Feb. 6, 1968 J. G. W. BOM ET AL 3,367,313

DEVICE FOR PRODUCING HIGH-VOLTAGE PULSES

Filed March 17, 1965

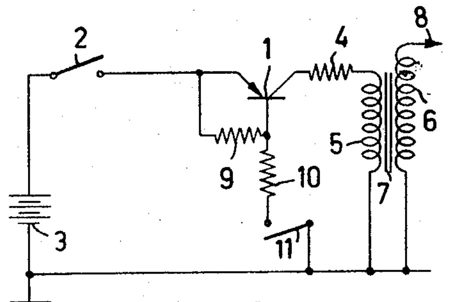

FIG.1

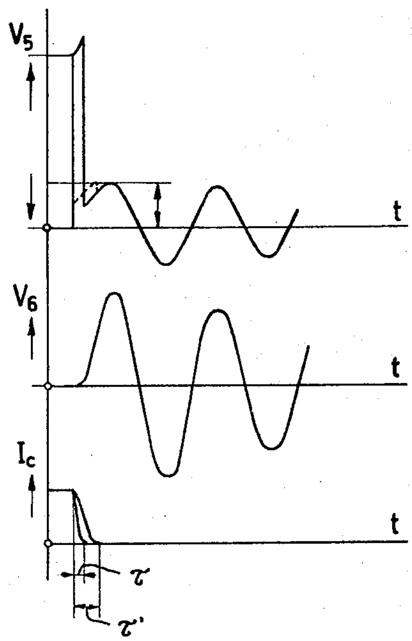

FIG.2

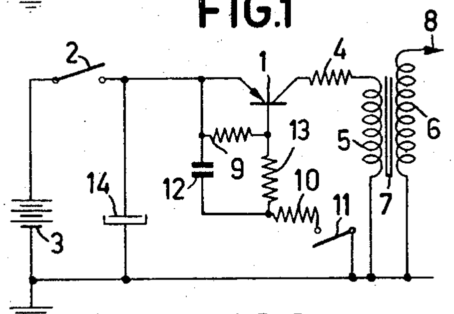

FIG.3

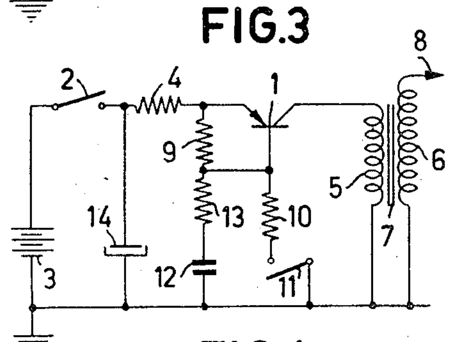

FIG.4

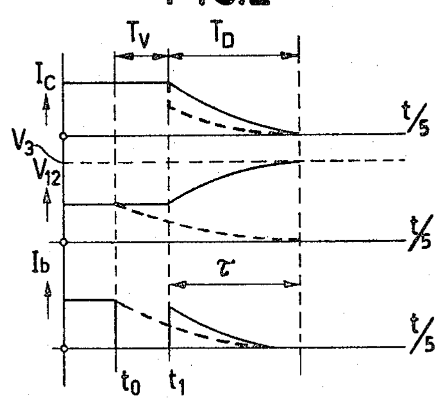

FIG.5

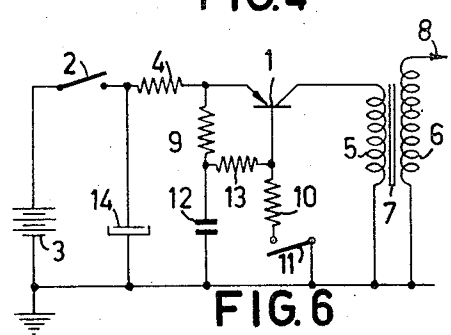

FIG.6

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# United States Patent Office

