Modeling Automotive Ignition Systems (Rev. 2)

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Introduction

The work described in this document was motivated by two sources. One is a set of documents by H. Holden [1], describing (among other things) a test machine for measuring spark energy in automotive ignition systems, and the other, by W. Kahan [2], is a description of a simple electronic ignition module. An ignition module based on Kahan's circuit was constructed but was not entirely satisfactory, as the circuit dates from the 1960s and specifies parts (such as germanium transistors) that are no longer available. The closest modern parts were not really equivalent, so the results were not as good as expected. An improved ignition module was based on modern power MOSFETs. That worked well, but the spark energy, relative to an original (Kettering) system, was uncertain. Rather than build a energy-measuring device like Holden's, an attempt was made to compare the spark energies of the conventional and electronic systems from circuit simulation. That effort, described in this document, provided considerable insight on the operation of automotive ignition systems.

The Ignition Coil

The ignition coil is modeled by the equivalent circuit shown in Figure 1. The model consists of a pair of imperfectly coupled inductors, in effect a nonideal transformer; resistors that represent losses; and capacitors that model interwinding capacitance. Resistors R_1 and R_2 represent the winding resistances of the primary (low-voltage) and secondary (high-voltage) windings, respectively, and R_c accounts for core losses. C_1 represents the interwinding capacitance of the primary and C_2 the secondary. We have found this model to be accurate to

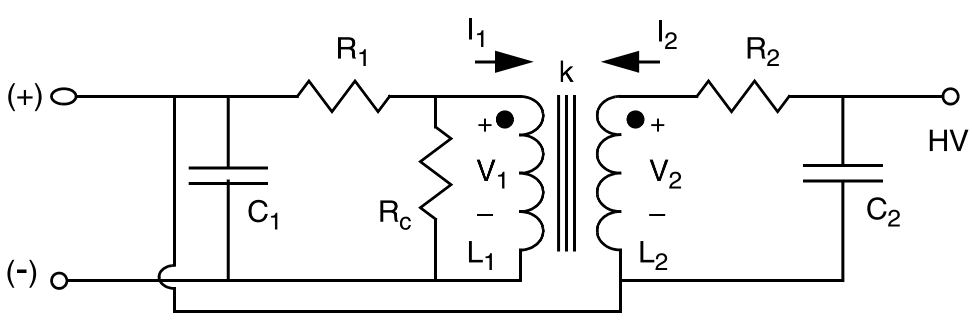

Figure 1. Equivalent circuit of an ignition coil. R_1 and R_2 represent coil resistances, C_1 and C_2 interwinding capacitances, and R_c models core loss.

at least 20 KHz for all the ignition coils we have tested, and it is adequate for transient analysis of an ignition system.

Note the polarity (dot convention) of the windings, and the fact that the high-voltage winding is returned to the positive terminal of the coil's primary, not to ground. In coils originally intended for cars having positive-ground electrical systems, the secondary would logically be returned to the negative (supply voltage) terminal. Today, however, positive-ground cars invariably use coils designed for negative-ground electrics, with the primary polarity reversed, so the secondary current is returned via the capacitor. Either way, the winding polarity guarantees that the secondary voltage at the spark plug is a negative pulse. That maximizes emission of electrons and thus optimizes spark formation.

Any transformer consists of a pair of magnetically coupled inductors described by their self and mutual inductances. A pair of coupled inductors is described by the matrix equations,

$$\begin{bmatrix} v_1(t) \\ v_2(t) \end{bmatrix} = \begin{bmatrix} L_1 & L_m \\ L_m & L_2 \end{bmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} \tag{1}$$

or, in phasor notation,

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} L_1 & L_m \\ L_m & L_2 \end{bmatrix} j\omega \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{2}$$

where the quantities are defined in Figure 1. L_m, the mutual inductance, can be expressed as

$$L_m = k\sqrt{L_1 L_2} \tag{3}$$

The constant k is called the *coupling coefficient*. Thus, three quantities are required to describe a set of coupled inductors: L_m or k, L_1, and L_2.

Some useful relations can be derived from (1) and (3). If port 1 is excited and $I_2 = 0$, we have

$$\frac{V_2}{V_1} = \frac{L_m}{L_1} = k\sqrt{\frac{L_2}{L_1}} \tag{4}$$

The inductance of an ordinary solenoid is proportional to the square of the number of turns of wire, so

$$\frac{V_2}{V_1} = k\frac{n_2}{n_1} \tag{5}$$

where n_2 and n_1 are the number of turns on L_2 and L_1, respectively. If port 2 is excited and $I_1 = 0$,

$$\frac{V_1}{V_2} = k\frac{n_1}{n_2} \tag{6}$$

With *perfect coupling*, when all the magnetic flux is common to both windings, $k = 1.0$ and there is no *flux leakage*. If $k = 0$, the coils are completely uncoupled and behave as two separate inductors. Furthermore, when $k = 1.0$ and $L_1, L_2 \to \infty$, we have an *ideal transformer*, in which (5) and (6) are valid for all values of terminating impedance.

Eq. (1) can be represented by the equivalent circuit of Figure 2. This circuit is occasionally useful for transformer calculations.

For ordinary, oil-filled solenoidal ignition coils, n_2 / n_1 is usually in the range of 60 to 70; $k \approx 0.95$, $L_1 \approx 10$ mH, $L_2 \approx 45$ H, $R_1 \approx 3\Omega$, $R_2 \approx 10\text{K}\Omega$, C_1 is a few thousand pF, and C_2 is a few tens of pF.

