United States Patent [19]

Asik et al.

[11] **3,906,919**

[45] **Sept. 23, 1975**

[54] CAPACITOR DISCHARGE IGNITION SYSTEM WITH CONTROLLED SPARK DURATION

[75] Inventors: **Joseph R. Asik**, Bloomfield Hills; **Mitsugu Hanabusa**, Ann Arbor, both of Mich.

[73] Assignee: **Ford Motor Company**, Dearborn, Mich.

[22] Filed: **Apr. 24, 1974**

[21] Appl. No.: **463,692**

[52] **U.S. Cl.**........................ **123/148 E**; 315/209 CD

[51] **Int. Cl.**... **F02p 3/06**

[58] **Field of Search**.............. 123/148 E, 148 OCD; 315/209 CD

[56] **References Cited**

UNITED STATES PATENTS

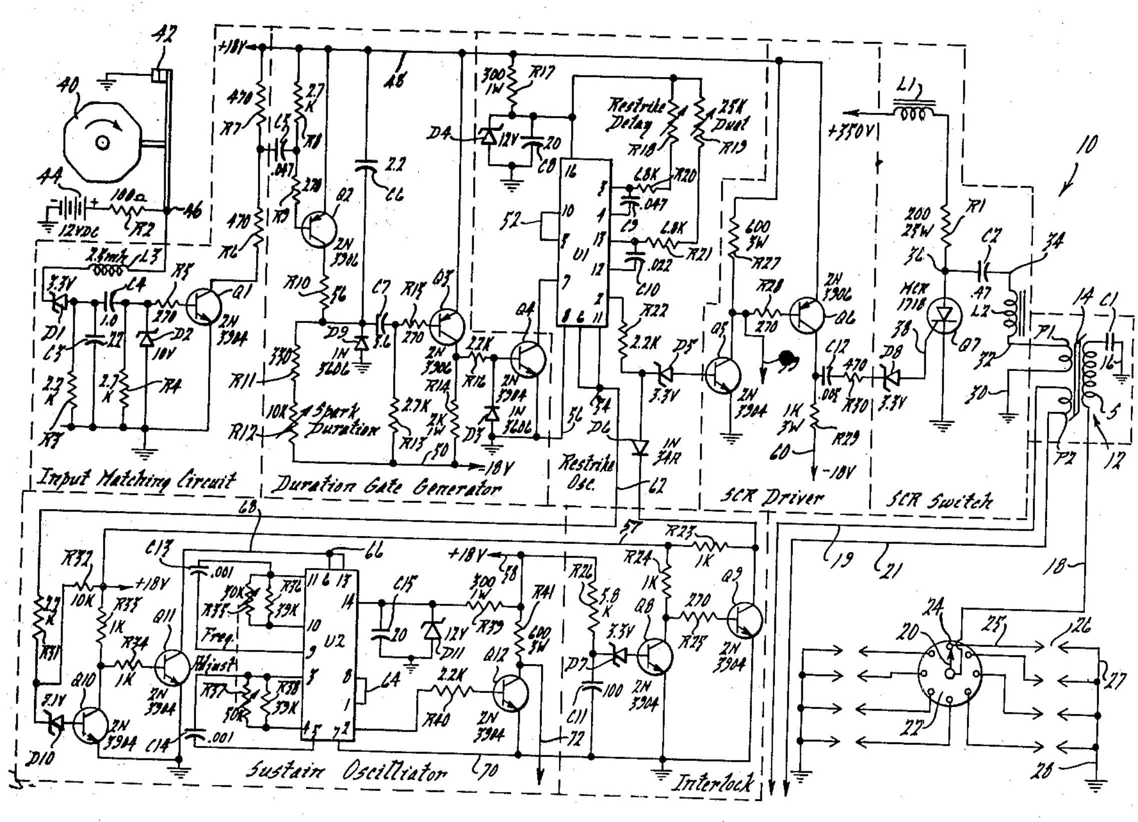
3,549,944	12/1970	Minks	123/148 E
3,593,696	7/1971	Guido	123/148 E
3,636,936	1/1972	Schuette et al.	123/148 E

Primary Examiner—Charles J. Myhre
Assistant Examiner—Joseph Cangelosi
Attorney, Agent, or Firm—Robert W. Brown; Keith L. Zerschling

[57] **ABSTRACT**

A capacitor discharge ignition system for a spark-ignition internal combustion engine. The ignition system includes an ignition coil having first and second primary windings, a secondary winding and a ferromagnetic core about which the windings are wound. A spark plug has electrodes which are spaced apart to form a spark gap which is connected in series with a first capacitor. The series-connected spark gap and first capacitor are connected across the secondary winding. A second capacitor is coupled to the first winding and a DC source of electrical energy is provided. First circuit means charge the second capacitor from the DC source and discharge this capacitor through the first primary winding in timed relation to operation of the engine. Second circuit means are provided for producing a fixed frequency oscillatory current in the second primary winding for a predetermined time interval subsequent to each discharge of the second capacitor through the first primary winding. The discharge of the second capacitor through the first primary winding and the subsequent supply of fixed frequency oscillatory current to the second primary winding causes ferroresonant oscillations in the secondary circuit of the ignition coil for at least a portion of the aforementioned predetermined time interval. The spark which occurs between the spark plug electrodes exists during the predetermined time interval and has a duration which may be varied as desired.