3,367,313

Patented Feb. 6, 1968





3,367,313


## DEVICE FOR PRODUCING HIGH-VOLTAGE PULSES


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Filed Mar. 17, 1965, Ser. No. 440,578
Claims priority, application Netherlands, Mar. 17, 1964, 64—2,796
7 Claims. (Cl. 123—148)



### ABSTRACT OF THE DISCLOSURE

A transistor ignition system for an internal combustion engine includes an engine-driven switch connected in the base circuit of the transistor so as to interrupt current flow in the primary winding of an ignition coil connected in the emitter-collector circuit of the transistor. An RC network connected to the base electrode and a resistor in series with the emitter electrode cooperate upon opening of the switch to maintain a flow of base current thereby to prevent high voltage surges across the transistor during the turn-off period.


This invention relates to devices for producing high-voltage pulses, more particularly to an ignition system for an internal combustion engine.

It is common practice to produce pulses for igniting a combustion engine by abruptly interrupting the current flowing through the primary winding of a transformer, usually referred to as an "ignition coil." The mechanical interruptor driven by the combustion engine is then loaded so heavily that the surfaces of its contacts are readily damaged and its life is comparatively short.

It has previously been suggested to produce the high-voltage pulses with the aid of one transistor or a plurality of transistors connected in series, the base current or currents of which is or are interrupted and the collector circuit or circuits of which includes or include the primary winding of a step-up transformer. The transistor or transistors is or are controlled by the interruptor, or an equivalent source of control pulses, which then switches only the comparatively very small base current of the transistor, so that the contacts of the interruptor are substantially not loaded and cannot be damaged by the sparks produced upon interruption of a strong current flowing through an inductive load.

However, devices of the kind above described involve the disadvantage that, although the voltage to be switched (for example, that of a 6 volt battery used in a motor car) is much less than half the maximum collector-emitter or collector-base voltage permissible for the transistor employed, nevertheless the transistor is damaged or deteriorated by switching. This has been found to be due to a comparatively very high and short voltage peak produced upon abrupt interruption of the current flowing through the primary circuit of the ignition coil. The secondary circuit of this coil usually constitutes an under damped resonant circuit which is shock excited by interruption of the direct current flowing through the primary circuit. Thus damped oscillations are produced in the resonant circuit and these oscillations are of course transformed into the primary circuit of the coil.

Due to the imperfect coupling between the primary and secondary circuits ($k<1$), an additional phenomenon also occurs in the primary circuit: as the direct current



flowing through the primary circuit is switched off a voltage peak having an amplitude approximately equal to

$$\frac{(1-k^2)L_1I_1}{\tau}$$

appears across the said circuit, wherein $k$ is the above-mentioned coupling factor between the primary and secondary circuits, $L_1$ is the inductance of the primary winding of the ignition coil, $I_1$ is the value of the direct current flowing through the primary circuit being interrupted, and $\tau$ is the switching-off time which elapses from the instant when the direct current through the primary circuit starts to decrease until it has fallen off from its maximum value to zero.

This formula holds good for the case where the direct current flowing through the primary circuit decreases linearly with time. From this it may be concluded that, for the usual value of $I_1$ and even for the smallest possible value of $L_1$, with $k$ less than unity and low values for $\tau$, very high voltage peaks may occur, which, when using transistors, may damage same. In the majority of cases, $k$ lies at most between 0.9 and 0.95, $L_1$ cannot be made arbitrarily small and $I_1$ must be chosen in accordance with the energy required in the secondary circuit.

$\tau$ is normally equal to the recovery time of the transistor, that is the time which elapses from the instant when the transistor departs from its saturated state due to the dissipation of the excessive charge carriers stored until its emitter current and/or collector current has decreased substantially to zero due to exhaustion of the charge carriers stored. A possible solution of the problem just described consists therefore in the use of a transistor having a recovery time such that, while avoiding dangerously high values for the voltage variation $dV/dt$, the amplitude of the voltage peak produced across the primary winding of the ignition coil by interruption of its collector current is smaller than the maximum collector-base and/or collector-emitter voltage permissible for this transistor, and is preferably also at most equal to the amplitude of the damped oscillation voltage across the secondary winding of the ignition coil transformed across the primary winding thereof.