The coil model's parameters can be found by the following procedure:

1. The resistances R_1 and R_2 are measured directly by a multimeter.
2. The primary inductance, L_1, is measured by an inductance meter, with the secondary (high-voltage winding) open-circuited. L_2 is usually outside the range of most meters, so it requires a different method.
3. The k factor is found by measuring the leakage inductance, L_l, the primary inductance with the secondary shorted[1]. From (1) or the equivalent circuit of Figure 2, one can easily derive

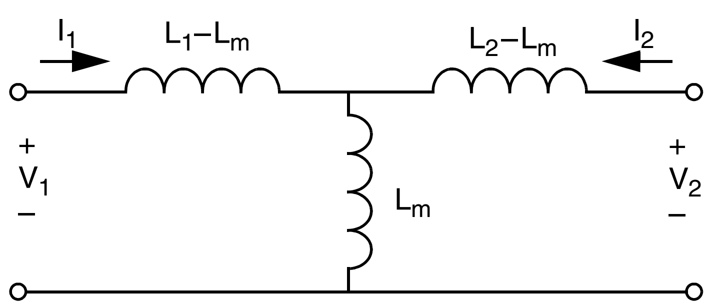

Figure 2. Equivalent circuit of a pair of coupled coils. It should be clear by inspection that it is described by (1).

1. Leakage inductance can be defined for either the primary or secondary, but cannot be determined uniquely for both, as the set of coupled inductors is characterized by only three parameters.

$$L_l = (1 - k^2) L_1 \tag{7}$$

and then simply solve for k.

4. The turns ratio is found from (6) after measuring the voltage gain in the reverse direction. Connecting a signal generator to the secondary winding swamps the capacitance C_2, so it does not affect the measurement; the reverse voltage gain then is flat from 1 KHz to at least 10 KHz.

5. L_2 is found from (4) and (5):

$$L_2 = L_1 \left(\frac{n_2}{n_1}\right)^2 \tag{8}$$

6. The capacitances are determined from small-signal measurements of the forward voltage gain and input impedance vs. frequency at the primary. For the solenoidal coils, the gain has a maximum around 5 KHz; the impedance has a maximum near 2 KHz and a minimum at approximately 9 KHz. The capacitances are chosen so the calculated gain and impedance have maxima and a minima at the same frequencies. Since there are only two capacitances, it is not possible to fit more than two points precisely, but we have observed that the calculated values throughout the frequency range are consistently close to the measured ones. The calculated gain and impedance were relatively insensitive to C_1, so that parameter could not be determined with high accuracy.

   It is important to note that, in the V_2 / V_1 measurement, the capacitance of the oscilloscope probe (~15 pF) is not negligible. It must be subtracted from the fitted value of C_2. To minimize the uncertainly due to probe capacitance, a 10x attenuator probe should be used for the measurement.

7. The core-loss resistance, R_c, is difficult to estimate from small-signal measurements. It was selected to match the decay of the sinusoidal voltage across the capacitor in the period after the spark was extinguished. Although we use a linear resistance in the model, is likely that this resistance is actually significantly nonlinear.

In the small-signal measurements, it is important to minimize the excitation level. If it is too great, distortion of the waveform is evident. This distortion is probably caused by magnetic nonlinearity, primarily hysteresis, in the core.

Table 1 gives the parameter values for five solenoidal ignition coils and one “E-core” coil. The solenoidal coils are (1) an Intermotor Sports Coil (which appears to be identical to a Lucas Sports Coil), (2) a Bosch “blue” coil, (3) an unlabeled general-purpose replacement coil, probably Lucas, (4) an NGK U1163 coil, and (5) a Beru ZS 172 coil. The E-core coil is a Holley "Sniper EFI" unit. The parameters of the solenoidal coils are similar and, in particular, the sports coil does not differ significantly from the others. However, the last parameter, cost, does show significant differences.

The Holley coil is intended for high-performance, capacitor-discharge ignitions. Its primary resistance is too low for it to be used directly as a replacement for the other coils, but it could be used with a ballast resistor. A resistor of ~1.4Ω would increase the maximum current to ~7A and provide the same low-speed energy as a solenoidal coil, while retaining a shorter charging time and thus better high-speed spark energy. It is not clear whether this would be acceptable, as Holley, unfortunately, does not specify this coil's maximum primary current. In a system using mechanical ignition points, it would also increase point current, probably leading to faster point erosion. It is interesting that the Holley coil has virtually the same coupling coefficient as the other coils; E-core coils might be expected to have greater coupling.

All the solenoidal coils have approximately 3Ω primary resistance and are appropriate for use in classic cars having 12V electrical systems. Similar coils with ~1.5Ω resistance can be obtained for use in 6V systems. Finally, there exist "non ballasted" coils, which have low primary resistance and require an external ballast resistor. Except for the primary resistance, they are similar to the listed solenoidal coils. Catalogs also list coils for use in specialized applications, including ones from Pertronix, MSD, Summit, and other manufacturers, which are shaped like the solenoidal coils but have very different characteristics.

Spark-Plug Model

When a high voltage is applied to a spark plug, a high electric field is established in the space between its electrodes, ionizing the gas in that space. The resulting low-resistance path conducts a surge of current, which heats the ionized gas, creating a visible spark. The voltage required for breakdown depends on the width of the gap, the condition of the plugs, the shape of the electrodes, the type and pressure of the gas, and perhaps other factors. In automotive use, it is on the order of 10,000 volts. Once breakdown occurs, the voltage drop across the gap required to sustain the spark is much smaller than the breakdown voltage, approximately 1000 volts. The spark resistance is around 1000Ω.

