Economic, High Performance, High Efficiency Electronic Ignition with Avalanche-Rated HEXFETs®

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Introduction

Gasoline engine ignition circuits represent a severe environment for semiconductor switches. A transistor used in place of the traditional mechanical contact breaker is called upon to block high voltage at the moment it interrupts the coil current. Bipolar transistors, with a susceptibility to second breakdown, have found this a difficult situation in which to perform reliably. Power MOSFETs, on the other hand, having no second breakdown limitation, are ideally suited to this role and do not require the use of snubbers for load-line shaping.

International Rectifier's HEXFET III power MOSFETs are especially well suited to this application since they can tolerate high levels of energy in avalanche breakdown. Overvoltage produced at turn-off by the coil leakage inductance or excessive primary coil voltage resulting from a disconnected high tension lead can both be clamped by avalanching of the HEXFET (Ref. 1).

The advantages of the HEXFET which make it a particularly suitable device for use in electronic ignition systems are:

- High reliability
- Square Safe Operating Area
- Voltage control
  (no base drive required)
- Avalanche capability

The suitability of power MOSFETs for this application has sometimes been overlooked because of concern over the resistance of the MOSFET due to the high voltage rating required by the application. In fact, as this application note shows, an ignition system using a HEXFET as the switching device can meet all the necessary specifications, including performance at crank voltage, with a higher efficiency than that typically encountered in systems employing a bipolar transistor.

Electronic Ignition

The introduction of electronic ignition — initially as an "after sales add-on" — was instigated as a means of overcoming the inherent weaknesses of the mechanically switched system as utilized with the Kettering distributor. Improved overall performance was the justification for the high initial purchase price.

The earliest electronic ignition systems were invariably capacitor discharge (CDI) systems, and for very good reasons: the standard ignition coil, as fitted by the car maker, was retained. Inductive discharge (ID) systems, at that time, were not possible without a change of ignition coil. This was fundamentally due to the lack of high voltage power switching transistors. When high voltage power bipolar transistors became readily available at an economical price, inductive discharge systems (with the standard ignition coil) proved to be a reality.

Unfortunately by then the standard coil had been discarded by the car maker in favor of low inductance coils with ballast resistors in order to obtain improved cold starting. The bipolar transistor was therefore called upon typically to switch 6 amperes. To do so with relative reliability, safe operating area clamps were used, raising both cost and dissipation. HEXFETs, being majority carrier devices, are not subject to second breakdown, and therefore do not require safe operating area clamping.

Ignition modules of today have not changed dramatically, although as this application note demonstrates, higher efficiency could be achieved, without any sacrifice in performance, with a lower current, high inductance coil.

Ignition Requirements of Modern Gasoline Engines

These requirements can be quantified into four distinct categories: (i) Aiming voltage at the sparking plug; (ii) Available energy from the coil; (iii) Spark duration; (iv) Crank voltage. Besides these four major categories there are several others, including efficiency, reliability and cost.

i) *Aiming Voltage*

This requirement may be defined as the open circuit voltage available at the high tension terminal of the coil prior to the interelectrode gap of the sparking plug breaking down. This voltage should not be confused with the "arc voltage" developed across the gap of the sparking plug after breakdown. The aiming voltage is frequently specified as 16 kilovolts at a minimum battery voltage of 13.2 volts and is derived from measurements originally made with contact breaker systems. It is desirable that the aiming voltage be as high as possible (without endangering coil winding insulation) in order to successfully "fire" fouled plugs. Simplistically, aiming voltage (Va) may be expressed as:

$$Va = ip \cdot \sqrt{Lp/Cs} \quad (1)$$

where Lp is the inductance of the primary (low tension) winding, ip is the peak instantaneous current flowing in the winding when the power switch "opens" and Cs is the interwinding capacitance of the high tension winding.

(ii) *Available energy from the coil*

The minimum value required can be demonstrated to be less than 2 millijoules. Specifications for engines frequently quote a value of 6 millijoules for a crank voltage of 6 volts. Extrapolation for crank voltages of 4.5 volts gives a minimum energy of 4 millijoules. It should be remembered that too high an energy level will accelerate spark plug electrode erosion.

The coil energy may be found from:

$$E_{coil} = ½\, L_p \left(\frac{V_b}{R_{coil} + R_{SW}} \right)^2$$

(iii) *Spark duration*

Many variables determine the requirements of this parameter. These may be listed as follows:

a) The number of cylinders
b) Maximum revolution rate of the engine
c) Fuel/air mixture in the combustion chamber
d) Static ignition timing at engine idle

Consider an eight cylinder engine running at 6000 revolutions/minute. The maximum time interval between the commencement of one spark and the next approximates to 2.5 milliseconds. The crankshaft angular velocity is 360 degrees in 10 milliseconds, or 1 degree in 27.8 microseconds. Centrifugal advance can be up to 21 degrees Before Top Dead Centre (BTDC). Frequently quoted spark durations for CDI of 400 microseconds are normally considered adequate. If the dwell time is 1.8 milliseconds maximum, then a spark duration of 700 microseconds should be perfectly adequate to avoid detonation due to premature extinguishing of the flame front.