9 Claims, 17 Drawing Figures



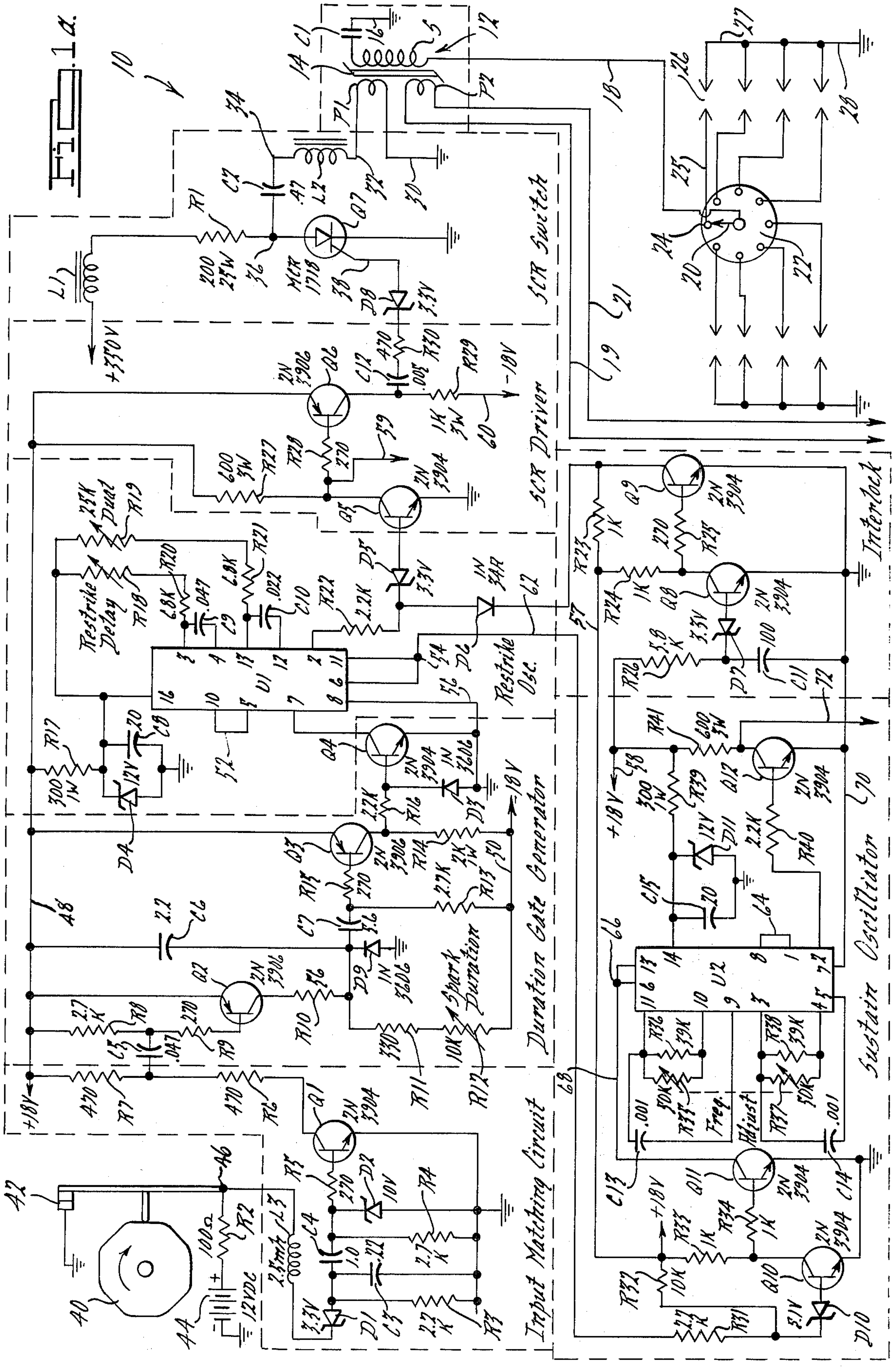
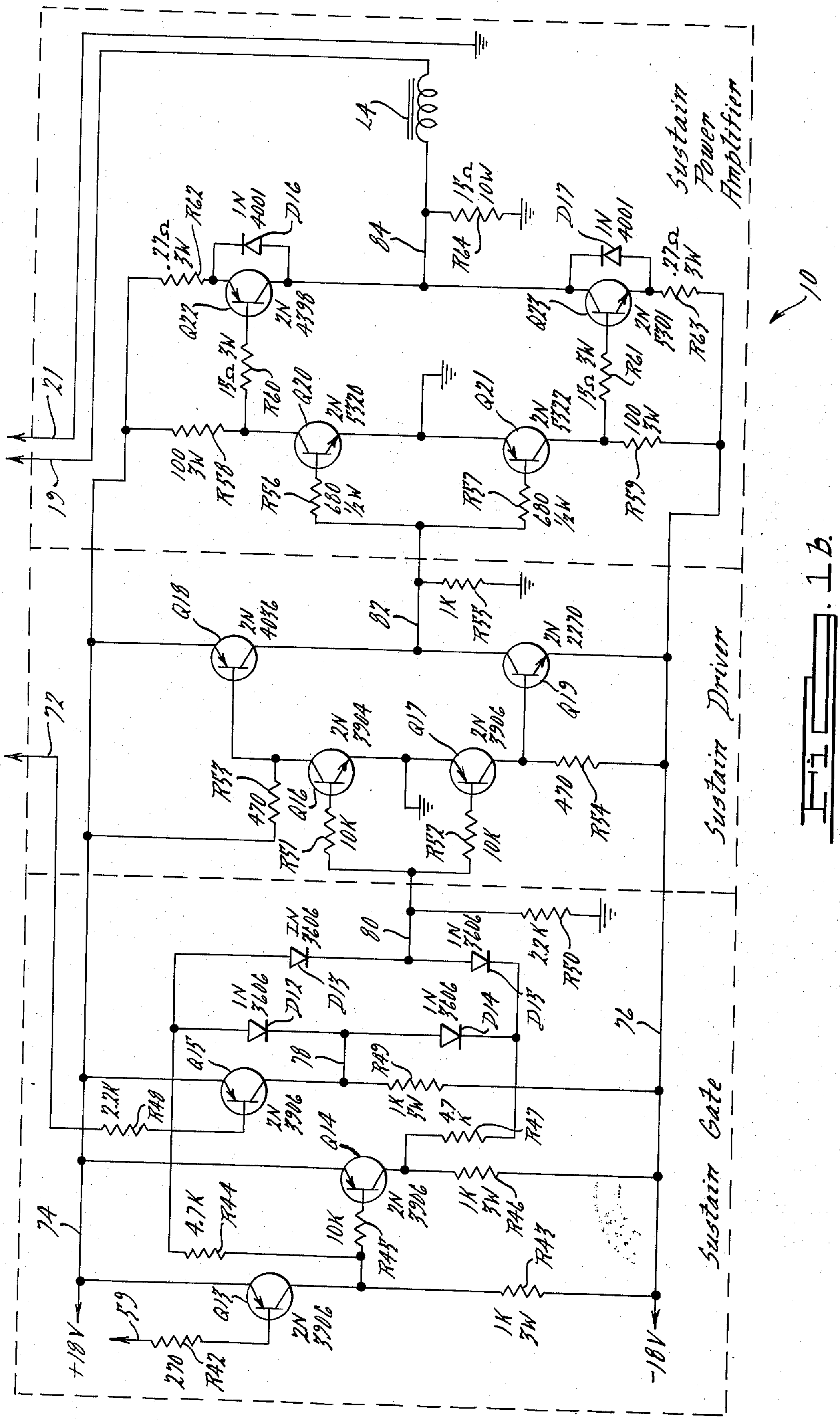
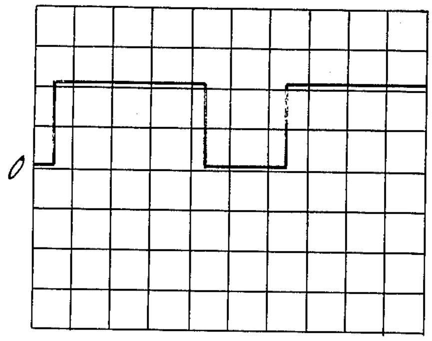


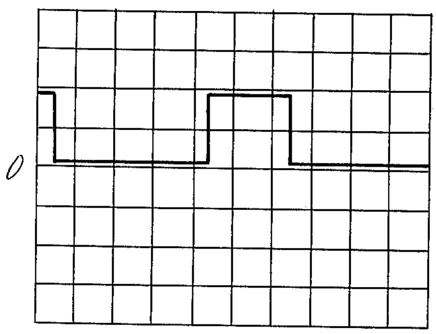
Fig. 1a
SCR Switch
SCR Driver
Restrike Delay
Restrike Osc.
Duration Gate Generator
Spark Duration
Input Matching Circuit
Interlock
Sustain Oscillator
Freq. Adjust
+330V
-18V
+18V
12VDC


Sustain Power Amplifier
Sustain Driver
Sustain Gate
+18V
-18V
Fig. 1B



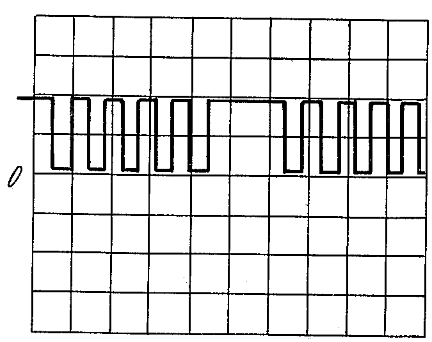
Gate Signal At Pin 2 Of U1
Vert.- 5V/Div.
Horiz.- 50μs/Div.

FIG. 2.



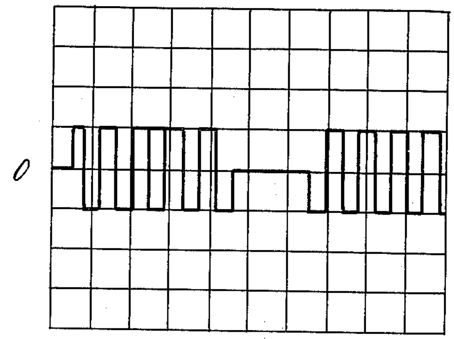
Gate Signal On Lead 59
Vert.- 10V/Div.
Horiz.- 50μs/Div.

FIG. 3.



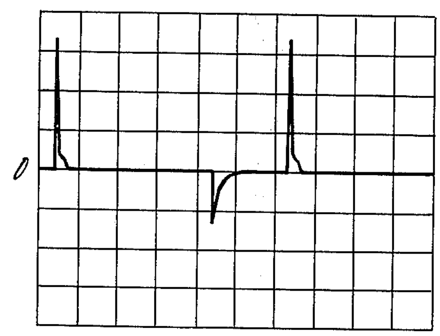
Output Of Sustain Oscillator (Collector Of Q12)
Vert.- 10V/Div.
Horiz.- 50μs/Div.

FIG. 4.