Table 1: Coil Model Parameters

Parameter	Bosch Blue	Intermotor Sports Coil	Unlabeled	NGK U1163	Beru ZS 172	Holley
L_1	11.7 mH	9.5 mH	10.7 mH	9.9 mH	7.77 mH	3.78 mH
L_2	48.1 H	47.0 H	48.2 H	33.4 H	33.7	26.0 H
k	0.93	0.94	0.94	0.95	0.92	0.954
n_2 / n_1	64.1	70.3	67.1	58.0	65.9	83.0
R_1 (Note 2)	3.5 Ω	2.9 Ω	2.9 Ω	3.2Ω	3.5Ω	0.36Ω
R_2	8.6 KΩ	9.0 KΩ	10.2 KΩ	10.3 KΩ	7.4 KΩ	4.82 KΩ
R_c (Note 1)	800 Ω	800 Ω	800 Ω	(Note 3)	(Note 3)	800 Ω
C_1	5000 pF	3000 pF	5000 pF	(Note 3)	(Note 3)	2000 pF
C_2	37 pF	60 pF	20 pF	(Note 3)	(Note 3)	30 pF
Cost (USD)	$70	$45	$20	$22	$36	$45

Notes:

1. Estimate based on the decay of the sinusoidal voltage after the spark is extinguished. This value was determined only for the unlabeled coil. Others are assumed similar.
2. Four-wire resistance measurement.
3. This quantity was not measured.

Following Holden [1], we model the spark plug in breakdown as a voltage source having a constant voltage of 1000V and resistance of 1000Ω. This is most easily done by representing the gap by a zener diode; we use two diodes in series with reverse polarities to account for either spark polarity. Resistor plugs have an internal resistor, usually around 5000Ω, which helps to minimize electromagnetic interference. That resistance can be included in the spark-plug model, as appropriate.

The estimate of 1000V is just that–an estimate–and it comes from experience, not theory. We have found that the spark energy depends only weakly on that voltage, but the lifetime of the spark depends on it strongly. In simulations, that voltage was adjusted to make the spark lifetime equal to that which was measured. Invariably it was within a couple hundred volts of 1000V.

Kettering Ignition

In a Kettering (conventional, points-capacitor) ignition system, shown in Figure 3, the primary of the ignition coil is "charged" with current while the points are closed. During this period, the coil's secondary is open-circuited, so it has no effect on the primary current. The current in the coil rises, initially at the rate

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \frac{V}{L_1} \tag{9}$$

where V is the car's system voltage, usually 12.5-14.5V, and L_1, as before, is the primary inductance. If the points are closed long enough, the current levels off at the value

$$I_{max} = \frac{V}{R_1} \tag{10}$$

where R_1 is the primary resistance. More precisely, the current waveform, $I(t)$, is

$$I(t) = I_{max}\left(1 - \exp\frac{-t}{L_1/R_1}\right) \tag{11}$$

The time constant, L_1 / R_1, is typically ~3 mSec. At higher engine speeds, the points are not closed long enough for the current to reach I_{max}. The energy is stored in the coil, E, is then

$$E = \frac{L_1 I_0^2}{2} \tag{12}$$

where I_0 is the current in the coil when the points open. That energy, minus losses, powers the spark at the spark plug. It is possible to show that, without resistive losses and with perfect coupling, the spark energy is equal to the value given by (12).

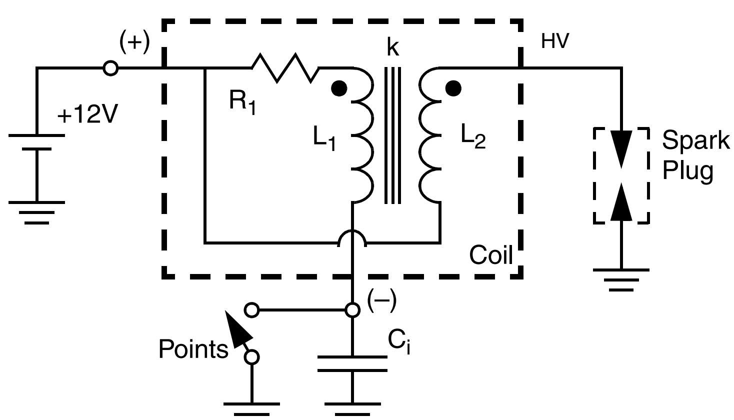

Figure 3. Kettering (points-capacitor) ignition system. Although the coil includes all the elements of Figure 1, here only R_1 is shown explicitly.

If there were no ignition capacitor, the coil voltage, when the points open, would have a short-lived spike of several thousand volts, which would cause severe arcing at the points, damaging them quickly. Additionally, the coil probably could not respond so quickly, and any output would be too short in duration to create a useful spark at the plugs. The ignition capacitor, C_i, extends that pulse. By slowing the voltage increase at the points, it also (ideally) keeps the voltage below breakdown as the points separate, thus minimizing arcing.

The natural response of the LC circuit consisting of L_1 and C_i is oscillatory at a frequency of approximately 3 KHz. When the points open, the voltage across C_i rises rapidly, the beginning of the sinusoid. If there were no spark plug and no arcing at the points, this voltage would rise to ~900V, which would generate something like 55kV at the secondary. Long before that can happen, however, in a few microseconds, the primary voltage reaches approximately 150V, the secondary voltage reaches the 10kV breakdown, and the spark plug ignites. The secondary voltage then drops to ~1000V. That clamps the primary voltage, per (6), to 1000V divided by the coil's reverse voltage gain, or approximately 16V. The car's system voltage is applied continuously to C_i as well, so the total voltage at C_i is ~30V. This voltage remains constant as long as the spark plug is ignited.

