ELECTRONIC IGNITION SYSTEMS

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Design considerations and operating characteristics of both the capacity discharge and the standard transistor ignition circuits. Comparison is made with present conventional system.

OUR advancing semiconductor technology has given us devices capable of handling the high voltages and currents required in automotive ignition circuits. Up until now, we had a choice of two different ignition circuits: the 1928 Kettering system, which is still standard on all cars, and the magneto. The magneto is still considered to be the best of all available systems, however, the price ($250 up) puts it out of the range of all but the most serious racing enthusiasts. Because of its limited application, the magneto system will not be discussed here. This leaves three basic practical circuits which will be considered: the conventional system; the transistor ignition; and the newest and perhaps most promising, the capacitive-discharge system.

First, however, we should clearly understand just what each of these circuits must do and how it does it.

Voltage Requirements

Essentially, we are concerned with producing "spark" to the spark plugs, using only the 6 or 12 volts available from the car's battery. We wish to amplify battery voltage to the potential necessary to ionize the gas between the spark-plug electrodes, thus producing the spark necessary to ignite the charge in the cylinders. This problem is further complicated by the fact that we must use direct current.

Fig. 1 shows the ionization potential of air *versus* the product of pressure × distance apart of the electrodes (pressure in millimeters of mercury × distance in cm). However, we are interested in a mixture of vaporized gasoline and air—not air alone. We can approximate this effect by increasing the voltage required in Fig. 1 by 20 percent. This factor is considered an average value since the gasoline-to-air mixture ratio varies from 1:10 to 1:18 with 1:16 being considered the ideal value. However, 20 percent is a reasonable factor. From Fig. 1, we see:

$$V \approx C\ Pd \text{ (in dry air)} \dots\dots\dots\dots\dots\dots (1)$$

where C is some constant, for $Pd > 10$ mm Hg × cm. Whereas for our purposes:

$$V = a\ C\ Pd \dots\dots\dots\dots\dots\dots\dots\dots (2)$$

where $a = 1.2$ to take into account the 20% figure mentioned above for the gasoline and air mixture.

Temperature has the effect of reducing the required voltage but we can neglect any beneficial effect since we intend to approach the problem as a worse-possible case.

Frequency, in this case engine rpm, has no effect on the output potential required.

Typical spark electrode gap settings will vary from 0.025 to 0.035 inch. We shall consider an air gap of 0.040 inch for a worst-possible case.

Pressure is the next point of concern. Since the spark must be excited when the piston is at or very near the top of its compression stroke, typical compression ratios must be considered. They can vary from 7:1 to 13.5:1 with 16:1 being considered the maximum since charge detonation at

these high pressures exhibits a sort of "diesel" effect. This sounds good but actually is not because it means that the engine would fire at 0 degrees advance (the very top of its compression stroke) and would not allow sufficient time for the charge to burn completely. For this very reason an automatic advancing mechanism is built into every engine and this senses the amount of advanced firing necessary to produce maximum horsepower at any engine speed.

Since about 90% of all cars have compression ratios between 8:1 and 9:1 we will arbitrarily choose 10:1 as our value.