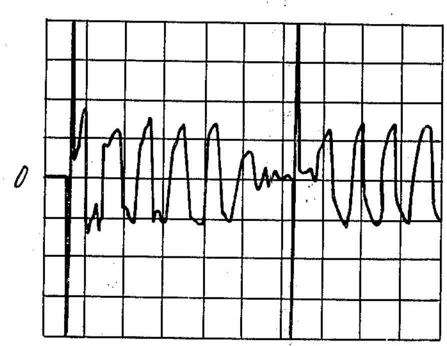
Output Of Sustain Gate (Voltage On Lead 80)
Vert.- 10V/Div. Horiz.- 50μs/Div.

FIG. 5.



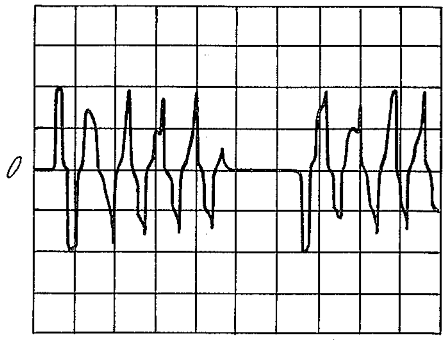
SCR Gate Signal On 470Ω Resistor R30 To Gate Of Q7
Vert.- 10V/Div. Horiz.- 50μs/Div.

FIG. 6.



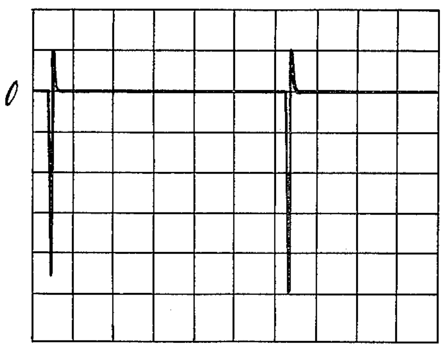
Voltage Across Sustain Primary P2.
Vert.- 10V/Div Horiz.- 50μs/Div.

FIG. 7.



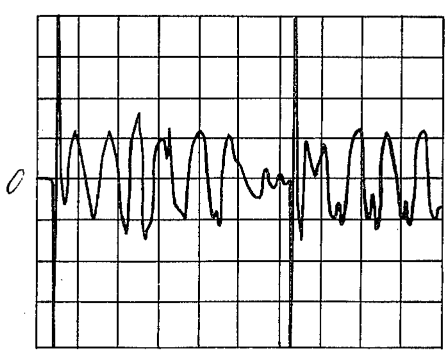
Current Through Sustain Primary P2
Vert.-10A/Div. Horiz.-50μs/Div.

FIG. 8.



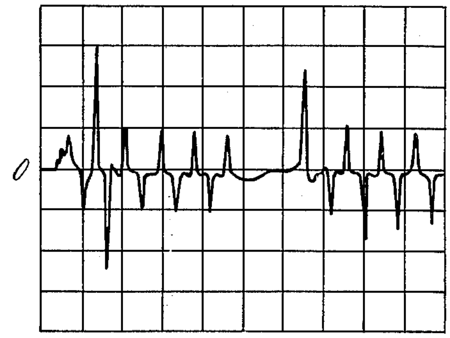
Current Through Primary Winding P1
Vert.-50A/Div. Horiz.-50μs/Div.

FIG. 9.



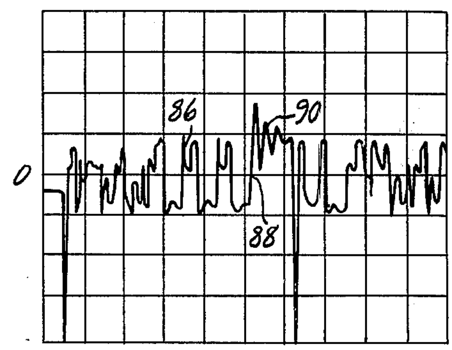
Voltage Across Primary Winding P1
Vert.-10V/Div. Horiz.-50μs/Div.

FIG. 10.



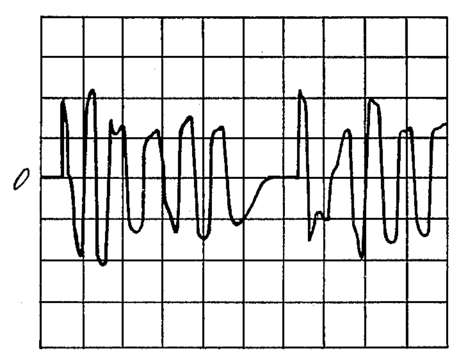
Current Through 35 Mil Spark Gap In Air
Vert.-0.5A/Div. Horiz.-50μs/Div.

FIG. 11.



Voltage Across 35 Mil Spark Gap In Air
Vert.-500V/Div. Horiz.-50μs/Div.

FIG. 12.



Voltage Across Capacitor C1 When A 35 Mil Spark Gap In Air Is Connected Across 5
Vert-1000V/Div. Horiz-50μs/Div.

FIG. 13.

CAPACITOR DISCHARGE IGNITION SYSTEM WITH CONTROLLED SPARK DURATION

BACKGROUND

This invention relates to a capacitor discharge ignition system for a spark-ignition internal combustion engine. More particularly, it relates to a ferroresonant capacitor discharge ignition system which produces a spark discharge in the gap of a spark plug. The spark discharge is of controllable duration and is characterized by alternating current flow in the spark gap and a sustained alternating voltage in the secondary circuit of an ignition coil. This voltage oscillates at a ferroresonant frequency. The present invention is related to our commonly assigned patent application Ser. No. 463,919 filed Apr. 24, 1974 and entitled "Ferroresonant Capacitor Discharge Ignition System."

Our copending patent application identified above relates to a capacitor discharge ignition system which has an ignition coil with a primary winding and a secondary winding wound about a ferromagnetic core. The system includes a spark gap which is connected in series with a first capacitor. The series-connected first capacitor and spark gap are connected across the ignition coil secondary winding and a second capacitor is coupled to the ignition coil primary winding and to a DC source of electrical energy. Circuit means are provided for charging the second capacitor and for discharging it through the primary winding in timed relation to engine operation. This produces breakdown of the spark gap in the secondary circuit and subsequent oscillations in this circuit. The secondary circuit oscillations are at a frequency f defined by the expression $f = V_m/4N_s \Phi_s$ where V_m is the instantaneous maximum voltage across the first capacitor, N_s is the number of turns in the secondary winding of the ignition coil and Φ_s is the magnetic flux enclosed by the secondary winding of the ignition coil at saturation of its ferromagnetic core.

The present invention is an improvement over the capacitor discharge ignition system described above in that it provides an ignition system which operates in a ferroresonant mode as defined by the above expression, but which also provides sustained and controllable spark duration characterized by ferroresonant oscillations in the secondary circuit of the ignition coil.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a capacitor discharge ignition system which has controllable spark duration.

Another object of the invention is to provide an ignition system which is characterized by sustained oscillation in the secondary circuit of an ignition coil at ferroresonant frequency $f = V_m/4N_s\Phi_s$.

A further object of the invention is to provide an ignition system that causes an alternating current to flow through the gap of a spark plug.

A still further object of the invention is to provide an ignition system which causes a spark discharge or breakdown in the gap of a spark plug subsequent to which the spark is sustained and ferroresonant oscillations occur in the secondary circuit of the ignition coil for a predetermined time interval.

Still another object of the invention is to provide an ignition system having restrike capability such that multiple sparks of sustained duration may be produced within the gap of the spark plug during one combustion cycle in a combustion chamber of an internal combustion engine.

A capacitor discharge ignition system in accordance with the invention comprises an ignition coil having first and second primary windings, a secondary winding and a ferromagnetic core about which the windings are wound. A spark plug has electrodes spaced to form a spark gap. One of the electrodes is coupled to one terminal of the secondary winding and the spark gap is connected in series with the first capacitor. One terminal of the capacitor is coupled to the other terminal of the secondary winding. A second capacitor is coupled to the first primary winding and a DC source of electrical energy is provided.