Because the voltage across C_i is constant, the current in C_i, and therefore L_1, is zero. That effectively disconnects L_1 from the circuit, so the spark voltage and current waveforms are determined by L_2 alone. The ignited spark plug is, in effect, a voltage source connected to the ignition coil's secondary. The initial current in L_2, $I_{2,0}$, is established by the current in L_1 when the points open; it is simply

$$I_{2,0} = k I_0 \frac{n_1}{n_2} \tag{13}$$

which, for most coils, is ideally ~50 mA, but losses reduce this considerably. The current decreases at a constant rate,

$$\frac{\mathrm{d}I_2}{\mathrm{d}t} = \frac{V}{L_2} \tag{14}$$

and when it reaches zero, the spark is extinguished.

An LTSpice [3] model of the Kettering ignition system, using the unlabeled coil of Table 1, is shown in Figure 4. The ignition-coil model is visible in the top portion of the figure[1]. The

1. The component designations in the LTSpice circuit of Figure 4 are not the same as in those of Figure 3 and the previous text.

1600Ω resistor, R_3, represents the ignition-wire resistance and the 20 pF capacitor, C_4, represents the capacitance of the spark plug. D_1 and D_3 implement the spark-plug model, described above; we assume that these are non-resistor plugs. C_1 is the ignition capacitor (C_i in Figure 3) and the switch is, of course, the points. D_2 and D_4 are another spark-gap model, which accounts for arcing at the points. Without them, the calculated C_1 voltage is consistently higher than the measured value; arcing is one possible cause of that discrepancy. V_1 is the car's dc system voltage.

The simulated voltage across C_1 of Figure 4, shown in Figure 5, includes a decaying sinusoidal component. That sinusoid is caused by a resonance between the coil's primary leakage inductance of approximately 1 mH and the 0.22 μF ignition capacitor. The oscillation sits on top of the 30V dc component described earlier. This oscillation has a negligible effect on the spark, as its energy is not coupled to the coil's secondary. At the 3 mSec point, the waveform changes abruptly; the dc component drops, and a much lower-frequency decaying sinusoid is visible. That change occurs when the spark current reaches zero and the spark has expended its available energy. The entire 10.7 mH primary inductance then resonates with C_1, resulting in the lower-frequency oscillation.

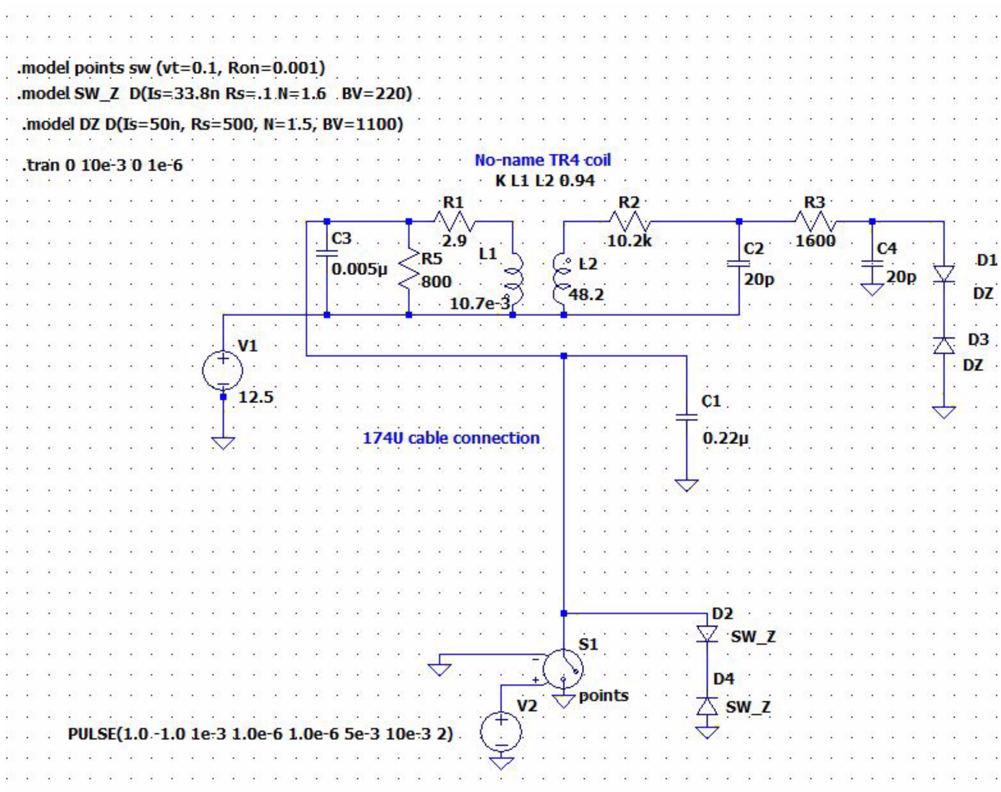

Figure 4. The Kettering ignition circuit model in LTSpice.

In this simulation, the coil was initially “charged” to its maximum possible dc current, V_1 / R_1, a bit over 4A. At higher engine speeds, the coil has less time to charge, so the current when the points open will not be as great; at idle, however, where the waveform was measured, the coil has ~15 mSec to charge. Since the time constant is ~3.5 mSec, this charge time is adequate to reach I_{max}.

The voltage and current at the spark plug are shown in Figure 6. The voltage at the plugs is a constant 1100V, plus a small voltage drop across the spark resistance; the current exhibits an initial 10 KHz oscillation and the linear decreasing component described above. The oscillating current in the primary, responsible for the oscillating voltage component in C_1, causes the oscillatory component in the current waveform. This component contributes only microjoules to the spark’s energy.

The linear component of current has a slope of approximately 24 A / Sec. That is consistent with the 48 H secondary inductance, the 1100V spark voltage, and (9). This explains why the spark energy is relatively insensitive to spark voltage: if V is lower, dI / dt is also lower, so the spark lasts longer. The available spark energy is, in all cases, the energy stored in the coil’s primary, minus energy losses in resistors, arcing, and the magnetic core. That depends on spark duration only as a second-order effect.