However, the condition to be fulfilled for this solution is by no means always satisfied since the transistor must also be capable of fulfilling other requirements, more particularly with regard to the collector current flowing through the primary winding of the ignition coil in the no-load condition and the maximum dissipation permissible. Each time the transistor is switched off, a power is dissipated in it which is proportional to the time integral over the switching-off time $\tau$ of the product of the collector current and the collector-emitter voltage. The transistor has to dissipate substantially the sum of the losses corresponding to the no-load current and of these switching-off losses which increase with the switching-off period $\tau$ and with the pulse-recurrence frequency. The recovery time of the majority of transistors usable with regard to the maximum permissible no-load current and dissipation is too short, more particularly in the case of switching transistors for computers and similar uses, or too long, for example, in the case of low-frequency power transistors.

The recovery time of a transistor may, of course, be lengthened in a very simple manner by increasing its collector-base capacitance by means of a small capacitor, but this step would increase the value of the capacitance active across the primary winding of the ignition coil, which is undesirable, and also cause a negative feedback coupling of the collector-base voltage which would strongly counteract the control of the transistor by the interruptor.

The use of a collector-base capacitor is undesirable because of the said two effects since it unduly attenuates the pulses produced across the secondary winding of the ignition coil.

The same disadvantage of a decrease of the natural frequency of the emitter-collector circuit of the transistor, which includes the primary winding of the ignition coil, and of attenuation of the pulses produced, also applies for the case where a capacitor is included between the collector and the emitter of the transistor.

United States Patent 3,087,090 shows and describes a network comprising a capacitor in series with a resistor, of the kind referred to hereabove, and which is connected in parallel with the base-emitter path of the transistor, said capacitor and resistor having values such that, after interruption of the base circiut of the transistor, its base current decreases continuously to zero at a given rate.

However, in spite of the said network, there remains a comparatively small discontinuity in the decrease of the collector current at the instant when the transistor leaves its saturated condition, and this discontinuity can suffice to produce, across the highly inductive load, voltage peaks capable of destroying the transistor.

An object of the invention is to provide an advantageous solution of this difficulty.

The device according to the present invention is characterized in that a first resistor is included in the emitter circuit of the transistor and the capacitor is connected between its base and a source of forward voltage, a second resistor being included between the emitter and the terminal of the capacitor connected to the base of the transistor, so that, upon interruption of the base circuit of the transistor, its base current first becomes zero and, after the excessive free charge carriers have disappeared from the base zone, increases to a given value and then again decreases continuously to zero within a determined time interval. As a result, the collector current of the transistor decreases continuously substantially to zero within said time interval.

In order that the invention may be readily carried into effect, it will now be described in detail, by way of example, with reference to the accompanying diagrammatic drawing, in which:

FIGURE 1 is the circuit diagram of a known device of the kind defined in the preamble;

FIGURE 2 shows voltage and current-time diagrams serving to explain the difficulties arising with this device;

FIGURE 3 is the circuit diagram of an improved device in accordance with U.S. Patent 3,087,090;

FIGURE 4 is the circuit diagram of an embodiment of the device according to the invention;

FIGURE 5 shows voltage and current-time diagrams serving to explain the operation of this embodiment; and

FIGURE 6 is the circuit diagram of a modification of the embodiment of FIGURE 4.

The circuit diagram of FIGURE 1 relates to a known device for producing high-voltage pulses, for example, pulses for igniting a combustion engine. This device comprises a switching transistor 1, for example, of the type Philips AU 101, the emitter of which is connected through an on-off switch **2** to the positive terminal of a direct voltage source **3**, for example, a 6 volt storage battery.