First circuit means are coupled to the second capacitor and to the first primary winding. The first circuit means controls the charging of the second capacitor from the DC source of electrical energy and controls its discharge through the first primary winding in timed relation to operation of the engine. Second circuit means, coupled to the second primary winding, are provided for producing a fixed frequency oscillatory current in the second primary winding for a predetermined time interval subsequent to each discharge of the second capacitor through the first primary winding. The discharge of the second capacitor through the first primary winding and the subsequent supply of the fixed frequency oscillatory current to the second primary winding produces, for at least a portion of the predetermined time interval, a voltage in the secondary circuit of the ignition coil which oscillates at a fixed frequency f defined by the expression $f = V_n/4N_s\Phi_s$ where V_m is the instantaneous maximum voltage across the first capacitor, N_s is the number of turns in the secondary winding and Φ_s is the magnetic flux within the secondary winding when the core of the ignition coil is magnetically saturated.

The invention may be better understood by reference to the detailed description which follows and to the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1***a* and **1***b* together form a complete schematic diagram of a capacitor discharge ignition system in accordance with the invention;

FIGS. **2** through **13** are reproductions of actual voltage and current waveforms observed on an oscilloscope; these waveforms have the same time base and illustrate the phase relationships of signals which occur at various points in the circuit shown schematically in FIGS. **1***a* and **1***b*.

DETAILED DESCRIPTION

With reference now to the drawings, wherein like numerals refer to like parts in the several views, there is shown in FIGS. **1***a* and **1***b* a complete schematic diagram of a capacitor discharge ignition system capable of operation in a ferroresonant mode in accordance with the invention. Various portions of the electrical circuit are enclosed by broken lines and given designations with respect to their function in the circuit. The complete ignition circuit of FIGS. **1***a* and **1***b* is designated by the numeral **10**.

In FIG. **1***a*, it may be seen that the ignition system **10** includes an ignition coil **12** which has a first primary winding **P1**, a second primary winding **P2** and a secondary winding 5. The ignition coil 12 has a ferromagnetic core 14 which in the circuit 10 is capable of being saturated repetitively after the initial breakdown of a spark gap 26. More specifically, the secondary winding S of the ignition coil has one of its leads connected to one terminal of a capacitor C1. The other terminal of the capacitor C1 is connected to ground at 16. A lead 18 extends from the other terminal of the secondary winding S to the rotor 20 of a conventional distributor 22 for a spark-ignition internal combustion engine. The distributor 22 has eight contacts 24 which are repetitively and serially contacted by the rotor 20 such that repetitive electrical contact is made with the eight spark gaps 26 contained in the spark plugs of the internal combustion engine. Thus, each of the spark plugs has one of its electrodes, represented by a lead 25, connected to the secondary winding S of the ignition coil and has its other electrode 27 connected to ground at 28. It should be noted that the ground connections 16 and 28 are common and, therefore, each of the spark gaps 26 is connected, sequentially as the rotor 20 rotates, in series with the capacitor C1. The capacitor C1 need not be located as shown in FIG. 1, but rather may be connected in series with the spark gap 26, for example, by its insertion in the lead 18, the lead 25 or the lead 27. If the capacitor C1 is inserted in the leads 25 or 27, a separate capacitor is required for each spark gap. Similarly, a separate secondary winding S may be provided for each of the spark gaps 26 if desired. Separate secondary windings S and capacitors C1 for each of the spark gaps 26 may be housed within the spark plug, for example, as depicted in the spark plug design of U.S. Pat. No. 3,267,325 issued Aug. 16, 1966 to J. F. Why.

The first primary winding P1 of the ignition coil 12 has one of its terminals connected to ground at 30 and has its other terminal 32 coupled, through a saturable, ferromagnetic core inductor L2 and a lead 34, to a capacitor C2. The capacitor C2 is connected to a junction 36 formed between a resistor R1 and the anode of a semiconductor controlled rectifier (SCR) Q7. The cathode of the SCR is connected to ground. The SCR has a gate or control electrode 38. The current limiting resistor R1 is connected through another saturable, ferromagnetic core inductor L1 to a +350 volt DC source of electrical energy. This voltage, as well as the other Dc voltages shown in FIG. 1, may be obtained from a 12 volt DC source of electrical energy, such as the storage battery 44 conventional in motor vehicles, through use of a DC to DC converter well known to those skilled in the art.

An input matching circuit, a duration gate generator, a restrike oscillator, an SCR driver and an SCR switch comprise circuit means for charging the capacitor C2 from the DC source of electrical energy and for discharging this capacitor through the first primary winding P1 in timed relation to operation of the engine. The charging and discharging of the capacitor C2 in timed relation to the engine operation may be obtained in the conventional manner by a cam 40 mechanically coupled to the distributor rotor 20, driven by the engine, and used to intermittently open and close a set of breaker points 42, one of which is connected to ground and the other of which is connected at a junction 46. Because the DC source of electrical energy 44 has its negative terminal corrected to ground has has its positive terminal connected through a resistor R2 to the junction 46, the junction 46 is at ground potential when the breaker points 42 are closed and is at the +12 volt potential of the storage battery 44 when the breaker points are open. The voltage rise at the junction 46 which occurs each time the breaker points open is supplied to an input matching circuit to cause the production of a spark in one of the spark gaps 26.

As indicated above, the circuitry 10 includes an input matching circuit. The function of this circuit is to couple the pulses occurring at the junction 46 to a duration gate generator. The duration gate generator produces a pulse output signal which has a controllable duration and which is supplied to the restrike oscillator. The function of the restrike oscillator is to produce one or more pulse signals during the duration of the signal from the duration gate generator. Each pulse produced at the output of the restrike oscillator is used to initiate the discharge of the capacitor C2 through the ignition coil first primary winding P1. The output pulses from the restrike oscillator circuit are supplied to an SCR driver circuit which utilizes the restrike oscillator pulses to produce pulse spikes which are applied to the gate 38 of the SCR Q7. An interlock circuit is provided to prevent, when the ignition circuit 10 is first put into operation, the supply of a pulse to the gate electrode 38 until the capacitor C2 has had sufficient time to charge. In the paragraphs which follow, the above circuit portions are described in detail.

The input matching circuit includes a choke inductor L3 which has one of its terminals connected to the junction 46 and which has its other terminal connected to the cathode of a zener diode D1. The anode of this zener diode is coupled to ground through a resistor R3 connected in parallel with a noise suppression capacitor C3. The anode of the zener diode also is connected through the series combination of a DC blocking capacitor C4 and a current limiting R5 to the base of an NPN transistor Q1. The junction formed between the capacitor C4 and the resistor R5 is connected to the cathode of a zener diode D2 whose anode is connected to ground. A resistor R4 is connected in parallel with the zener diode D2. The emitter of the transistor Q1 also is connected to ground and its collector is connected through resistors R6 and R7 to a +18 volt DC supply lead 48.

The function of the resistor R3 and capacitor C3 is to suppress high frequency noise signals that may appear at the anode of the zener diode D1. The capacitor C4 permits the positive step voltage, which occurs at the junction 46 when the breaker points 42 open, to momentarily pass through the resistor R5 to the base of the transistor Q1 to render it momentarily conductive in its collector-emitter output circuit. This permits current to flow through the resistors R7 and R6 to ground.

The duration gate generator has a blocking capacitor C5 connected to the junction formed between the resistors R6 and R7. The opposite terminal of the capacitor C5 is connected through a current limiting resistor R9 to the base of a PNP transistor Q2. The junction formed between the capacitor C5 and the resistor R9 is connected through a resistor R8 to the voltage supply lead 48. The emitter of the transistor Q2 also is connected to the supply lead 48 and its collector is connected through series-connected resistors R10, R11 and R12 to a −18 volt DC supply lead 50. The resistor R12 is variable and controls the duration (total length of time) of multiple spark discharges produced in a given spark gap 26 during one combustion cycle in the engine. More specifically the resistor R12 controls the duration of the output signal pulse from the duration gate generator. In a reciprocating spark-ignition internal combustion engine, the length or duration of this output pulse is the length of time available for the production of one or more sparks in the spark gap **26** in a given cylinder to cause ignition of a combustible mixture of fuel and air and a resultant power stroke of the piston in that cylinder.