Although C_1 minimizes arcing at the points, minor arcing is usually still visible. This occurs because the points do not open fast enough to prevent it; the voltage across the points rises to

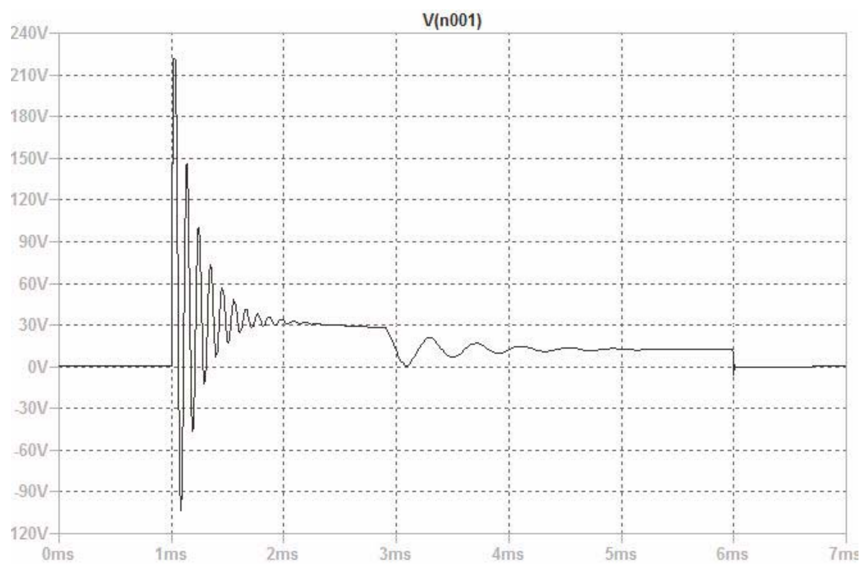

Figure 5. Simulated voltage of C_1 in the Kettering ignition. The points open at 1 mSec and close at 6 mSec. The change at 3 mSec occurs when the spark is extinguished.

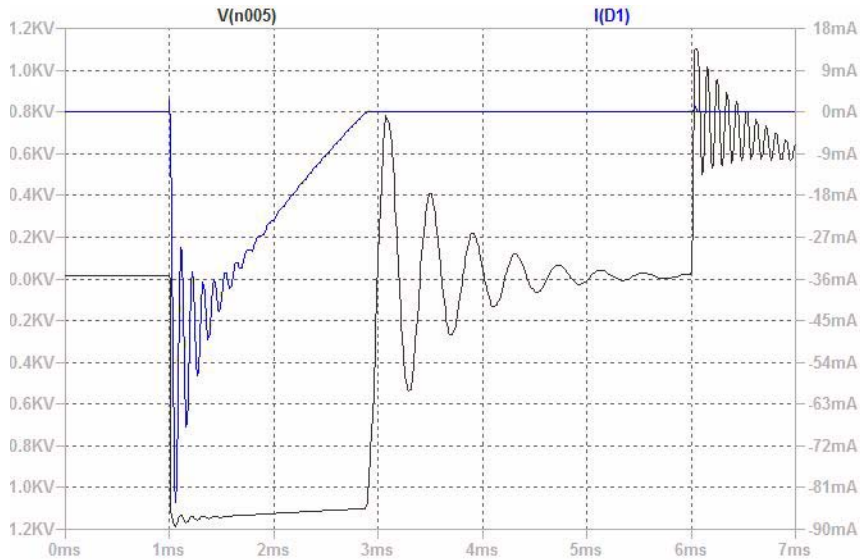

Figure 6. Spark voltage and current. The voltage is relatively constant at 1100V and the current has a straight-line component. The spark is extinguished when the current reaches zero, indicating that its available energy has been dissipated.

the ignition value in 5-10 μS, and at that time the points are just barely open. The D_2 and D_4 zeners model this arcing in much the same way as D_1 and D_3 model the spark plug.

Figure 7 shows the measured waveform at C_1. It agrees well with the simulated waveform of Figure 5.

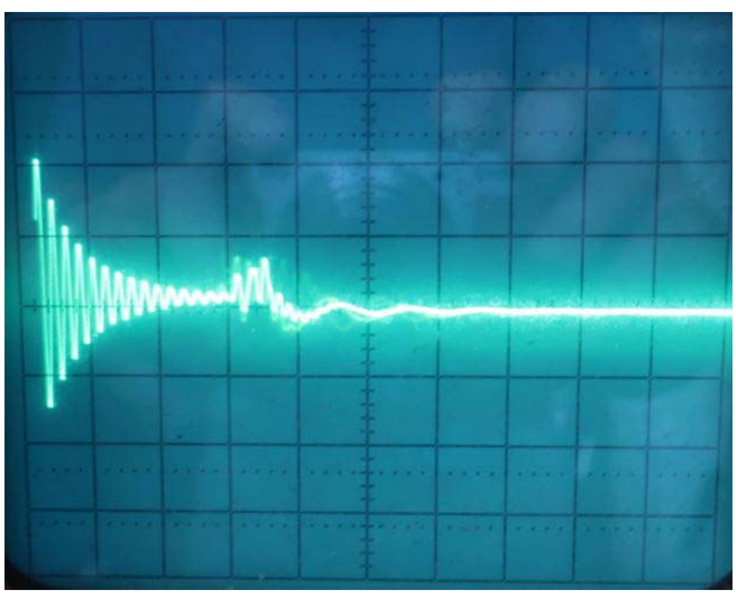

Figure 7. Measured voltage across C_1. The scale is 0.5 mSec and 100V per division.

