"The Ignition Coil"

by Tony Cripps

As nearly all BMC owners know, the standard ignition system on our cars consists of points, condenser, coil, distributor, and spark plugs. This highly evolved system was preceded by trembler coil and hot wire methods. As is now well known, in our systems it is the switching action of the mechanical points that induces a high voltage in the ignition coil which is sufficient to create a hot spark at the spark plug inside the cylinder. The distributor itself distributes this spark to the correct spark plug at the correct time in the compression stroke.

However, there are some details about this process that are worth knowing in case of problems and modifications.

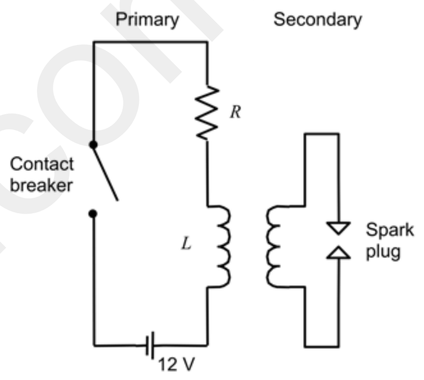

Fig. 1 *Schematic of ignition system*

Faraday's Law

Fig. 1 shows the general arrangement. The whole thing depends upon Faraday's law of induction. This law states that the induced voltage in a coil depends upon the rate of change of current through the coil and the nature (the "inductance") of the coil. So, when the points are closed, current flows from the battery into the primary side of the ignition coil. The rate of change of current during this process depends upon the resistance of the coil, the inductance of the coil, and the voltage applied to the coil.

There is an equation that describes how the current changes in the coil when the points close:

$$i = \frac{V}{R}\left(1 - e^{\frac{-Rt}{L}}\right) \qquad \text{Eq. 1}$$

In this equation, i is the primary current at some time t, V is the 12 V applied to the coil, R is the resistance of the primary, L is the inductance of the coil and "e" (if you were wondering and are still with us) is the base of Naperian logarithms. Having got that out of the way, we can go back to what we really want to know.

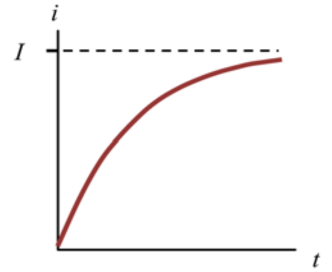

Fig. 2 *Current vs time in the primary side of the ignition coil.*

What this equation tells us is that the current increases over time as shown in Fig. 2. I is the final current reached after a long time.

The initial rate of increase in current is often called the “time constant”. We want the time constant to be fairly short because the points are only closed for a brief time, and if the rate of current increase is too slow, then we will not get a very good build up of current flowing in the primary during the time available that the points are closed. You will see in a moment why this is important. As the rpm of our engine increases, the rate of current rise in the primary has to be even shorter to take into account the even less time that the points remain closed.

So, what determines this *rate* of current rise in the primary? The equation above tells us. By employing a little bit of mathematics, it can be shown that the rate of current increase is:

$$\frac{\Delta i}{\Delta t} = \frac{V}{L} e^{-\frac{R}{L}t}$$
$$@t = 0$$
$$\frac{\Delta i}{\Delta t} = \frac{V}{L}$$

Eq. 2

At t = 0, we get the initial rate of increase. This says that the initial rate of increase is greater when the inductance of the primary side of the coil is low or the applied voltage is high. Essentially what is happening is that the current in the primary creates a magnetic field (much like an electromagnet). In an ignition coil, when this field *changes* (by virtue of the current increasing or decreasing in the primary side), the changing magnetic field induces a voltage in the secondary coil (much like a transformer does). The problem is that we need a fairly large inductance to generate a high voltage in the secondary because the induced voltage in the secondary is given by:

$$V_{\mathrm{sec}} = L \frac{\Delta i_p}{\Delta t}$$

Eq. 3

So, the rate of increase of the primary current is a tradeoff between the coil being made with a low inductance *L* for rapid rise, and a high inductance *L* for a high voltage to be produced at the secondary.

