIG. 11 shows a different form of mechanism for controlling the potential supplied to the control electrode 5*b* of the controlled rectifier 5. This circuit is in other respects similar to that shown and described in FIG. 10. Those elements which correspond, both as to structure and function, to their counterparts in FIG. 10, have been given the same reference numerals.

The circuitry for supplying a potential to control electrode 5*b* includes a first voltage divider connected across the terminals of the battery 1 and traceable through a resistor 46*a*, a resistor 47, a capacitor 48, and a transformer winding 49 to ground at 50. A capacitor 51 is connected in parallel with resistor 46*a*. A second voltage divider is also connected across the battery 1 and includes resistors 52 and 53 in series. A capacitor 54 is connected across the resistor 53.

A transistor 55 has an emitter electrode 55*e*, a base electrode 55*b*, and a collector electrode 55*c*. In the present circuit, the base serves as the input electrode, the emitter as the output electrode, and the collector as the common electrode. Collector 55*c* is connected to the junction 56 between resistors 46 and 47. Base electrode 55*b* is connected to the opposite terminal of resistor 47. Emitter electrode 55*e* is connected through a secondary winding 57 of a transformer 58 to the common junction 59 of resistors 52 and 53. Transformer 58 has an output winding 60 having one terminal connected to ground and the other connected through a wire 61 to the control electrode 5*b*. A Zener diode 62 is connected between junction 56 and ground.

FIGURE 11—OPERATION

It is desired to keep the power output to the igniter 45 at a substantially constant value, regardless of changes in the potential of battery 1. An increase in the potential of battery 1 tends to increase the energy output per pulse of the capacitor 3. In order to maintain the total power to the igniter 45 substantially constant, the triggering system which times the pulses from the capacitor 3 is made to respond to an increase in the battery potential in such a manner as to decrease the pulse rate. The increase in energy per pulse is compensated by the decrease in pulse rate, resulting in a substantially constant power output.

The circuit, including transistor 55, transformer 58, and related elements may be described as a blocking oscillator. It operates to apply periodically to the control electrode 5*b* potentials which are effective to trigger the controlled rectifier 5 to its low impedance value, thereby producing an output pulse through the transformer 9.

The transistor 55 is shown as an NPN type, so that it is held off by an emitter potential more positive than the base potential, and is turned on by an emitter potential more negative than the base potential.

The Zener diode 62 fixes the potential at junction 56 and collector 55*c* with respect to ground. The impedances of resistors 52 and 53 are selected so that when the transistor is not conducting the junction 59 is negative with respect to junction 56.

When power is first applied to the circuit, emitter 55*e* is substantially at the potential of junction 59, since there is then no current flow through or potential induced in the winding 57. Base 55*b* is connected through the uncharged capacitor 48 to ground, there being substantially no potential across winding 49. Base 55*b* is therefore more negative than emitter 55*e*, and the transistor is off. The capacitor 48 immediately starts to charge through resistors 46 and 47, and its terminal nearest the resistor 47 swings in a positive sense, eventually becoming more positive than the potential of emitter 55*e*, whereupon the transistor starts to conduct.

As the current flow through emitter 55*e* increases, it passes through primary winding 57, inducing a potential in secondary winding 49 of a polarity tending to charge capacitor 48 reversely, i.e., with its lower terminal positive. This charging current flows through base 55*b* and tends to drive the transistor to conduct more strongly. Finally, the charge on capacitor 48 reaches a condition of balance with the potential across secondary winding 49, and the charging current stops. The potential stored on capacitor 48 is then effective to swing base 55*b* in a negative sense, thereby cutting off the transistor 55. Current then stops flowing through winding 57. The charge on capacitor 48 then holds the transistor off until that charge is dissipated by current supplied through resistors 46 and 47. The cycle then repeats. The pulse of current in winding 57 induces a potential in winding 60, where it is effective to control the thyratron device 5.

If the potential of battery 1 increases, the potential of junction 59 swings more positive, while the potential of junction 56 remains fixed at a value more positive than junction 59. The emitter potential, when the transistor is off, is substantially the same as that of junction 56. Hence, in order to turn the transistor on, the capcitor 48 must charge to a more positive potential to make the base 55*b* more positive than emitter 55*e*. This charging of capacitor 48 to a higher potential takes a longer time, with a consequent decrease in the rate of supply of tripping pulses to the thyratron device 5. The increase in pulse energy is compensated by the decrease in the pulse rate, so that the power output remains substantially constant.

While I have described the operation of the invention, with respect to its constant power output characteristics, in terms of an increase in battery potential, it should be apparent that a decrease in battery potential produces an analogous but reverse operation, with a compensating increase in the pulse frequency, and a similar ultimate result, i.e., constant power output spark energy at the igniter.

Resistor 46*a* is provided to limit the current flow through the diode 62.

Capacitor 51 provides a low impedance path to alternating current, so that resistor 46*a* does not limit the operation of the blocking oscillator. Capacitor 54 provides a similar alternating current by-pass around resistor 53, so that during pulsing of the blocking oscillator, resistors 46 and 53 are by-passed, and the full battery potential is effective between the emitter and collector of the transistor.