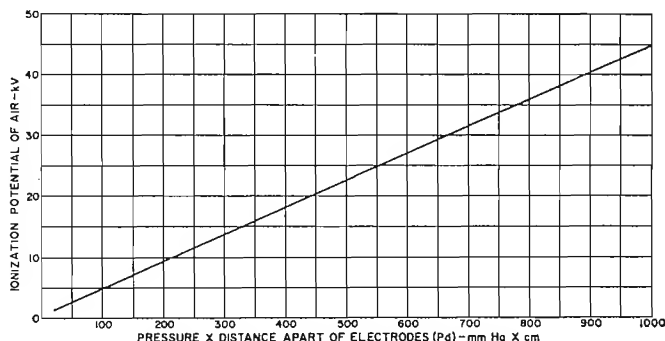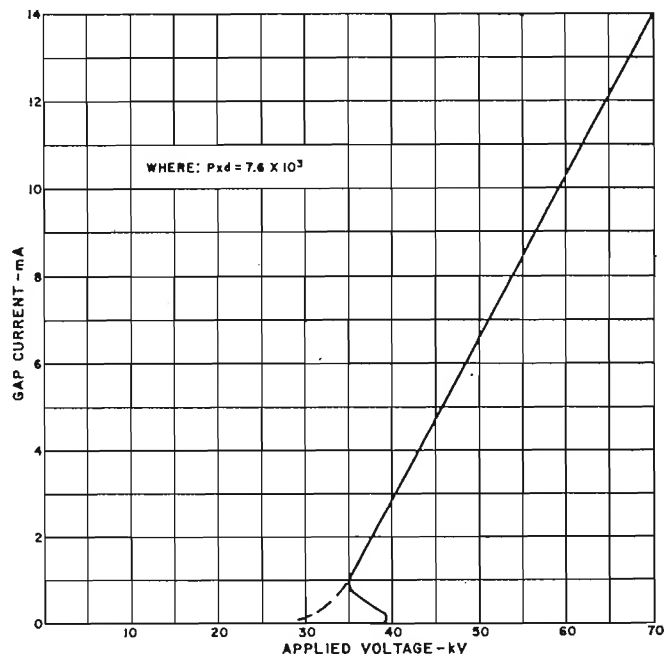With these two assumptions, from Fig. 1 we find that it

Fig. 1. Ionization potential of dry air rises with an increase in the pressure and the separation of the electrodes.

Fig. 2. The current in the air gap increases linearly above the voltage potential at which arcover condition takes place.

takes about 40 kV to operate the spark plugs. This 40 kV should be considered a minimum requirement. To assure complete combustion, this value should be exceeded if possible. Theoretically the more molecules of gas ionized, the greater the probability of complete combustion. At a given $P \times d$, current is proportional to the number of ionized molecules. Fig. 2 shows typical I-V characteristics of an air-gap discharge for a constant $P \times d$ of 7.6×10^3.

Let us look at the basic circuits to be considered.

Ignition-Coil Function

There are two ways to use an ignition coil to produce high-voltage pulses. First is the rate-of-change of current, or inductive mode, and the second is the transformer mode. The circuits shown in Figs. 3A and 3B use the first means mainly, while the circuit of Fig. 3C uses the second. The principal functional difference between the conventional system and the transistor system is that the latter is capable of switching higher currents.

Obviously both have limitations. Our purpose is to analyze circuit operation and determine whether or not circuit limitations occur at some point well beyond the maximum practical operating point of the car's engine.

In the transformer mode, the coil performs only one function—that of a voltage amplifier. However, the inductive mode requires two coil properties to produce high voltages: it must inductively "create" a high primary voltage and then amplify this self-induced voltage by transformer action. The amplification factor is common to both modes.

The voltage amplification factor is given by:
$$V_{out} = k \times V_{in}\, N1/N2 \dots\dots\dots\dots\dots\dots\dots (3)$$
where: V_{out} is the output or secondary voltage; V_{in} is the input or primary voltage; $N1$ is the number of secondary turns; $N2$ is the number of primary turns; and k is the coefficient of coupling, a figure of merit relating to the coil's efficiency. Its maximum value is 1. With almost all coils and transformers, it is fairly safe to assume that $k = 1$.

Most engineers agree that 30 millijoules of energy must be stored in an ignition coil to fire the spark plugs reliably. This figure should be kept in mind when comparing the different systems.

A current is passed in the primary of the coil and then the current flow is interrupted abruptly. This creates a short-duration inductive voltage of from 100 to 300 volts, depending on the inductance of the coil itself and the amount of current being switched. This voltage is coupled,

via the core flux, to the secondary of the coil and thence to the spark plug in the form of a high-voltage pulse. This method is simple and reliable, but less efficient, typically 15 to 50% less. In this mode energy is given by:
$$W = (\tfrac{1}{2})\, LI^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4)$$
where: W is energy in watt-seconds (joules); L is inductance in henrys; and I is current in amperes.

Here we sense the problem. We cannot have both high inductance and high current simultaneously since high inductance requires more turns of wire, with its attendant resistance. Also, it is easy enough to store 30 millijoules in the coil at low frequencies, but it becomes more difficult as the engine rpm is increased.