As mentioned above, the second equation tells us that the rate of increase in the primary current depends upon V - the primary side battery voltage (12V). If the battery voltage falls (such as it almost certainly does when the engine is cranked over by the starter motor) the rate of increase in I in the primary also falls.

In the third equation, this secondary voltage V_{sec} is induced when the points close, and again when the points open. However, we only get a spark when the points open because the rate of current increase (or decrease – it is the *change* in current that is important), isn’t large enough when the point close to induce a high enough voltage to cause a spark.

One more thing that needs to be known is that when the current in a coil changes, it rises and falls according to the above equations as a result of an induced opposing voltage (which we customarily refer to as an “emf” (for electromotive force). For example, if we have a “charged” coil (steady current flowing), and then turn the current off, the magnetic field around surrounding the coil starts to collapse. This changing magnetic field induces an emf in the coil so as to try to keep the current flowing in the direction it was before it was turned off. That is, a “forward” emf is produced just from the magnetic field created by the initial current. When a coil is first energised, there is a “back” emf produced which tends to oppose the applied voltage (and this is why the current builds up over time and doesn’t just appear suddenly as soon as the switch is closed). The magnitude of the forward or back emf depends upon the rate of change of current in the coil. The generation of this forward and back emf is known as Lenz's Law.

So, now that we understand the mathematics involved, let's look in detail what happens in our ignition system.

Generating a High Voltage

When the ignition points close, current flows into the primary side of the coil. The primary, being an inductor, opposes this current via the formation of a "back emf" according to Lenz's law. The magnitude of the back emf depends upon the inductance and the dc resistance of the coil, both of which determine the rate of change of current. The result is that the current flow through the primary starts off at a low value (since the rate of change of current is a maximum as the beginning of the process) and rises to a steady state value which ultimately depends upon the dc resistance of the primary coil. The energy of the primary current becomes stored in the magnetic field of the primary within which the secondary coil is also located as it is wrapped around the primary. A high voltage is generated in the secondary coil at this point, but not sufficient to cross the spark plug gap. The ratio of turns of primary to secondary is of the order of 100, and so for a 12 volt system, the induced secondary voltage at the time the points close is only about 100V.

When the coil is fully "charged", the rate of change of current is zero and there is a dc current of several amps flowing through the primary. When the engine is running, this condition is momentary due to the dwell angle of the points but may be continuous if the ignition is turned on, the points closed, and the engine stalled. At this point the current is flowing from the SW terminal into the coil and to the CB terminal to earth (assuming "conventional current flow" and a negative earth system).

When the points open, the current is abruptly interrupted. The magnetic field thus changes (collapses), and since a changing magnetic field induces a current in the coil the induced emf tends to want to keep the primary current flowing (Lenz's law again). The rate of change of current is very high (because the points open suddenly, and there is no "resistor" in the circuit as there was when the points closed). This rate of change of current is opposite in sign compared to the rate of change of current when the coil was being charged. That is to say, a falling current rather than a rising current.

When the points were closed, the back emf opposed the 12 V applied to the SW terminal with this opposing emf occurred in a gradually decreasing manner. The presence of the DC resistance of the primary coil causes this gradual change. Because the opening of the points is very sudden, the rate of change of current in the primary is very high. The "forward" emf is of the order of 200 to 300V and appears at the CB terminal of the coil – which is now no longer connected to earth. The forward emf, sometimes called the "kick" voltage, or the "primary kick", is responsible for a far higher voltage generated in the secondary compared to the case when the points were closing.