The capacitor C6 has one of its terminals connected to the voltage supply lead **48** and has its other terminal connected to the junction formed between the resistors R10 and R11. Also connected to this junction is the cathode of a clamping diode D9 which has its anode connected to ground. The diode D9 limits the negative voltage at this junction to one diode voltage drop below ground potential. The junction formed between the resistors R10 and R11 also is connected through a coupling capacitor C7 and a current limiting resistor R15 to the base of a PNP transistor Q3. The junction formed between the capacitor C7 and resistor R15 is connected through a resistor R13 to the negative voltage supply lead **50**. The collector of the transistor Q3 also is connected through a resistor R15 to the supply lead **50**, and the emitter of this transistor is connected to the positive voltage supply lead **48**. The collector of the transistor Q3 is connected through a resistor R16 to the base of an NPN transistor Q4 whose emitter is connected to ground. A clamping diode D3 has its cathode connected to the base of the transistor Q4 and has its anode connected to ground to limit the base voltage to one diode voltage drop below ground potential. The output signal of the duration gate generator is taken at the collector of the transistor Q4 which is connected to pin 7 of a dual monostable multivibrator U1, which as shown is a Teledyne type **342**. A Texas Instruments type **15342** or the equivalent also may be used for U1.

The duration gate generator is a sawtooth generator which is triggered when the transistor Q1 is rendered conductive, which occurs, as previously stated, when the breaker points 42 open. When the transistor Q1 is rendered conductive, the resistor R8 and capacitor C5 differentiate the resulting negative voltage step at the collector of Q1. The negative voltage spike which results is applied to the base of the transistor Q2. This renders the transistor Q2 conductive in its emitter-collector output circuit for a time sufficient to permit the discharge of the capacitor C6 through the resistor R10 and the emitter-collector circuit of the transistor Q2. The capacitor C6 will have previously been charged to a voltage slightly in excess of **18** volts DC. The transistor Q3 is normally conductive in its emitter-collector output circuit due to the flow of current from the voltage supply lead **48**, through its emitter-base junction, through the resistor R15, and primarily through the resistor R13 to the negative voltage supply lead **50**. However, when the capacitor C6 discharges, a positive voltage approximately equal to the voltage on the supply lead **48** appears at the junction formed between resistors R10 and R11. This voltage is applied through the capacitor C7 and the resistor R15 to the base of the transistor Q3 to render it nonconductive. The transistor Q3 remains nonconductive for the length of time required for the capacitor C6, after the transistor Q2 again becomes nonconductive, to recharge through the series resistors R11 and R12. Typically, the transistor Q3 is nonconductive for a time period of from **1** to **5** ms. When the transistor Q3 is rendered nonconductive and for so long as it is nonconductive, the transistor Q4 has no base drive and also is nonconductive which results in the application of a positive voltage at the pin 7 of the dual monostable multivibrator U1.

The dual monostable multivibrator U1 has one monostable multivibrator with an input A_1 and an output $\overline{Q}_1$. The other monostable multivibrator in the integrated circuit U1 has an input A_2 and an output $\overline{Q}_2$. By the connection of the $\overline{Q}_1$ output to the A_2 input and the connection of the $\overline{Q}_2$ output to the A_1 input, as is accomplished by the connection of the lead **52** between the pins **5** and **10** and the connection of the pins **6** and **11** at a junction **54**, the dual monostable multivibrator U1 becomes a pulse generator, the output of which is taken at its pin **2**. The Q_1 output at pin **2** alternates between a high voltage level of about **10** volts and a low voltage level near ground potential. With the circuit values indicated in the drawings, the high voltage portion of the signal at pin **2** is approximately **68** percent of the signal period. Dual variable resitors R18 and R19 are connected, respectively, through a resistor R20 and a capacitor C9 to the pins **3** and **4** and through a resistor R21 and a capacitor C10 to the pins **12** and **13**. These components determine the duty cycle or pulse width at output pin **2** of the multivibrator and permit the period of the signal at pin **2** to be varied from about **0.30** ms to **1.5** ms. The period of the signal at pin **2** represents the restrike delay, that is, the delay between multiple ignition sparks produced in each of the spark gaps **26** by repetitive triggering of the SCR Q7.

The dual monostable multivibrator U1 is triggered or gated when the output circuit of the transistor Q4 is rendered nonconductive. When the transistor Q4 is conductive, the signal at pin **2** of the dual monostable multivibrator U1 remains constant at a low voltage level, but when the transistor Q4 becomes nonconductive, gating multivibrator U1, the signal at pin **2** becomes a series of pulses which continually gate the SCR Q7 to produce a spark in a spark gap **26** each time a pulse occurs at pin **2**. These repetitive and restriking sparks continue to occur until the transistor Q4 is once again rendered conductive.

The dual monostable multivibrator U1 receives its positive voltage supply from a voltage regulator comprising a resistor R17 connected in series with the parallel combination of a zener diode D4 and a capacitor C8. The junction formed between these components is connected to the voltage supply pin **16** of U1 and also is connected to the variable resistors R18 and R19. Pin **8** of the multivibrator U1 is connected to ground. Pin **2** of the multivibrator is connected through a current limiting resistor R22 and a zener diode D5 to the base of an NPN transistor Q5.

The transistor Q5 is located in the SCR driver portion of the circuit **10** and has its emitter connected to ground. Its collector is connected through a resistor R27 to the voltage supply lead **48** and also is connected through a current limiting resistor R28 to the base of PNP transistor Q6. The emitter of the transistor Q6 is connected to the voltage supply lead **48** and its collector is connected through a resistor R29 and a lead **60** to a −**18** volt DC voltage supply. The collector of the transistor Q6 also is connected, through a series circuit including differentiating capacitor C12, resistor R30 and zener diode D8, to the gate electrode 38 of the SCR Q7.

The waveforms shown in FIGS. 2 through 13 are representations of signals which occur at various points in the circuit schematically illustrated in FIG. 1, with the exception that the waveforms 11, 12 and 13 pertain to a 35 mil spark gap located in air at atmospheric pressure rather than to a spark gap located in the cylinder of an operating internal combustion engine.

FIG. 2 shows the voltage waveform that occurs at pin 2 of the dual monostable multivibrator U1. This voltage is the oscillatory output voltage of the multivibrator which occurs so long as the input transistor Q4 connected to its pin 7 is in a nonconductive state. Of course, Q4 is rendered nonconductive each time, and for a predetermined time established by the duration gate generator, that the cam 40 opens the breaker points 42. On each positive going edge of the pulses in FIG. 2, the transistor Q5 is rendered conductive. This reduces its collector voltage to substantially ground potential to cause the conduction of the PNP transistor Q6. When nonconductive, the collector of the transistor Q6 is at approximately −18 volts DC, but when rendered conductive, its collector achieves a voltage of almost +18 volts DC. This step voltage on the collector of the transistor Q6 is differentiated by the capacitor C12 to produce a voltage spike which gates the SCR Q7. The voltage spikes are represented in FIG. 6, which illustrates the voltage spikes occurring on the resistor R30 at points corresponding to the positive going edges of the pulses of FIG. 2, which pulses occur at pin 2 of the multivibrator. Thus, it is apparent that the SCR Q7 is gated or triggered on each positive going edge of the oscillatory signal occurring at pin 2 of the multivibrator U1 and that this continues so long as the transistor Q4 is nonconductive. If the duration gate generator is adjusted such that the transistor Q4 is nonconductive for 5 milliseconds and if the restrike delay resistor R18 and R19 are adjusted such that the signal of FIG. 2 has a period of 0.33 ms, then the gate 38 of the SCR Q7 will receive 16 trigger pulses during the course of the 5 ms that the transistor Q4 is nonconductive. This produces a corresponding 16 spark discharge in a single one of the spark gaps 26. It should be noted that 5 ms is approximately the time required for the piston in an eight-cylinder, four-cycle reciprocating internal combustion engine to travel from its top-dead-center positin to its bottom-dead-center position when the engine is operating at 6,000 rpm.

With respect to the interlock portion of the circuitry 10, it may be seen that this circuit portion comprises NPN transistors Q8 and Q9. The emitters of these transistors are connected to ground potential. The collector of the transistor Q9 is connected, through a diode D6, to the junction formed between the resistor R22 and the zener diode D5. The collector of this transistor also is connected through a resistor 23 to a lead 57 connected to a +18 volt DC source of electrical energy. A current limiting resistor R25 is connected between the lead 57 and the collector of the transistor Q8. The collector of the transistor Q8 also is connected through a current limiting resistor R25 to the base of the transistor Q9. A series-connected resistor R26 and capacitor C11 are connected between the lead 57 and ground potential. The junction formed between the resistor R26 and the capacitor C11 is connected through a zener diode D7 to the base of the transistor Q8. Upon the initial application of the DC supply potential to the lead 57, the transistor Q9 immediately is conductive in its collector-emitter output circuit. This has the effect of connecting connecting the pin 2 output of the multivibrator U1 to ground potential to prevent the conduction of the transistor Q5 and, consequently, to prevent the supply of a triggering Q5 and, consequently, to prevent the supply of a triggering pulse to the gate electrode 38 of the SCR Q7. At this time, the transistor Q8 is nonconductive in its output circuit because the capacitor C11 forms an effective short circuit of its base-emitter circuit. However, the continued application of the DC voltage on the lead 57 causes the capacitor C11 to be charged through the resistor R26.