The negative terminal of source **3** is connected to ground and the collector circuit of transistor **1** includes a resistor **4** of, for example, 0.3 ohm in series with the primary winding **5** of a step-up transformer, for example, an ignition coil. The said transformer has a secondary winding **6** having a number of turns equal to, for example, 250 times that of its primary winding **5**, and a core **7**. The terminal of winding **5** remote from the collector of transistor **1** is connected to ground, as is one of the terminals of winding **6**. The other end of winding **6** is connected to an output terminal **8**.

The base of transistor **1** is connected to its emitter through a resistor **9** of, for example, 15 ohms and to ground through a resistor **10** of, for example, 13.6 ohms and a switch **11**, for example, the interruptor of a gasoline engine. If the high voltage produced at the output terminal **8** is used for igniting a combustion engine, the said terminal is connected alternately, through the igniting-voltage distributor of the engine, to the spark plugs of its various cylinders.



When switch **2** is closed, transistor **1** remains cut off if switch **11** is open since its base then has the same potential as its emitter. When switch **11** is closed, a current of about 0.44 amp flows through resistor **10**, of which 0.4 amp flows through the base-emitter path of transistor **1** and about 0.04 amp through resistor **9**. Under these conditions transistor **1** is saturated and the current flowing through its collector circuit is limited only by the resistor **4** and the resistance (for example 0.3 ohm) of the winding **5**, the said current being from 8 to 10 amps.

When switch **11** is opened the base current $I_b$ of transistor **1**, and hence its collector current $I_c$ is interrupted. Due to this interruption the oscillating circuit formed by the secondary winding **6** and the load connected thereto, for example, a distributor, a spark plug and the corresponding connecting cables, is excited at its natural frequency of, for example, 2500 c./s., and a damped alternating voltage pulse $V_6$ appears across the winding **6** as shown on the second line of FIGURE 2. Said alternating voltage also appears, stepped down with the winding ratio of 250:1, across the primary winding **5**. Due to the interruption of the current a voltage pulse $LdI/dt$ is also set up across the primary winding **5** and added to the voltage $V_6$ transformed to the primary side. Whereby L is the inductance active in the primary circuit or stray inductance $L_5$, which in turn is equal to $(1-k^2)L_1$, wherein $L_1$ is the primary inductance and $k$ is the coupling factor between the primary and secondary windings. The amplitude of the said voltage pulse is approximately equal to

$$\frac{(1-k^2)L_1 \times I_c \max}{\tau}$$

wherein $I_c$ max is the value of the interrupted collector direct current and $\tau$ is the switching-off time, that is to say the time interval which elapses from the instant when the collector current starts to decrease to the instant when it has fallen off substantially to zero. A linear decrease of collector current $I_c$ with time is assumed for the sake of simplicity.

The inductance $L_1$ cannot be made arbitrarily small and neither can the coupling factor $k$ be made substantially equal to unity. On the other hand, the value for $L_c$ max is prescribed by the energy of the desired high voltage pulses and the value for $\tau$ is determined by the recovery time of transistor **1**, so that this first peak of the voltage $V_5$ (FIGURE 2) across the primary winding **5** may become dangerously high for transistor **1**.

An additional damping of the secondary oscillating circuit including the winding **6** would considerably reduce the high voltage produced, which is undesirable, and would have substantially no influence on the objectionable initial peak across the primary winding **5** since the voltage $V_6$ increases as 1 cos $\omega t$ during the time $\tau$ and is thus still very small.

An additional damping of the primary circuit including the winding **5** and/or a reduction of the natural frequency of the said circuit would indeed reduce the initial peak but would also equally reduce the amplitude of the approximately sinusoidal component of the primary voltage $V_5$ and hence that of the secondary voltage $V_6$, which is again undesirable.

The optimum solution would be an increase of $k$ because no voltage peak would occur with a coupling factor $k=1$. However, it is difficult to exceed a value of 0.93 for $k$, especially in the case of an ignition coil having a very high ratio between the numbers of turns of the secondary and primary windings.