The electronic ignition exhibits little of that sinusoidal component, yet has essentially the same spark energy as the Kettering. The rectangular pulse, not the sinusoidal component, is what establishes the spark energy.

MOSFET Ignition

The MOSFET ignition is simply a Kettering ignition with a MOSFET used as a switch instead of the points. This relieves the points of the need to carry a large current, enormously improving the ignition system's reliability.

Although electronic ignition systems for older cars usually have magnetic or optical triggers, the use of points is a simple and practical way to implement ignition triggering. In the ignition circuit described here, the points carry only 7 mA of current and cut only the 12.5V to 14.5V system voltage. With such low stress, the points don't experience measurable wear; only the block that rides on the distributor cam is subject to wear, so periodically rechecking the points gap is prudent. Kahan states that, with regular lubrication, the block's rate of wear drops close to zero after a few thousand miles. Presumably this occurs as the block "wears in" on the distributor cam.

In a Kettering ignition, the points' gap, and therefore its dwell, is a trade-off between the need for a long charging time and opening far and fast enough to prevent excessive arcing. The latter consideration is no longer important in the electronic ignition, so the points' gap can be reduced somewhat (i.e., dwell can be increased) to allow longer charging time, modestly increasing the coil's stored energy. That reduction is limited by block wear, which might eventually allow the points to close completely if their initial gap is too small. Longer charging time, however, increases the coil current and therefore heating, but it is unlikely that this modest increase would be enough to damage the coil.

In the circuit of Figure 8, a power MOSFET, the Infineon IRFI4229, performs the high-current switching. This MOSFET includes an integral zener diode, which prevents the drain-to-source voltage from reaching a value that could damage the transistor. A 15V protective zener also has been connected to the gate.

An IRF3315, another power device, is used as an inverter. A smaller device probably could be used instead, but the low *on* voltage and high drain-current capability of this device ensure fast switching. Switching time should be only a few microseconds; since one degree of crankshaft rotation is 28 μS at 6000 RPM, the switching delay should not measurably retard the ignition timing, even at high speeds. The gate of the inverter FET also has a zener, in this case to protect it from voltage spikes that might be induced on the lead to the points. That lead is shielded to prevent coupling of voltage spikes from the high-voltage leads, which might cause spurious triggering.

The ignition capacitor normally mounted in the distributor has been replaced by a 0.22 μF metal-film polypropylene capacitor. This capacitor must be capable of carrying high current; it must have a “dV/dt” rating of at least 25 V/μSec. Ordinary radio capacitors cannot be used here. It is also important that the circuit have a low-resistance ground to the engine block.

The circuit includes a switch that will cut out the electronic portion of the circuit and return it to a conventional Kettering circuit. This capability was included to allow comparisons between the two systems. It can also be used to switch to the Kettering mode if something fails in the electronics.

Figure 9 shows the LTSpice model of the MOSFET ignition. Only the switching stage has been included, as the effect of the inverter on the spark waveforms is negligible. The MOSFET model was supplied by the manufacturer, and the coil and spark plug use the same models as the Kettering system.

Figure 10 shows the simulated voltage waveform at C_1. The waveform shows an initial 250V spike, clearly limited by breakdown of the internal zener diode. Negative excursions of the sinusoidal voltage component are clipped by forward conduction of that same zener. This tends to damp that oscillation, causing it to die out quickly. The 30V dc component is identical to that of the Kettering system. The spark duration is slightly greater, though, approximately 2.5 mSec. After the spark period ends, a low-frequency oscillation is observed. Figure 11 shows the measured waveform, which is virtually identical to the calculated one.

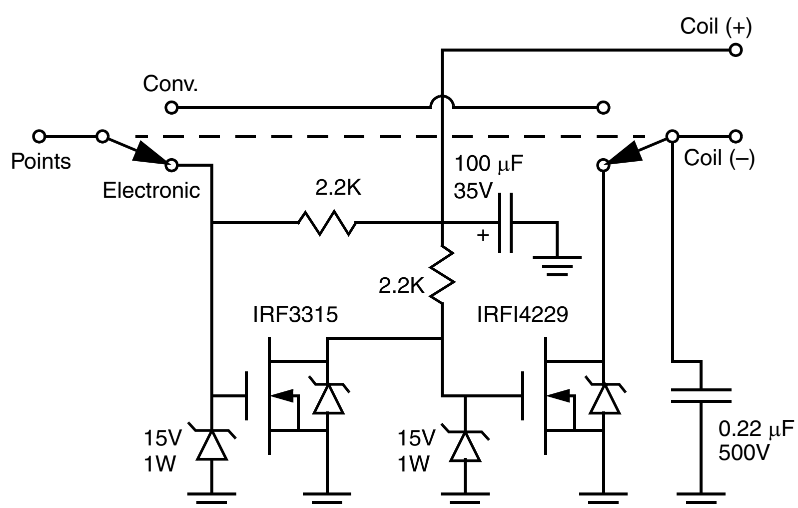

Figure 8. The MOSFET ignition circuit. The 0.22 μF capacitor replaces the capacitor usually mounted in the distributor. The switch allows the use of the conventional ignition mode if desired.