When the voltage on the upper terminal of the capacitor C11 exceeds the sum of the breakdown voltage of the zener diode D7 and the base-emitter voltage drop required to render the transistor Q8 conductive, then the collector-emitter circuit of transistor Q8 becomes conductive and shunts the base-emitter circuit of the transistor Q9. The transistor Q9 then becomes nonconductive and the positive going edges of the oscillatory signal at pin 2 of the multivibrator U1 are permitted to cause the repetitive triggering of the gate electrode 38 of the SCR Q7. The time required to charge the capacitor C11 exceeds considerably the time required to charge the capacitor C2 connected to the first primary winding P1 of the ignition coil 12. The capacitor C2 must be fully charged before the SCR Q7 is triggered because the latter is self-commutated as a result of the discharge of the capacitor C2 through it and the first primary winding P1. Of course, the interlock circuitry shown in FIG. 1a may be replaced by gate circuitry which prevents the application of a trigger signal on the gate electrode 38 of the SCR prior to the required charge level on the capacitor C2 being attained.

When the SCR Q7 is nonconductive between its anode and cathode, the capacitor C2 is charged from the +350 volt DC power suply through the current path including the inductor L1, the resistor R1, the inductor L2, the first primary winding P1 of the ignition coil 12 and the ground circuit. When the SCR Q7 is triggered by a positive pulse applied to its gate electrode 38, a current spike is produced. Two such current spikes, caused by two successive trigger pulses applied to the gate electrode 38 are shown in waveform of FIG. 9. It may be seen that these current spikes have an alternating current waveform. At the end of the spike, the SCR Q7 is self-commutated. This self-commutation is aided by the saturable inductor L2 which offers little impedance to current flow due to its saturable character.

FIG. 10 shows the voltage across the first primary winding P1 upon the occurrence of the current spikes shown in FIG. 9. It may be seen that this voltage is oscillatory, that it has a voltage spike corresponds to the breakdown of one of the spark gaps 26, and that the amplitude is substantially constant for the time interval during which current flows through the spark gap (this current is shown in FIG. 11 hereinafter described).

The sustain oscillator, the sustain gate, the sustain driver and the sustain power amplifier generally comprise circuit means for producing a fixed frequency oscillatory current in the second primary winding P2 for a predetermined time interval subsequent to each discharge of the capacitor C2 through the first primary winding P1. The sustain gate is triggered by a signal which triggers the SCR Q7 and produces oscillations of a square-wave character and of fixed frequency. These oscillations receive current and power amplification through the sustain driver and sustain power amplifier circuits, and the amplified oscillatory currents flow through the second primary winding P2 of the ignition coil **12**.

The sustain oscillator includes a dual monostable multivibrator integrated circuit U2. The dual monostable multivibrator U2 as shown has the pin connections of a Motorola Semiconductor Corporation type MC **667**, but equivalent devices may be substituted. Dual monostable multivibrator U2 has its $\overline{Q}_2$ output connected to its T_1 input and has its $\overline{Q}_1$ output connected to its T_2 input. Thus, lead **64** interconnects pins **1** and **8** of U2 and pins **6** and **13** are interconnected at a junction **66** which forms the trigger input to the multivibrator U2. The trigger input is supplied via a lead **68** connected to the collector of a transistor Q11. The emitter of the transistor Q11 is connected to ground.

A lead **62** is connected to the junction **54** connected to pins **6** and **11** of the dual monostable multivibrator U1 in the restrike oscillator. The signal on these pins is the same as the pin **2** signal shown in FIG. **2**. Lead **62** is connected through a resistor R31 to the cathode of zener diode D10, the anode of which is connected to the base of NPN transistor Q10. The emitter of the transistor Q10 is connected to ground and its collector is connected through a current limiting resistor R33 to a +18 volt DC source of electrical energy. A resistor R32 is connected to this source and to the junction formed between the resistor R31 and the cathode of the zener diode D10. The collector of the transistor Q10 also is connected through a current limiting resistor R34 to the base of an NPN transistor Q11. When the voltage on the lead **62** is at its high voltage level, the transistor Q10 is conductive in its output circuit and its collector voltage is substantially at ground potential. This renders the transistor Q11 nonconductive in its output circuit and its collector is isolated from ground potential. On the other hand, when the signal on the lead **62** is a low voltage, the transistor Q10 is nonconductive, which causes the transistor Q11 to be conductive in its collector-emitter output circuit and results in the connection of the pins **6** and **13** of the dual monostable multivibrator U2 to substantially ground potential.

The dual monostable multivibrator U2 is connected as a square-wave oscillator which has a duty cycle and period determined by the parallel-connected resistors R35 and R36 connected across pins **10** and **11** and the capacitor C13 connected between pins **9** and **11** and by the parallel-conected resistors R37 and R38 connected across pins **3** and **4** and the capacitor C14 connected between the pins **3** and **5**. Resistors R36 and R37 are variable to provide an oscillator output signal on the Q_1 output at pin **2** of the multivibrator U2 which has a frequency variable between **17** KHz and **35.7** KHz. The output on the pin **2** of the dual monostable multivibrator U2 is a low level voltage whenever the voltage on pin **2** of the dual monostable multivibrator U1 is a low voltage, and the voltage on pin **2** of the dual monostable multivibrator U2 is oscillatory between **12** volts and ground potential whenever the voltage on pin **2** of the dual monostable multivibrator U1 is at a high voltage level. The oscillatory voltage at pin **2** of the multivibrator U2 is applied through a current limiting resistor R40 to the base of an NPN transistor Q12. The emitter of the transistor Q12 is connected to ground and its collector is connected through a current limiting resistor R41 to a lead **58** connected to a +**18** volt DC source of electrical energy. The voltage supply to the multivibrator U2 is obtained from a resistor R39 connected to the lead **48** and to the parallel combination of a filter capacitor C15 and a zener diode D11 which are connected between the pin **14** of U2 and ground potential. This provides a regulated supply voltage for multivibrator U2. Pin **7** of the multivibrator U2 is connected to a ground lead **70**.

The output signal of the sustain oscillator is obtained on a lead **72** connected to the collector of the transistor Q12. This signal is shown in FIG. **4** where it may be seen that the voltage oscillates between about +**18** volts DC and **0** volts DC. Because each of the high voltage-level pulses at pin **2** of the multivibrator U1 results in a trigger signal being applied to the gate **38** of the SCR Q7, and from the waveform of FIG. **4**, it is clear that an oscillatory signal is produced on the lead **72** of the sustain oscillator each time the SCR Q7 is triggered. This oscillatory signal has a duration corresponding to the duration of the high-voltage-level pulses shown in FIG. **2**. These sustained oscillations on the lead **72** cause, in a manner hereinafter described, current oscillations in the second primary winding P2 of the ignition coil **12**.

With particular reference now to FIG. **1***b*, there is shown the sustain gate, the sustain driver and the sustain power amplifier, the functions of which are to provide current and power amplification of the oscillatory signals occuring on the lead **72** which is connected through a current limiting resistor R48 to the base of PNP transistor Q15 in the sustain gate. The emitter of the transistor Q15 is connected to a +**18** volt DC supply lead **74** and its collector is connected through a current limiting resistor R49 to a −**18** volt DC supply lead **76**. The voltage on the collector of the transistor Q5 in the SCR driver portion of the circuitry is shown in FIG. **3** as the complement of the signal on pin **2** of the dual monostable multivibrator U1 and is supplied via a lead **59** and through a current limiting resistor R42 to the base of a PNP transistor Q13. The emitter of this transistor is connected to the voltage supply lead **74** and its collector through a resistor R43 to the negative voltage supply lead **76**. Its collector also is connected through a current limiting resistor R45 to the base of a PNP transistor Q14. The collector of Q14 is connected through a current limiting resistor R46 to the negative voltage supply lead **76** and its emitter is connected to the voltage supply lead **74**.