The following table shows a suggested set of values which will work in the circuit of FIG. 11. Obviously, the invention is not limited to any of these values.

Table

Resistor 46*a*	ohms	500
Resistor 47	do	4000
Capacitor 48	mfd	0.1
Resistor 52	ohms	10,000
Resistor 53	do	1,000

It should be understood that the circuits shown and described maintain the power output to capacitor 15 substantially constant only over a limited range of variation of the potential of battery 1. Given a particular range of source potential, however, it is easy to design a circuit following the invention which will hold the power output constant.

While we have shown and described certain preferred embodiments of our invention, other modifications thereof will readily occur to those skilled in the art, and we therefore intend our invention to be limited only by the appended claims.

We claim:

1. Capacitor charging apparatus comprising a source of unidirectional electrical energy, an inductance element and a capacitance element connected in series across the source, a transformer having a primary winding and a secondary winding, a thyratron semiconductor device having an anode, a cathode, and a gate electrode, means connecting the primary winding and the anode-cathode path of the thyratron semiconductor device in series across the capacitance element, a capacitor to be charged, an asymmetrically conductive device, means connecting the capacitor and the asymmetrically condutcive device in series across the secondary winding, means for deriving a control potential varying concurrently with the potential across the capacitance element, and means connecting the control potential deriving means to the gate electrode to trigger a pulse discharge through the thyratron semiconductor device whenever the capacitance element is charged to a predetermined potential, whereby the capacitor is charged by repeated pulses of substantially equal energy; an electric circuit branch connected in parallel with the electric path through the anode and cathode of the thyratron semiconductor device, and a diode connected in said branch and having its anode and cathode respectively connected to the cathode and anode of the thyratron semiconductor device, said circuit branch being effective after each discharge of the capacitance element through the thyratron semiconductor device to pass an oscillatory current of the opposite polarity.

2. Capacitor charging apparatus as defined in claim 1, including means directly and conductively connecting the anode and cathode of the diode respectively to the cathode and anode of the thyratron semiconductor device.

3. Capacitor charging apparatus as defined in claim 1, in which said circuit branch includes an inductor in series with the diode, and means connecting the terminals of the branch to the respective terminals of the capacitance element.

4. Capacitor charging apparatus as defined in claim 1, in which said control potential deriving means comprises a saturable core transformer having a primary winding and a secondary winding; said means connecting the control potential to the gate electrode connects the primary winding of the saturable core transformer between the gate electrode and the terminal of the first-mentioned transformer primary winding farthest from the thyratron semiconductor device, and said branch circuit includes the secondary winding of the saturable core transformer in series with the diode.

5. Capacitor charging apparatus comprising a source of unidirectional electrical energy, an inductance element and a capacitance element connected in series across the source, a transformer having a primary winding and a secondary winding, a thyratron semiconductor device having an anode, a cathode, and a gate electrode, means connecting the primary winding and the anode-cathode path of the thyratron semiconductor device in series across the capacitance element, a capacitor to be charged, an asymmetrically conductive device, means connecting the capacitor and the asymmetrically conductive device in series across the secondary winding, means for deriving a control potential varying concurrently with the potential across the capacitance element, and means connecting the control potential deriving means to the gate electrode to trigger a pulse discharge through the thyratron semiconductor device whenever the capacitance element is charged to a predetermined potential, whereby the capacitor is charged by repeated pulses of substantially equal energy; said control potential deriving means comprises a double base diode having two base electrodes and a control electrode, means connecting one base electrode to the terminal of the transformer winding farthest from the thyratron semiconductor device, a time constant network comprising a resistor and a capacitor in series, and means connecting the common terminal of the resistor and capacitor to the control electrode; and said means connecting the control potential deriving means to the gate electrode comprises a connection between the other base electrode and the gate electrode.

6. Capacitor charging apparatus as defined in claim 5, in which said control potential deriving means includes a separate source of electrical energy, and means connecting said time constant network across the separate source.

7. Capacitor charging apparatus as defined in claim 5, in which said control potential deriving means includes means connecting the time constant network across the capacitance element.

8. Capacitor charging apparatus as defined in claim 5, in which said network includes a second resistor and a diode in series, and means connecting the first-mentioned resistor and the capacitor in series across the diode.

9. Capacitor charging apparatus as defined in claim 5, in which said network includes a second resistor, a third resistor and a diode connected in series, and means con-

necting the first-mentioned resistor and the capacitor across the third resistor and the diode.

10. Capacitor charging apparatus as defined in claim 9, in which said network includes filter comprising a second inductance element and a second capacitance element connected in series across the source, and the second and third resistors and the diode are connected in series across the second capacitance element.