We would expect such a large kick voltage to result in arcing of the points. This arcing would act as a kind of resistor (current flows through the arc) and would thus decrease the rate of change of current and limit the magnitude of the secondary voltage. The capacitor is charged by the kick voltage, and this takes time. Time enough for the points to separate so that arcing across the points is much reduced. Because of the capacitor stores the energy which would otherwise be wasted at an arc at the points, the primary current is more abruptly terminated resulting in a larger kick and higher secondary voltage.

Initially, the capacitor is charged with the kick voltage, but when the voltage at the CB terminal reduces (as the magnetic field in the primary becomes weaker as it discharged), the capacitor then discharges current back into the primary (reverse direction to that which occurs when the coil is being “charged” by the voltage at the SW terminal), and as a result, there is a back emf opposing this current and the voltage at the CB terminal rises. This back emf dissipates as the capacitor is discharged, and then the coil now with a new magnetic field (of reduced intensity) discharges again. The result is a series of oscillations at the CB terminal of a diminishing nature and the spark (now established) continues until the oscillations are reduced along the “spark line”, or “burn line”.

As far as igniting the fuel air mixture is concerned, it is the spark at the kick voltage that is the most important. The remaining spark during the spark line does not contribute significantly to combustion of the fuel.

It requires more voltage to initiate a spark at the spark plug than to maintain it since the gases in the spark plug gap have first to be ionised. Once ionised, the gases under dielectric breakdown and the voltage needed to maintain the spark is much reduced. The spark continues until there is no more ionised hydrocarbon gas present to sustain the spark current. The spark at the plug gap continues while the magnetic field diminishes and the oscillations due to the capacitor are reduced. The energy in the magnetic field appears as heat at the discharge at the spark plug gap. After the spark is extinguished, the remaining magnetic field dissipates and the potential at the CB terminal (and thus placed also across the capacitor) thus reduces. When the points finally close, a back emf is produced at the primary SW terminal opposing the battery voltage and the potential at the CB terminal goes negative before slowly rising to zero.

All this occurs over a small fraction of a second but can easily be seen on an oscilloscope. But a warning. An ordinary laboratory oscilloscope is usually not set up to handle hundreds of volts (the kick voltage) even though the coil might be powered by 12V, so you have to use an automotive diagnostic oscilloscope which has the necessary capability to handle this input.

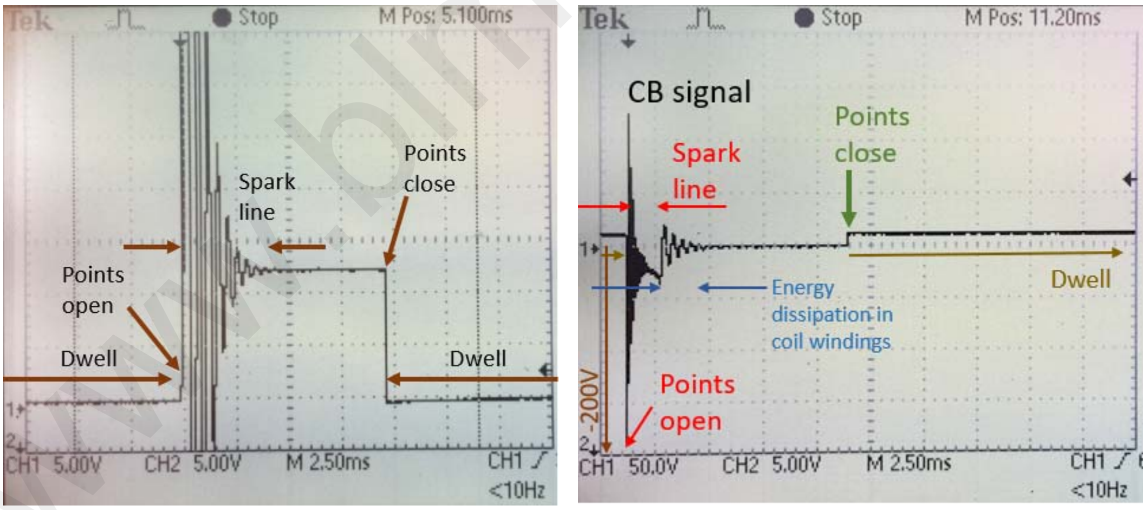

Fig. 3 Voltage waveform at the CB terminal while engine is running. (a) Negative earth configuration

So, what does this mean for us in our BMC cars?