A diode gate is formed by diodes D12, D13, D14 and D15. The anodes of the diodes D12 and D13 are connected together and, through a resistor R44, are connected to the collector of the transistor Q13. The cathode and anode junction formed between diodes D12 and D14 is connected by a lead **78** to the collector of the transistor Q15 and the cathodes of the diodes D14 and D15 are connected, through a resistor R47, to the collector of the transistor Q14. The junction formed between the cathode of the diode D13 and the anode of the diode D15 is connected by a lead **80**, which is the output of the sustain gate, to one terminal of a resistor R50 the other terminal of which is connected to ground. The lead **80** also is connected through a resistor R51 to the base of an NPN transistor Q16 and through a resistor R52 to the base of a PNP transistor Q17. Transistors Q16 and Q17 form a push-pull amplifier and thus have their emitters connected together and to ground potential. The collector of the transistor Q16 is connected through a current limiting resistor R53 to the voltage supply lead 74, and the collector of the transistor Q17 is connected through a resistor R54 to the negative voltage supply lead 76. Also, the collector of the transistor Q16 is connected to the base of a PNP transistor Q18 whose emitter is connected to the voltage supply lead 74 and whose collector is connected via a lead 82 and a resistor R55 to ground. Similarly, the collector of the transistor Q17 is connected to the base of NPN transistor Q19 whose emitter is connected to the negative voltage supply lead 76 and whose collector is connected to the lead 82 and, through the resistor R55 to ground potential. It may be appreciated that when the transistor Q16 is conductive in its collector-emitter output circuit, the transistor Q18 also is conductive to permit current flow from the voltage supply lead 74 to the lead 82, and, through the resistor R55, to ground. Likewise, when the transistor Q17 is conductive in its emitter-collector output circuit, the output circuit of the transistor Q19 is conductive to permit current to flow from ground, through the resistor R55 and through the colector-emitter output circuit of the transistor Q19 to the negative voltage supply lead 76.

As may be seen from FIGS. 3 and 4, prior to the occurrence of oscillations on the lead 72, the voltage on this lead is at about +18 volts, as is the voltage on the gate signal lead 59. Thus, the emitter-base junctions of the transistors Q15 and Q13 are reverse-biased and these transistors are non-conductive. In such case, the voltage on the sustain-gate output lead 80 is at ground potential. When the voltage at pin 2 of the dual monostable multivibrator U1 rises to about 10 volts to cause the application of a trigger signal on the gate lead 38 of the SCR Q7, the gate signal on lead 59 falls to a few volts as shown in FIG. 3. At the same time, the voltage on the lead 72, connected to the collector of the transistor Q12 in the sustain oscillator, oscillates between about +18 volts DC and substantially ground potential as shown in FIG. 4. The low voltage on the lead 59 renders the transistor Q13 conductive. This results in the application of about +18 volts to the base of the transistor Q14 and it is rendered nonconductive in its output circuit. The oscillations on the lead 72 are applied through the resistor R48 to the base of the transistor Q15 to render its emitter-collector output circuit conductive and nonconductive in a corresponding oscillatory manner. Thus, the lead 78 alternates between +18 volts and −18 volts. When the lead 78 is at +18 volts, current flows from the collector of the transistor Q13 through the resistor R44, through the diode D13 and into the lead 80. At the junction formed between lead 80 and the resistor R50 the current divides, part of it flowing to ground through the resistor R50 and the remainder flowing through the resistor R51 and base-emitter junction of the transistor Q16 to ground. When the lead 80 is at −18 volts, currents flow from ground through the resistor R50 and from ground through the emitter-base junction of the transistor Q17 and the resistor R52 to the lead 80 where there currents are combined. The combined current flows from the lead 80, through the diode D15, the resistor R47 and the resistor R46 to the negative voltage supply lead 76. Under such circumstances, the voltage waveform on the lead 80 is as shown in FIG. 5.

The transistors Q16 and Q17 are alternately conductive during the oscillatory voltage which occurs on the lead 72. These transistors amplify the alternating voltage signal on the lead 80.

When the transistor Q16 is conductive on alternative half cycles, the transistor Q18 also is conductive to provide current and power amplifications. Similarly, when the transistor Q17 is conductive, the transistor Q19 is also conductive to provide amplification. The voltage on the collectors of the transistors Q18 and Q19, during the oscillations on the lead 72, also oscillates between about +18 and −18 volts. This alternating voltage, when positive, is applied through a current limiting resistor R56 to the base of a transistor Q20 to render it conductive, and, when negative, is applied through a current limiting resistor R56 to the base of a transistor Q21 to render it conductive. The emitters of the transistor Q20 and Q21 are connected together and to ground, the collector of the transistor Q20 is connected through a resistor R58 to the voltage supply lead 74, and the collector of the transistor Q21 is connected through a resistor R59 to the voltage supply lead 76. The transistor Q20 and Q21 form a push-pull amplifier.

The collector of the transistor Q20 is connected through a current limiting resistor R60 to the base of a transistor Q22, the emitter of which is connected through a resistor R62 to the voltage supply lead 74. The colector of the transistor Q21 is connected through a current limiting resistor R61 to the base of a transistor Q23 whose emitter is connected through a resistor R63 to the voltage supply lead 76. The collectors of the transistors Q22 and Q23 are connected together. A diode D16 has its cathode connected to the emitter of the transistor Q22 and has its anode connected to the collector of this transistor. Similarly, a diode D17 has its cathode connected to the collector of the transistor Q23 and has its anode connected to the emitter of this transistor. Transistor Q22 is conductive when transistor Q20 is conductive, and transistor Q23 is conductive when transistor Q21 is conductive.

The junction formed between the collectors of the transistors Q22 and Q23 is connected by a lead 84 to the junction formed between a resistor R64 and a saturable inductor L4. The opposite terminal of the resistor R64 is connected to ground. Lead 19 connects the opposite terminal of the saturable inductor L4 to the second primary winding P2 of the ignition coil 12 and the lead 21, connected to the opposite terminal of this second primary winding, is connected to ground. Thus, the resistor R64 is connected in parallel with the series-connected saturable inductor L4 and second primary winding P2. The alternating conduction of the transistors Q22 and Q23 in response to the oscillations on the lead 72 causes an alternating current to flow through the saturable inductor L4 and the second primary winding P2 of the ignition coil to sustain a spark in the gap 26 of a spark plug for a time period determined by the length of time the oscillation continues on the lead 72. The alternating voltage across and current flow through the second primary winding P2 are shown, respectively, in FIGS. 7 and 8.

As was previously mentioned, FIG. 9 shows the current flow through the primary winding P1 for two spark discharges through a spark gap 26. It may be seen that two alternating current spikes occur, one for each of the SCR Q7 gate signal pulses which occur as shown in FIG. 6. These gate signal pulses result in conduction of the SCR Q7 and the discharge of the capacitor C2 through the first primary winding P1. This breaks down a spark gap 26, causes ferroresonant oscillations to occur in the secondary circuit of the ignition coil 12, and causes the sustain gate, sustain oscillator, and sustain amplifier circuitry to produce alternating current in the second primary winding P2. The frequency of this alternating current is selected to sustain a ferroresonant mode of oscillation in the ignition coil secondary circuit.

FIG. 11 depicts the current through a 35 mil spark gap, located in air at atmospheric pressure, for two spark discharges, each of which is initiated by the discharge of the capacitor C2 through the first primary winding P1 and each of which is sustained for a predetermined time interval as a result of the alternating current flow through the second primary winding P2. It may be seen that this current flow through the spark gap is alternating in direction, that the initial amplitude and frequency, that is, for about the first 75 microseconds of the spark discharge, is higher than the fixed frequency and amplitude of current flow which occurs thereafter, and that the alternating current flow through the spark gap is nonsinusoidal, which is the result of ferroresonent oscillation in the secondary circuit of the ignition coil 12, this ferroresonent oscillation resulting from repetitive variation of the ignition coil ferromagnetic core between saturated and unsaturated conditions.