The described difficulty can be partially overcome if, as shown in FIGURE 3, a network comprising a capacitor **12** in series with a resistor **13** and, if necessary, a resistor **9**, is connected in parallel with the base-emitter path of transistor **1**. The components of said network have values such that, after the base circuit of transistor **1** has been interrupted by the switch **11**, its base current decreases continuously to zero at a given rate.

In the device of FIGURE 3, the capacitor **12** is included between the emitter of transistor **1** and that end of resistor **10** which is adjacent the base of this transistor. The resistor **13** is connected between the common point of the base of transistor **1** and the resistor **9** and the common point of the capacitor **12** and the resistor **10**. The capacitor **12** has a value of, for example, 0.68 $\mu$f. and the resistor **13** has a value of, for example, 5.7 ohms. The value of resistor **10** is reduced by approximately the same value to 8 ohms.

If switch **11** is opened at the instant $t_0$ with switch **2** closed, the base current $I_b$ of transistor **1** is not interrupted immediately, but decreases approximately in accordance with the voltage curve of FIGURE 5 due to the discharge of capacitor **12** through resistor **13** and the base-emitter path of transistor **1**. The voltage $V_{12}$ across capacitor **12** then decreases in accordance with the voltage curve shown in broken line in FIGURE 5. At the same time, the collector current $I_c$ of transistor **1**, due to the saturation by charge carriers stored in its base zone, does not decrease, or decreases only very slightly, for the time being and during a storage period $T_v$.

At the instant $t_1$ when transistor **1** comes out of its saturated condition, its collector current decreases to a value corresponding to the instantaneous voltage across capacitor **12** and to the value of resistor **13**, hence to its instantaneous base current. Thereafter the collector current decreases continuously substantially to zero (that is the value of its leakage current). The duration of this recovery period is largely determined by the time constant of the network **12** and **13** and by the ratio of the resistors **10** and **13** which determines the initial value of the voltage $V_{12}$ across capacitor **12**. In a device realized in practice, the period of the oscillations produced across the secondary winding **6** was 400 $\mu$sec. and it was found that the initial peak across the primary winding **5** became smaller than the amplitude of the oscillation voltage, stepped down to this primary winding, as soon as the recovery period $T_D$ became longer than 0.04 times the said period, that is to say longer than 16 $\mu$sec.

If the transistor **1** employed has a comparatively long storage time, $T_v=t_1-t_0$, for example, 10 microseconds or longer, its base current $I_b$ and the voltage $V_{12}$ (FIGURE 5) across capacitor **12** have already considerably decreased at the instant when the said transistor comes out of its saturated condition due to dissipation of excessive charge carriers. This results in an abrupt decrease of its collector current from the saturation value to the value corresponding to the instantaneous value of its base current. If this abrupt variation in collector current has a sufficient amplitude, a high initial voltage peak across the primary winding **5** results therefrom, as well as from too abrupt a decrease in collector current due to an unduly short recovery period $T_D$.

According to the invention, this difficulty may be overcome with transistors having a long storage time $T_v$ by including, as shown in FIGURE 4, the small resistor **4** in the emitter circuit of transistor **1** and by connecting capacitor **12** between the end of resistor **9** which is adjacent the base of this transistor and ground. Depending upon the voltage of the source **3**, the capacitance of capacitor **12**, the no-load values of the collector and base currents, the values of the other resistors **4**, **9** and **10**, the storage and recovery periods $T_v$ and $T_D$ of transistor **1** and the desired switching-off time $\tau$, the resistor **13** of FIGURE 3 then can be connected in series with the capacitor **12**, as shown in FIGURE 4, or be completely omitted, or be connected between the common point of resistor **9** and capacitor **12** and the base of transistor **1**, as shown in FIGURE 6. In FIG. 4, the emitter-collector circuit of transistor **1** and the primary winding **5** are connected in series between a pair of terminals. The first terminal of the pair is the common junction between resistors **4** and **9** and the emitter of transistor **1**. The second terminal is the ground lead. The emitter-base circuit of transistor **1** is serially connected with resistor **10** and engine driven switch **11** between said terminals. An RC network including resistors **9** and **13** serially connected with capacitor **12** is also connected between the pair of terminals, and therefore in parallel with the last mentioned serial connection including switch **11**. A battery **3**, ignition switch **2** and a resistor **4** are also connected in series between the pair of terminals. The base of transistor **1** is connected to the junction of resistors **9** and **13** so that the emitter-base circuit of the transistor forms part of the capacitor charge path.