For convenience in making calculations, assume the following: battery voltage, 12 V negative ground; engine, 8 cylinders, which has four firing pulses per revolution; operating range, "cranking" speed to 6000 rpm or 12 to 400 Hz; conventional coil, 100:1 turns ratio, primary inductance 6 to 10 millihenrys; transistor ignition system coil, may vary, but typically 250:1 to 500:1 turns ratio. However, this is not as important as the lower primary inductance of 1 to 2 millihenrys.

The Duty Cycle

The systems shown in Figs. 3A and 3B have two operating conditions: a "on" time and an "off" time. The "on" time is when the distributor points are carrying direct current, i.e., a closed circuit. The "off" time is when the distributor points are an open circuit to the direct current. It is at the beginning of the "off" time that the high-voltage pulse is produced.

The times mentioned above will be designated as t_{on} and t_{off}, respectively. Typically, these times are related as follows.
$$t_{on} = 2t_{off} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$
and
$$t_{cycle} = t_{on} + t_{off} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$
where: t_{cycle} is the duration of one electrical cycle.

This duty cycle is in accordance with almost all auto manufacturers' specifications no matter what the number of cylinders. It corresponds to a dwell or "on" time setting of about 40 degrees for a 6-cylinder engine or 30 degrees for an 8-cylinder engine.

In order to relate these times to the operating ranges, we will use the formula:
$$f = 1/t_{cycle} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (7)$$
where: f is frequency in hertz; t is time in seconds.

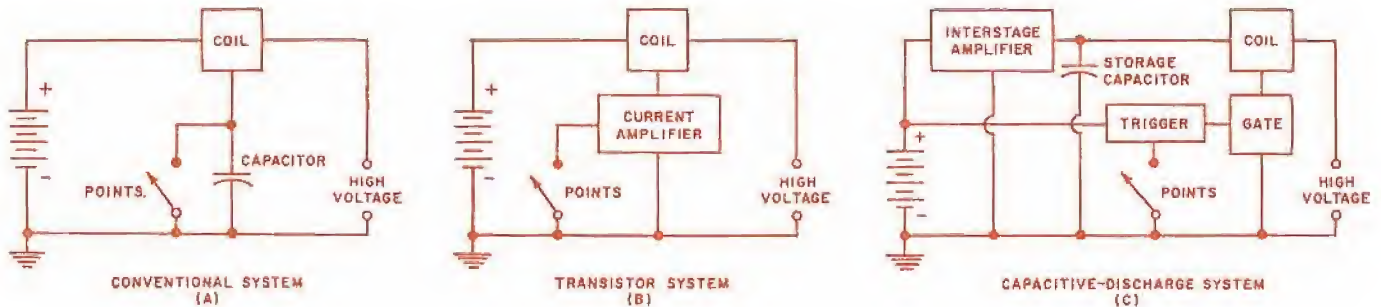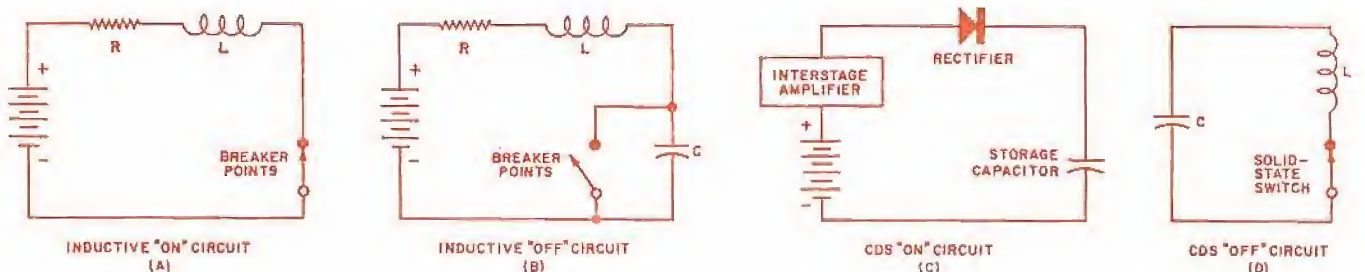To express f for an eight-cylinder engine in rpm:

Fig. 3. Basic circuit arrangements that are employed in the conventional, transistor, and capacitive-discharge ignition systems.