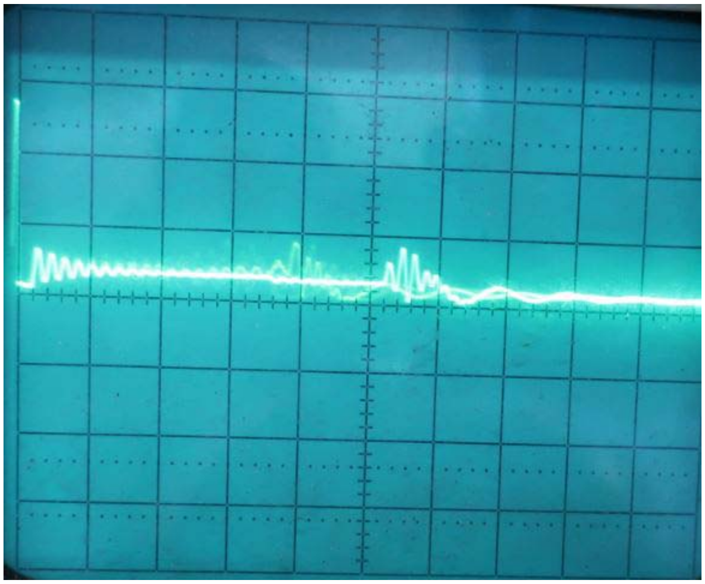

Figure 11. Measured voltage at C_1 in the MOSFET ignition. The scale is 0.5 mSec and 100V per division.

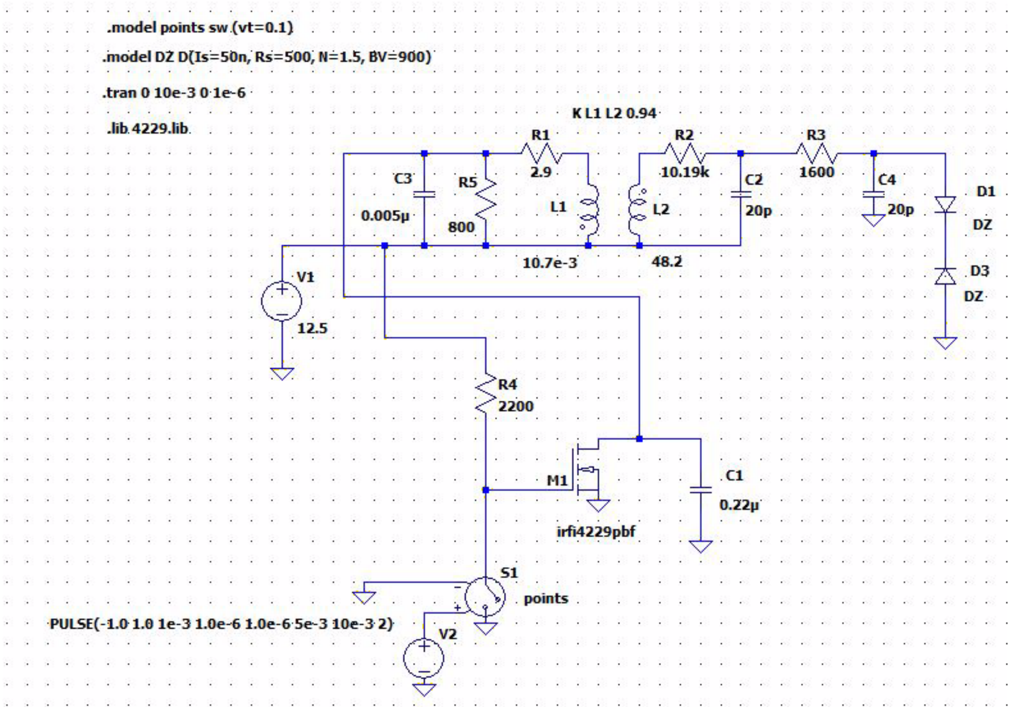

Figure 9. The MOSFET ignition. Only the switching stage is shown. The coil and spark-plug models are the same as in the Kettering circuit (Figure 4).

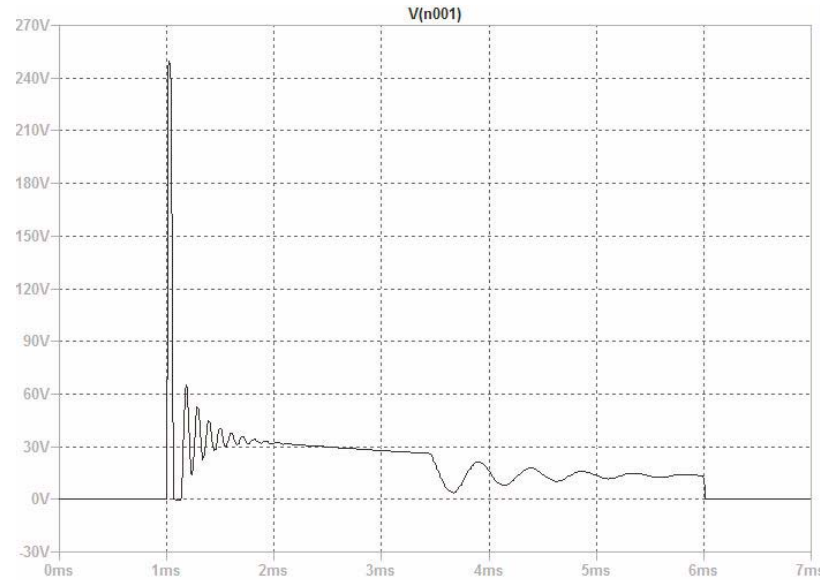

Figure 10. Simulated voltage of C_1 in the MOSFET ignition. As with Figure 5, the points open at 1 mSec and close at 6 mSec; the change at 3.5 mSec occurs when the spark is extinguished. The sinusoidal component of this voltage is much reduced by clipping in the FET's protective zener diode.

The simulated spark voltage with the MOSFET ignition is shown in Figure 12. The main differences in this waveform from that of Figure 6 is the reduced oscillation in the current, a consequence of the reduced sinusoidal voltage at C_1, and the slightly longer spark duration. The spark energy, in both cases, is approximately the same.