If switch **2** is opened with switch **11** closed, the current flowing through the winding **5** is abruptly interrupted notwithstanding the presence of the network comprising capacitor **12** and resistor **13**, and this sets up a high countervoltage across the winding **5**.

Although this interruption occurs only incidentally and not continuously and at a high recurrence frequency, a single interruption in certain cases suffices to damage the transistor **1**. This is prevented by a capacitor **14** of, for example, 300 $\mu$f. included between ground and that contact of switch **2** which is remote from the source **3**. When switch **2** is opened the current flowing through the winding **5** slowly decreases due to discharge of the capacitor **14** through the said winding, the resistor **4** and the emitter-collector path of transistor **1**.

In a device realised in practice in accordance with the diagram of FIGURE 4, the transistor **1** was of a type having a storage time of approximately 10 $\mu$sec. The source **3** had a voltage of 6 volts. The transformer **5**, **6**, **7** was again an ignition coil having a coupling factor

$$k=0.93$$

a primary resistance of 0.3 ohm, a transformation ratio $n_6/n_5$ of 250 and a secondary natural frequency (with the distributor and spark plugs connected) of 2.5 kc./s. The capacitor **12** had a capacitance of 0.56 $\mu$f., the resistors **4**, **9**, **10** and **13** had values of 0.4, 15, 2.7 and 0 ohms respectively and the capacitor **14** again had a capacitance of 300 $\mu$f.

The operation of the circuit arrangement of FIGURE 4 will now be described with reference to the curves shown in full lines in FIGURE 5.

At the instant when switch **11** is opened the capacitor **12** is charged to a voltage equal to $I_b \times R_{10}$, its positive electrode having a potential equal to that of the base of transistor **1**. The base current $I_b$ of transistor **1** is thus interrupted almost immediately, whereas its collector current $I_c$, and hence also its emitter current, remains substantially unchanged during the storage time $T_v$, from $t_0$ to $t_1$, due to the charge carriers stored in the base zone of the transistor. At the instant $t_1$ the transistor **1** comes out of its saturated condition and its collector current would tend abruptly to decrease to a value corresponding to a changed value of its base current. Since the potential of the base is also determined by the charge of capacitor **12**, and the potential of the emitter depends on the voltage drop across resistor **4**, any decrease in the collector current $I_c$ and in the emitter current causes an increase in the forward emitter base voltage. Thus a comparatively small decrease in collector current causes a comparatively large increase in the base current which fairly suddenly reaches a comparatively high value again. Thereafter, the capacitor **12** is charged comparatively slowly during the recovery time $T_D$, up to the voltage of the source **3** and via the resistor **4**, the resistor **9** in parallel with the emitter-base path of transistor **1**, and the resistor **13**. The charging time constant is substantially equal to

$C_{12}[(\alpha'+1)(R_4+R_e)+R_b+R_{13}]$ wherein $C_{12}$ is the capacitance of capacitor **12**, $\alpha'$ is the base-collector current amplification factor of transistor **1**, $R_e$ and $R_b$ are its emitter and base-electrode resistances, and $R_4$ and $R_{13}$ are the values of the resistors **4** and **13**, respectively.

The base current of transistor **1** constitutes the main portion of the charging current of capacitor **12** and hence decreases with the voltage difference $V_3-V_{12}$. The collector current also decreases approximately in proportion with the base current.