Fig. 4. The "on" and "off" circuits for conventional and transistor systems (A), (B) and capacitive-discharge systems (C), (D).

$$f = rpm/15 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (8)$$

or:

$$rpm = 15\,f \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (9)$$

Now let us examine closely what an induction coil looks like electrically. Since little can be done with the k and turns ratio of the coil (assuming both are reasonable), we can deal with the primary of the coil and the energy that can be stored in it as if it were a simple inductor.

Fig. 4A shows the simplest case of the "on" circuit and Fig. 4B, the "off" circuit.

The time constant for the "on" period is:

$$T_{on} = L/R \quad \dots\dots\dots\dots\dots\dots\dots\dots (10)$$

The time constant for the "off" period is:

$$T_{off} = \sqrt{LC} \quad \dots\dots\dots\dots\dots\dots\dots\dots (11)$$

Actually the "off" period time constant amounts to about one-sixth of one cycle of oscillation of the series resonant circuit and T_{on} is the time constant of the damping factor. R is the total d.c. resistance of the circuit, in ohms; L is the inductance of the coil primary windings, in henrys; while C is damping capacitance, optimized experimentally at 2×10^{-7} farad or 0.2 μF.

System limitations arise during one or both periods.

Let's discuss the "off" cycle first. Keeping eq. 11 in mind, we have found that the optimum t_{off} is about 20 μsec no matter which system is used. A faster system must be damped by addition of some capacitance. Since induced primary voltage is determined from the formula:

$$V_p = L\frac{\Delta I}{\Delta t} \approx L\frac{I}{t_{off}} \quad \dots\dots\dots\dots\dots (12)$$

our first thought would be to turn off a large current as rapidly as possible, since V_p obviously approaches infinity as t_{off} approaches zero. However, this doesn't take into account the coil's ability to transform the voltage as a function of frequency since the coil's efficiency drops off drastically above 50 kHz. Hence, a system which switches much faster than 20 μsec must be damped to about this value by additional capacitance, or suffer a large output loss.

Using the 20-μsec optimum t_{off} in eqs. 7 and 9, we find that we would have to approach 250,000 rpm in order for the established "off" cycle to impair system performance. Thus we can disregard the possibility of t_{off} affecting an actual engine's performance.

Let us next consider the "on" time and its effect on operation. First, we will assign values to the parts in Fig. 4A.

For a typical transistor ignition system (#1), R is 1.2 ohms, L is 1 millihenry, and T_{on} is 0.83 millisecond; for a second typical transistor ignition system (#2), R is 1.2 ohms, L is 2 mH, and T_{on} is 1.67 msec; for an optimized conventional system (#3), R is 2 ohms, L is 6 mH, and T_{on} is 3 msec; for a second optimized conventional system (#4), R is 2 ohms, L is 10 mH, and T_{on} is 5 msec.

Note that systems #1 and #2 are typical transistor-coil circuits with component values equivalent to those you would purchase, i.e., there was no attempt on the part of the author to enhance system performance.

This is not the case with systems #3 and #4. These are conventional systems optimized above their design limitations: they will not perform indefinitely at the V/R value of 6 peak amperes. Excessive heat generated by this current will eventually burn out these systems.

Fig. 5 shows actual current vs time for the four circuits being discussed. From this we can see that insufficient "on" time will impair system performance at the higher engine speeds, especially with the conventional ignition systems #3 and #4. With insufficient time for current build-up to occur, less energy is stored in the coil and the high voltage drops off.