The operation of the MOSFET ignition, is virtually the same as the Kettering, in that the MOSFET, instead of points, switches the coil current. The main differences are (1) the effect of the diode, and (2) the length of the spark. The latter implies a lower spark voltage. It is difficult to see why the spark's voltage should be different in the two systems, but it is possible that differences in the spark's ignition voltage may be responsible.

Both measured waveforms, Figures 7 and 11, show an odd oscillation as the spark is extinguished. The author has not observed this phenomenon in other automobiles. It may be caused by turbulence in the combustion chamber; that would explain why it is particular to the car in which both were measured (a 1966 Triumph TR4A).

Additional Energy Losses

The calculated spark energies determined by these simulations were in the range of 60-70 mJ. These significantly exceed the values measured by Holden, implying the existence of additional losses that could not be included in the simulation. A number of such losses can be identified. They include the following:

1. *Arcing at the points (in the Kettering system only)*. The frequency of the initial sinusoidal voltage across the points is approximately 3 KHz. At that frequency, spark ignition is reached in less than 10 μSec. The period during which the points are opening, from the time that the distributor cam contacts the rubbing block until they reach their maximum opening, is approximately 50-70 μSec at 1000 RPM engine speed. Thus, the points open very slowly relative to the build-up of voltage across them, so some degree of arc formation is inevitable. That arc accounts for energy loss, but it is difficult to say how much.

2. *Hysteresis and nonlinearity of the ignition coil's core*. In any magnetic system, hysteresis is a significant loss mechanism, and it is likely that other kinds of magnetic nonlinearity represent losses that we cannot easily quantify. We have seen evidence that these effects are present at the low voltages and currents used to characterize the coil. It is likely that they are more severe at the higher operating voltage and current.

3. *Imperfect coupling in the ignition coil*. Imperfect coupling gives rise to leakage

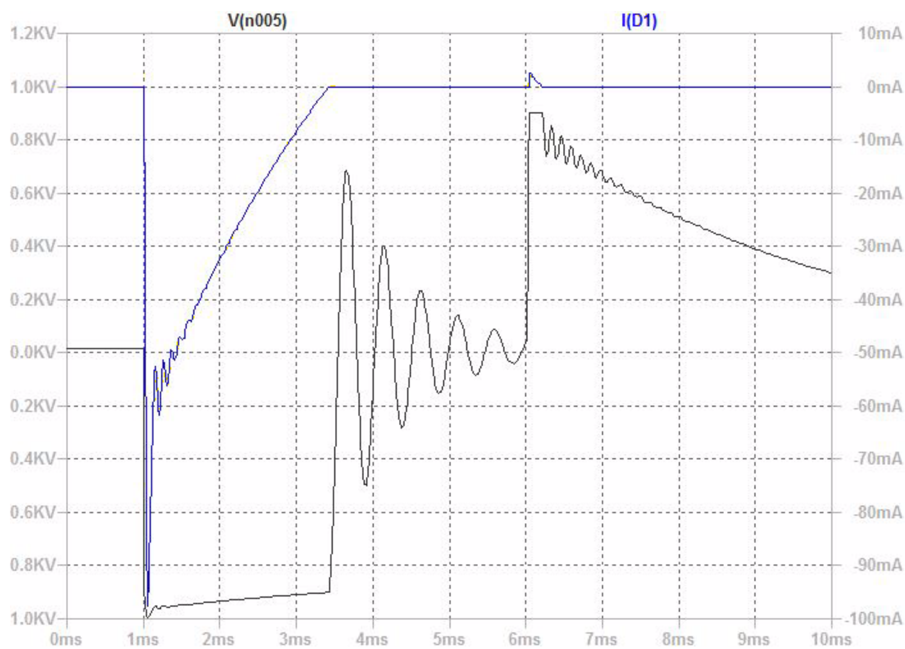

Figure 12. Spark voltage and current in the MOSFET ignition. The spark voltage is somewhat lower than in the Kettering and duration is longer; this is discussed in the text. Because of the reduced sinusoidal voltage component at C_1, the oscillatory part of the current is much smaller.

inductance. The energy stored in that inductance is not coupled to the secondary, and is largely dissipated in the primary resistance. This energy represents approximately 10% of the total energy given by (12).

4. *Contact time in the distributor cap*. At 6000 RPM, the distributor's rotor moves at 20 mSec per revolution. Depending on the design of the components, the rotor can stay connected to the electrical contact in the cap no more than 1/10 revolution, or 2 mSec, and probably less. Since the spark duration is in the range of 2 to 3.5 mSec, it is likely that the plug is disconnected before the spark has used all of its available energy. Since the spark current is a decreasing sawtooth waveform, the lost energy will be lowest if the rotor is close to the cap contact when the spark begins.

5. *Contact gap in the distributor cap*. The outer end of the distributor's rotor never makes physical contact with its electrical contacts in the cap, so those "contacts" are actually small spark gaps. Some energy is inevitably lost in jumping that gap. The voltage at that gap is much lower than the spark-plug voltage, as the gap is smaller and the lower air pressure in the cap results in a lower breakdown voltage.

Conclusions

This work has illustrated a number of nonintuitive features of an automotive ignition system. Among these is the nature of the spark waveform, a rectangular pulse with a triangular current. We also determined that the damped oscillation visible in the capacitor's voltage waveform is an artifact of the imperfect coupling between the windings of the ignition coil, and has negligible effect on the spark energy.

Although it was not possible to simulate the spark energy accurately, the simulation was helpful in identifying some of the factors that affect it and some that may limit it.

Finally, it seems clear that the MOSFET electronic ignition circuit is a practical and effective tool to reduce electrical stress on the points, and, when it is used, the spark energy is little different from that of the conventional Kettering ignition.

References

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