The modification shown in FIGURE 6 operates similarly to the embodiment of FIGURE 4 except that the resistor **9** is connected in parallel with the series-combination of the emitter-base resistance $(\alpha'+1)\ R_e+R_b$ of transistor **1** and of resistor **13**, thus exerting a stronger influence on the charging time-constant of capacitor **12**, the more so as the sum of the values of the resistor **9** and **13** of FIGURE 6 will have to be approximately equal to that of the resistor **9** of FIGURE 4, for example, 15 ohms. However, this influence, which is undesirable per se, reduces the differences in switching-off times occurring with different transistors, more particularly, with different transistors of the same type.

It will be evident that other modifications of the embodiment of FIGURE 4 are possible within the scope of the invention.

What is claimed is:

**1.** An electrical ignition system comprising, a pair of terminals, a source of different voltage, an ignition coil having a primary and a secondary winding, a transistor having emitter, collector and base electrodes, means connecting the emitter-collector circuit of said transistor and said primary winding in series circuit between said terminals, an engine-driven switch, means serially connecting the emitter-base circuit of said transistor and said switch between said terminals, an RC network comprising a resistor and capacitor serially connected between said terminals and in parallel with the serial connection comprising said emitter-base circuit and said switch, a second resistor connected to said emitter electrode, means connecting said voltage source in series with said second resistor between said pair of terminals, and means for coupling said base electrode to a junction in said RC network such that the emitter-base circuit of said transistor forms part of the charge path for said capacitor.

**2.** A system as described in claim **1** further comprising a second capacitor, an ignition switch, means connecting said second resistor, said ignition switch and said voltage source in series circuit across said pair of terminals with said second resistor connected to the emitter electrode, and means connecting said second capacitor in parallel across the series combination of the voltage source and the ignition switch and in a series circuit with the emitter-collector circuit of said transistor and said primary winding.

**3.** An electrical ignition system comprising a source of direct voltage, an ignition coil having a primary and a secondary winding, a transistor having emitter, collector and base electrodes, an RC network comprising a series connected resistor and capacitor, a second resistor connected between said emitter electrode and one terminal of said voltage source, means connecting said primary winding between said collector electrode and the other terminal of said voltage source, an engine-driven switch, means connecting said switch between said base electrode and said other terminal of the voltage source, means connecting said RC network between said base electrode and said other terminal of the voltage source, and a third resistor connected between said emitter electrode and the terminal of said capacitor closest to the base electrode.



**4.** A system as described in claim **3** further comprising a second switch means connecting said second switch in series with said voltage source between said second resistor and said primary winding, a second capacitor, and means connecting said second capacitor in shunt with the series combination of said second switch and said voltage source.

**5.** An electrical ignition system comprising a source of direct voltage, an ignition coil having a primary and a secondary winding, a transistor having emitter, collector and base electrodes, means connecting said emitter electrode to a first terminal, means connecting the emitter-collector circuit of said transistor and said primary winding in series circuit between said first terminal and a second termnial, an engine-driven switch, means connecting the emitter-base circuit of said transistor in series circuit with said switch between said terminals, an RC network comprising a series connected resistor and capacitor connected in that order between said base electrode and said second terminal, a second resistor connected between said first terminal and one terminal of said voltage source, means directly connecting the other terminal of said voltage source to said second terminal, and a third resistor interconnecting said emitter and base electrodes.

**6.** A system as described in claim **5** wherein said third resistor and said series connected resistor and capacitor are connected in series circuit between said first and second terminals in the order named, the junction between said third resistor and said series connected resistor being connected to said base electrode.

**7.** A system as described in claim **5** wherein said third resistor is connected between the emitter electrode and the junction formed between said series connected resistor and capacitor.


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J. HEYMAN, *Assistant Examiner.*

## UNITED STATES PATENT OFFICE

# CERTIFICATE OF CORRECTION

Patent No. 3,367,313 February 6, 1968

Johannes Gerardus Wouterus Bom et al.

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 4, line 49, "$L_c$" should read -- $I_c$ --.

Signed and sealed this 3rd day of March 1970.

(SEAL)
Attest:

Edward M. Fletcher, Jr.
Attesting Officer

WILLIAM E. SCHUYLER, JR.
Commissioner of Patents