Ballast Resistor:
BMC cars (in Australia) were usually not fitted with ballast resistors that are seen on some inferior makes, but it is worth knowing what they are for. The ballast resistor is placed in series with the primary side of the coil. Its resistance changes with temperature (doubling or tripling its resistance from cold to hot). The resistor is often bypassed by the cranking circuit.

What this ballast resistor does is to make the process of ignition more reliable when cranking a cold engine. In this system, the ignition coil is designed to work on about 8 to 10V. When the starter motor is engaged, the battery voltage drops to about 10 V, and so this is applied directly to the coil. The coil is designed to have an acceptable rate of current rise when 10V is applied to its primary. It does this by having a lower primary resistance in its windings. When cranking stops and the engine is running, the primary current (now passing through the ballast resistor) causes the resistor to heat up and become more resistive, and so the 12 V gets lowered to about 10 V or so for the coil. Thus, the ignition coil operates at about 10 V all the time.

If you use a coil designed for a ballast resistor without the resistor, the 12 V battery voltage will be applied directly across the primary winding and it will become very hot, draw a lot of current, and burn out the points in short order.

Condenser:
The condenser, or capacitor, absorbs the electric shock of the points opening and closing. Without the condenser, the points will burn out from arcing. If arcing occurs, the change in current in the primary will not be so rapid and the production of the required secondary voltage will be impaired – that is, the engine will misfire or just not run at all.

Coil:
Experiments show that the most efficient spark occurs when the centre electrode is negative in polarity with respect to the engine block. The polarity of the spark depends upon the polarity of the voltage applied to the primary terminals. So, it is important (but not absolutely necessary) that the terminals marked “CB” and “SW” (for contact breaker and ignition switch) are correctly connected.

This applies even for a negative earth car. The centre electrode should be made negative with respect to the chassis. Since the secondary voltage (thousands of volts) is far greater than the vehicle’s electrical system (12V), then having the centre electrode more negative than the chassis isn’t a problem.

The coil, as some will know, is filled with oil. The process of induction and current flow in both primary and secondary is not 100% efficient. That is, considerable heat is generated in the coil when it is operating. The oil serves to insulate the windings, provide a method of cooling, and also, assists in contributing to the inductance of the device by virtue of its electrical properties (what is called the oil’s permittivity). You will find that large power transformers are often immersed in oil for the same reasons.

Contact breaker
The action of the contact breaker is essential for good running. The contact breaker has to open and close at the right time, and remain closed for a long enough time for current to build up in the primary, open smartly so that a high voltage is induced in the secondary, and all at high speed. Mechanically, this depends on the profile of the cam lobes in the distributor. The shape of this cam is a compromise between good electrical performance and acceptable insensitivity to variations in contact gap caused by mechanical wear and user skill in setting the gap. In short, one must adhere to the manufacturer’s dwell angle as closely as possible.

Electronic ignition
These days, electronic systems are the norm, and many BMC vehicle owners have fitted such systems to their cars. The simplest, and probably the easiest, is to replace the mechanical points and condenser with a solid state transistor switch. This has the advantage of retaining the original exterior appearance of the distributor. An important point when fitting this system is to apply the white heat conduction compound (that should be supplied with the

kit) to the base of the switch body so that heat generated inside the switch (by the large power transistor contained therein) will not overheat and fail.

Despite being more reliable, and able to be more accurately controlled by a computer, electronic systems still rely on Faraday to induce a spark at the spark plug and so the principles above are still relevant.

After reading all of the above, one gets an appreciation of how many things work together to form a working ignition system that has to cater for a wide range of operating conditions.

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