11. Capacitor charging apparatus comprising a source of unidirectional electrical energy, an inductance element and a capacitance element connected in series with the source, a transformer having a primary winding and a secondary winding, a thyratron semiconductor device having an anode, a cathode, and a gate electrode, means connecting the primary winding and the anode-cathode path of the thyratron semiconductor device in series across the capacitance element, a capacitor to be charged, an asymmetrically conductive device, means connecting the capacitor and the asymmetrically conductive device in series across the secondary winding, means connected across the source in parallel with the series-connected inductance and capacitance elements for deriving a control potential varying concurrently with the potential across the capacitance element, and means connecting the control potential deriving means to the gate electrode to trigger a pulse discharge through the thyratron semiconductor device whenever the capacitance element is charged to a predetermined potential.

12. Capacitor charging apparatus as defined in claim 11, wherein said control potential deriving means comprises a second inductance element and a second capacitance element connected in series across the source, and a time constant network connected between the common terminal of said second inductance and second capacitance elements and one terminal of said source.

13. Capacitor charging apparatus as defined in claim 11, in which said control potential deriving means includes a blocking oscillator.

14. Capacitor charging apparatus as defined in claim 13, in which said control potential deriving means comprises two voltage dividers connected across said source, and said blocking oscillator comprises a transistor having input, output and common electrodes, a transformer having a primary winding, an output secondary winding and a feedback secondary winding, means including said primary winding connecting said transistor output electrode to a point on one of said voltage dividers, means including said feedback winding connecting the input electrode of the transistor to one terminal of said source, means connecting the common electrode of the transistor to the other voltage divider, and means connecting the output secondary winding to the gate electrode of the thyratron semiconductor device.

15. Capacitor charging apparatus comprising a source of unidirectional electrical energy, an inductance element and a capacitance element connected in series across the source, a transformer having a primary winding and a secondary winding, a thyratron semiconductor device having an anode, a cathode, and a gate electrode, means connecting the primary winding and the anode-cathode path of the thyratron semiconductor device in series across the capacitance element, a capacitor to be charged, an asymmetrically conductive device, means connecting the capacitor and the asymmetrically conductive device in series across the secondary winding, means for deriving a control potential varying concurrently with the potential across the capacitance element, and means connecting the control potential deriving means to the gate electrode to trigger a pulse discharge through the thyratron semiconductor device whenever the capacitance element is charged to a predetermined potential, whereby the capacitor is charged by repeated pulses of substantially equal energy; said control potential deriving means comprising a double base diode having two base electrodes and a control electrode, means connecting one base electrode to the terminal of the transformer winding farthest from the thyratron semiconductor device, a time constant network comprising a resistor and a capacitor in series, and means connecting the common terminal of the resistor and capacitor to the control electrode; and said means connecting the control potential deriving means to the gate electrode comprises a step-up transformer having a primary winding connected between the other base electrode and a common terminal and a secondary winding connected between the common terminal and the gate electrode.

16. Capacitor charging apparatus as defined in claim 15, including a diode connected in parallel with the secondary winding and poled to block passage of current to the gate electrode due to overshoot of the transformer.

17. Capacitor charging apparatus comprising a source of unidirectional electrical energy, an inductance element and a capacitance element connected in series across the source, a transformer having a primary winding and a secondary winding, a thyratron semiconductor device having an anode, a cathode, and a gate electrode, means connecting the primary winding and the anode-cathode path of the thyratron semiconductor device in series across the capacitance element, a capacitor to be charged, an asymmetrically conductive device, means connecting the capacitor and the asymmetrically conductive device in series across the secondary winding, means for deriving a control potential varying concurrently with the potential across the capacitance element, and means connecting the control potential deriving means to the gate electrode to trigger a pulse discharge through the thyratron semiconductor device whenever the capacitance element is charged to a predetermined potential, whereby the capacitor is charged by repeated pulses of substantially equal energy; a second capacitor connected in parallel with the secondary winding and effective to provide a substantial capacitive load on the thyratron semiconductor device under high impedance conditions in said series connecting means.

18. Capacitor charging apparatus as defined in claim 11, in which said control potential deriving means includes control pulse producing means, and means responsive to the source potential for varying the rate of production of control pulses to reduce said rate as the source potential increases and increase said rate as the source potential decreases.

19. Capacitor charging apparatus, comprising a source of unidirectional electrical energy, an inductance element and a capacitance element connected in series across the source, a transformer having a primary winding and a secondary winding, a thyratron semiconductor device having an anode, a cathode, and a gate electrode, means connecting the primary winding and the anode-cathode path of the thyratron semiconductor device in series across the capacitance element, a capacitor to be charged, an asymmetrically conductive device, means connecting the capacitor and the asymmetrically conductive device in series across the secondary winding, a diode connected between the gate electrode and the terminal of the transformer primary winding farthest from the thyratron semiconductor device, said diode being poled to present its high impedance to the potential across the capacitance element, said diode being effective when the last-mentioned potential exceeds the breakdown potential of the diode to transmit a trigger pulse to the gate electrode and thereby to trigger a pulse discharge through the thyratron semiconductor device whenever the capacitance element is charged to the diode breakdown potential, whereby the capacitor is charged by repeated pulses of substantially equal energy.

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