FIG. 12 shows the voltage across the 35 mil spark gap, located in air at atmospheric pressure, during the current discharge through this spark gap as depicted in FIG. 11. The waveform of FIG. 12 has notch-like portions 86 which correspond to the current spikes shown in FIG. 11, leading to strong arcs within the spark gap 26. The spark is extinguished at the point 88. Following this, a sinusoidal and decreasing amplitude oscillation 90 take place.

FIG. 13 depicts the voltage across the capacitor C1 for two spark discharges corresponding to the current and voltage waveforms shown, respectively, in FIGS. 11 and 12. It may be seen that the frequency of this voltage across the capacitor C1 for about the first 75 microseconds oscillates at a voltage and frequency which is in excess of that which follows. The oscillations of voltage across the capacitor C1 during this initial 75 microseconds is a ferroresonant oscillation defined by the equation $f = V_m/4N_s\Phi_s$. The oscillations which follow also behave in accordance with this equation, but the frequency of oscillation is that produced by the alternating current flowing through the second primary winding P2. In other words, the ferroresonant oscillations lock-in at the fixed frequency of the sustaining alternating current oscillations in the second primary winding P2. The voltage V_m across the capacitor C1 assumes a value defined by the foregoing equation for operation at such fixed frequency.

The voltage and current waveforms shown in FIG. 2 through 13 were obtained with an ignition coil 12 having a first and second primary windings P1 and P2 each of one turn and a secondary winding of 160 turns. The primary windings P1 and P2 and the secondary winding S were wound on a ferrite (manganese zinc) core having the shape of a closed, hollow cylinder with a central core running along its axis. The cylinder had an outside diameter of 42 millimeters and a height of 29 millimeters. The primary and secondary windings were wound about the central core. The capacitor C1 had a value of 500 picofarads. The remaining components in the circuit of FIGS. 1*a* and 1*b* were of the values indicated therein. The capacitance values are given in microfarads, unless otherwise specified, and the resistance values are in ohms or, as indicated, in kilohms.

The design of the saturable ferromagnetic ignition coil 12 is not critical and may take various forms other than that described in the preceding paragraph. Also, the value of the capacitor C1 is of importance in producing ferroresonance in the secondary circuit during the discharge of the capacitor C2 through the ignition coil primary winding P1, but the capacitance C1 may be within a broad range. Values in excess of 1,000 picofarads for the capacitor C1 have been used.

The DC voltage supply for charging the capacitor C2 and the value of this capacitor must be sufficiently large to permit the discharge of this capacitor through the first primary winding P1 of the ignition coil 12 to produce a ferroresonant condition, as depicted in FIGS. 7 through 13, in the ignition system.

The circuitry of FIGS. 1a and 1b is designed to provide multiple sustained sparks during a given combustion cycle in a given combustion chamber of an engine. If it is desired to produce only one sustained spark per combustion cycle, then the circuitry may be simplified considerably. Of course, a transistorized ignition system using a pulse generator driven by a distributor or the like may be used in place of the cam 40 and breaker points 42. Such breakerless ignition systems are well known.

The inventors have found that the first and second primary windings P1 and P2 may, if desired, be replaced by a single primary winding connected to the SCR Q7 in the manner shown in FIG. 1a, but also having its terminal leads connected, for example, by the leads 19 and 21 in FIG. 1*b*, to the output of the sustain oscillator.

Based on the foregoing description of the invention, what is claimed is:

1. In combination with an internal combustion engine, a capacitor discharge ignition system, which comprises:

an ignition coil having first and second primary windings, a secondary winding and a ferromagnetic core about which said windings were wound;

a spark plug having electrodes spaced to form a spark gap, one of said electrodes being coupled to one terminal of said secondary winding;

a first capacitor connected in series with said spark gap, one terminal of said first capacitor being coupled to the other terminal of said secondary winding;

a second capacitor coupled to said first primary winding;

a DC source of electrical energy;

first circuit means, coupled to said second capacitor and to said first primary winding, for charging said second capacitor from said DC source of electrical energy and for discharging said second capacitor through said first primary winding in timed relation to operation of said engine;

second circuit means, coupled to said second primary winding, for producing an oscillatory current in said second primary winding for a predetermined time interval subsequent to each discharge of said second capacitor through said first primary winding;

the discharge of said second capacitor through said first primary winding and the subsequent production of said oscillatory current in said second primary winding producing, for at least a portion of said predetermined time interval, a voltage in the secondary circuit of ignition coil which oscillates at a frequency defined by the expresion $f = V_m/4N_s\Phi_s$ where V_m is the instantaneous maximum voltage across said first capacitor, N_s is the number of turns in said secondary winding, and Φ_s is the magnetic flux within said secondary winding when said ferromagnetic core of said ignition coil is magnetically saturated.

2. An ignition system according to claim **1** where said first circuit means includes means for generating a gating signal for causing the discharge of said second capacitor through said first primary winding and wherein said second circuit means includes an oscillator for generating an oscillatory signal and an amplifier means for amplifying said oscillatory signal, said amplifier means being coupled to said second primary winding to produce said oscillatory current in said second primary winding, said oscillator being controlled by said gating signal generated by said first circuit means.

3. An ignition system according to claim **2** wherein said means for generating said gating signal includes a second oscillator, said second oscillator being triggered in timed relation to operation of said engine, said second oscillator having an output signal from which said gating signal is derived and which determines said predetermined time interval.

4. In combination with an internal combustion engine, a capacitor discharge ignition system, which comprises:

an ignition coil having first and second primary windings, a secondary winding and a ferromagnetic core about which said windings are wound;

a spark plug having electrodes spaced to form a spark gap, one of said electrodes being coupled to one terminal of said secondary winding;

a first capacitor connected in series with said spark gap, one terminal of said capacitor being coupled to the other terminal of said secondary winding;

a second capacitor coupled to said first primary winding;

a DC source of electrical energy;

first circuit means, coupled to said second capacitor and to said first primary winding, for charging said second capacitor from said DC source of electrical energy and for discharging said second capacitor through said first primary winding in timed relation to operation of said engine;

second circuit means for producing an alternating current through said spark gap subsequent to each discharge of said second capacitor through said first primary winding, said alternating current having a frequency f defined by the expression $f = V_m/4N_s\Phi_s$ where V_m is the instantaneous maximum voltage across said first capacitor, N_s is the number of turns in said secondary winding and Φ_s is the magnetic flux within said secondary winding when said ferromagnetic core of said ignition coil is magnetically saturated.

5. An ignition system according to claim **4** wherein said second circuit means includes an oscillator controlled by said first circuit means, said oscillator being coupled to said second primary winding to cause an oscillatory current to flow through said second primary winding subsequent to each discharge of said second capacitor through said first primary winding.

6. An ignition system according to claim **5** wherein said alternating current through said spark gap, during at least a portion of the the time it exists, has a frequency equal to the frequency of said oscillatory current in said second primary winding.

7. An ignition system according to claim **6** wherein said alternating current through said spark gap has a frequency greater than **17** KHz.

8. An ignition system according to claim **6** wherein said oscillator has an output frequency in the range from **17** to **35.7** KHz.

9. In combination with an internal combustion engine, a capacitor discharge ignition system, which comprises:

an ignition coil having a primary winding, a secondary winding and a ferromagnetic core about which said windings are wound;

a spark plug having electrodes spaced to form a spark gap, one of said electrodes being coupled to one terminal of said secondary winding;

a first capacitor connected in series with said spark gap, one terminal of said first capacitor being coupled to the other terminal of said secondary winding;

a second capacitor coupled to said primary winding;

a DC source of electrical energy;

a first circuit means, coupled to said second capacitor and to said primary winding, for charging said second capacitor from said DC source of electrical energy and for discharging said second capacitor through said primary winding in timed relation to operation of said engine;

second circuit means, coupled to said primary winding, for producing an oscillatory current in said primary winding for a predetermined time interval subsequent to each discharge of said second capacitor through said primary winding;

the discharge of said second capacitor through said primary winding and the subsequent production of said oscillatory current in said primary winding producing, for at least a portion of said predetermined time interval, a voltage in the secondary circuit of ignition coil which oscillates at a frequency defined by the expression $f = V_m/4N_s\Phi_s$ where V_m is the instantaneous maximum voltage across said first capacitor, N_s is the number of turns in said secondary winding, and Φ_s is the magnetic flux within said secondary winding when said ferromagnetic core of said ignition coil is magnetically saturated.

* * * * *