Capacitive-Discharge System

Fig. 3C diagrams the transformer mode in a capacitive-discharge ignition system. In these circuits an intermediate
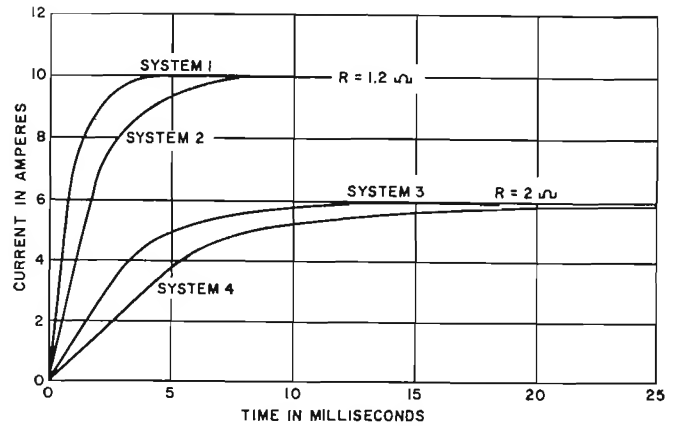

Fig. 5. Current build-up in two transistor ignition systems (1 and 2) and in two optimized conventional systems (3 and 4). Although the transistor systems have faster rise times, even they may prevent optimum engine performance at very high speeds.

stage of amplification charges a storage capacitor to several hundred volts, which is then discharged through the ignition coil primary, thus producing the desired high output voltage. This method is very efficient, typically 75% to 90%, and gives faster rise and fall times than the other methods. However, the cost will be usually about two to three times higher.

Although these systems use many more components, their basic operation is fairly straightforward. The battery voltage is converted into alternating current by means of an oscillator. This a.c. is transformed to several hundred volts, then rectified and stored in the storage capacitor. The points, when open, now trigger a silicon controlled rectifier or gate controlled switch which rapidly discharges the capacitor through the ignition coil primary, producing the spark.

Fig. 6. Coil primary energy should be above 30 millijoules at all times. Note that systems 1 and 2 are transistorized ignitions, while systems 3 and 4 are optimized conventional ignitions. The capacitive-discharge ignition system is shown to produce the same coil primary energy at all engine speeds.
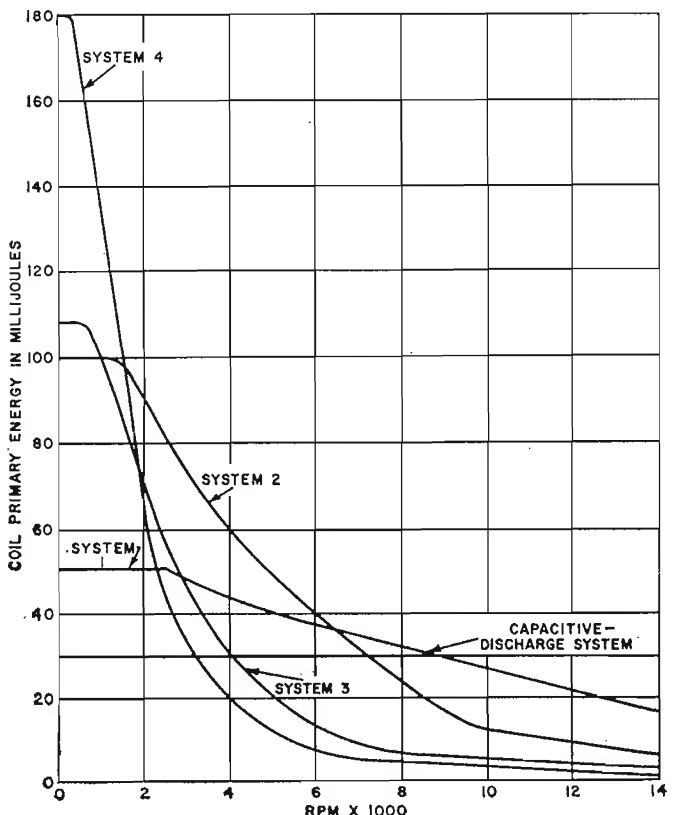
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It is fairly easy to see just why the capacitive discharge system (CDS) is more appealing since the energy is determined by the formula:

$$W = (\tfrac{1}{2}) CV^2 \dots\dots\dots\dots (13)$$

where: W is energy in joules (watt-seconds); C is the storage capacitance in farads; and V is the voltage to which the storage capacitor is charged.

C and V assume quite reasonable values in order to produce the necessary 30 millijoules for the coil primary.

In analyzing the CDS, we again find the two time intervals, t_{off} and t_{on}, having the same relationship as in eqs. 5 and 6. During t_{on} the distributor points are closed while during t_{off} they are open. However, there is a difference between the CDS and two inductive circuits discussed. For a CDS, during t_{on} no current flows through the ignition coil since the trigger input pulse is shunted to ground, keeping the gate turned "off". At t_{off} a positive trigger pulse turns the gate "on", thus discharging the storage capacitor through the ignition coil.

Fig. 4D illustrates t_{off}, while Fig. 4C approximates the t_{on} circuit with the interstage amplifier actually consisting of an oscillator directly coupled to a step-up transformer. In most cases, these transformers are special low-inductance, high-"Q" components since they must operate at frequencies up to several hundred hertz.

Eq. 11 again is the time constant for t_{off}. However, there is little or no damping involved as is the case with the inductive system. For our calculations, we shall keep C constant at 1 μF, although the value of C may vary from 0.33 to 1 μF, depending on the manufacturer's circuit. For L we shall use the upper and lower limits of 10 and 1 mH, respectively. Using these values in the previous equations, we find that the electrical limitations of t_{off} far exceed the engine's operating range. For the 10-mH ignition coil we would have to exceed 50,000 rpm in order for the electronics to impair performance, and for the 1-mH ignition coil, this figure would be 160,000 rpm.

If the ability to discharge C through L is not limited, let's consider the problems of charging C to the required several hundred volts *via* the intermediate stage of amplification. All this must take place during t_{on} as seen in Fig. 4C. The rectifier shown is actually a full-wave bridge. The special transformer permits a maximum effective oscillation frequency of, typically, 400 Hz. Bearing in mind that the stepped-up oscillations are sinusoidal and full-wave rectified, we find that the capacitor reaches maximum voltage, V_{max}, in about one-fourth of a cycle or, in this case, about 0.6 millisecond. Using $t_{on} = 0.6$ msec in the previous equations, we arrive at a value of almost 17,000 rpm before the electronics circuit limits engine operation. This, too, is considerably above practical engine operating speeds.

Most of the CDS circuits used have charge-up oscillations somewhat proportional to rpm, as the oscillations themselves are triggered by the discharge of the storage capacitor. The efficiency of the system is improved since most of the input power is dissipated during capacitor charge-up, *i.e.*, one-fourth of the first oscillation. Subsequent oscillations merely maintain the capacitor's charge. This is not the case with the inductive systems since they constantly draw current during t_{on}.

Finally, Fig. 6 shows the effect of rpm on coil primary energy. Obviously, all systems exceed the two conventional systems #3 and #4 over most of an engine's operating range except for the lowest engine speeds. However, the transistor systems (#1 and #2) are consuming 120 peak watts against the conventional systems (#3 and #4) 72 peak watts. The CDS also requires about 72 watts, but in terms of average power, it draws considerably less. Even 120 watts is not appreciable when compared to the battery's almost 1 kW of available power, and is of even less concern once the engine is started and the generator or alternator is producing the required power. It is interesting to note that conventional system #3 is the optimized version of a system that is standard in a popular American racing car whose engine is designed to operate in the 7000-8000 rpm range.

Fig. 6 leads us to the conclusion that conventional systems do an adequate job up to the 3000-4000 range (65-85 mph for most cars). But remember that these are optimized results. In actual practice, the circuit energy would be about 20 to 50% less than the values shown. Also, by merely increasing the dwell angle, *i.e.*, altering the effective duty cycle, we can improve the transistor ignition system's performance. In this case, we could reasonably switch 12 amperes instead of 10 by reducing R from 1.2 ohms to 1 ohm, thus obtaining an average energy increase of around 20% for the same rpm. This assumes, of course, that the switching transistor and coil can handle the added current.

The CDS offers efficiency as well as performance. There seem to be only two drawbacks. Initial expense may run two to three times that of transistor ignition systems and reliability may be less since there are many more components involved. ▲