On the other hand, consider the same engine at idle (800 revs/min). The maximum time interval between the commencement of one spark and the next approximates to 18.75 milliseconds. The crankshaft angular velocity corresponds to 360 degrees in 75 milliseconds or 1 degree in 208 microseconds. The spark advance at static idle may be 6 degrees BTDC. The 400 microsecond spark duration of CDI seriously enhances the possibility of detonation due to premature extinguishing of the flame front upon cessation of the spark. This phenomenon is more likely to occur in modern fuel efficient (lean burn) engines. Volt-second product balance for the ID system should provide a spark duration at idle long enough to prevent detonation.

(iv) *Crank voltage*

This voltage may be defined as the available battery voltage during operation of the starter motor — that is, the cranking voltage. Various specifications for 12 volt cars place this voltage at 6.0 volts and in some instances as low as 4.5 volts (worst case).

A bipolar Darlington transistor and a 4 mH coil (limited to 6 amperes) will provide an aiming voltage of 12 kV. An 8 mH coil (limited to 3.5 amperes) with a HEXFET, such as the one described in this application note, will provide an aiming voltage of 13 kV. Therefore, both systems perform equally well in this respect, with the HEXFET system consuming less power and, therefore, providing higher efficiency.

Design of a HEXFET Ignition System

All the requirements previously encountered can all be easily fulfilled, but not necessarily optimized in terms of performance, cost and efficiency. A bipolar Darlington transistor with an 8 mH coil would only generate an aiming voltage of 9 kV at a crank voltage of 4.5 volts. This may be insufficient to "fire" the plugs. The 4 mH coil and Darlington transistor would be adequate for the crank voltage of 4.5 volts but power consumption would increase, as will be demonstrated.

The first priority is to select a coil with as low a primary current as possible (commensurate with the minimum energy requirements of the system). The coil primary inductance should be 8 millihenries (nominal). The primary resistance should not be less than 2.5 Ohms and not greater than 3.75 Ohms. The turns ratio of the coil should be a nominal 55:1.

The HEXFET for the power switch should ideally be an IRF741. This device will give maximum clamped aiming voltages of 19 kV for minimum BV_{DSS} and 21 kV for maximum BV_{DSS}. (Aiming voltages are quoted for open circuit HT terminal.) These aiming voltages will not cause internal breakdown in the coil. HEXFET data sheets specify a minimum value of BV_{DSS} but not a maximum value of BV_{DSS}. The maximum BV_{DSS} assumed here is the minimum BV_{DSS} of the prime voltage version of the IRF741, the IRF740.

The combination of coil and HEXFET described above would give the following theoretical performance figures:

1. Aiming voltage during cranking (at 4.5 volts): 10 kilovolts minimum.
2. Spark energy during cranking (at 4.5 volts): 4.7 millijoules (specified minimum typically 4 millijoules).
3. Spark duration during cranking: 150 microseconds minimum (low cost CDI systems have spark durations of 150 microseconds).
4. (a) Maximum power consumption = 17 watts at 6000 RPM, 8 cylinder engine (32 watts for 4 mH coil and Darlington bipolar transistor).
   (b) Maximum power consumption = 25 watts at 800 RPM, 8 cylinder engine (42 watts for 4 mH coil and Darlington bipolar transistor).

Practical Circuit and Performance

The schematic of Figure 1 shows a practical ignition module with built-in test oscillator composed of R1, R2, R3, C3 and half of IC1. This oscillator provides a 50 Hz, 50% duty cycle pulse to the base of Q2, with S1 open. With S1 closed, normal ignition triggering is via the IGNITION INPUT (input high for Q6 off).

Q1, D2, D3, C6, C7 and the second half of IC1 comprise a gated "charge pump" for maintaining adequate gate voltage for Q6, for battery voltages less than 10V (during cranking). Q6 avalanches repetitively and absorbs the energy stored in the leakage inductance of the coil. Table 1 provides the component listing for the schematic of Figure 1.

Table 2 gives details of the performance unit. The minimum available energy at 4.5 volt (crank voltage) is a healthy 5.92 millijoules against a requirement of 4.7 millijoules.

Photograph 1 shows the waveforms of HT voltage (upper trace: 5 kV/div) and drain source voltage across Q6 (lower trace: 100V/div). The battery voltage is 4.5 volts and the HT terminal is unterminated. It would appear that the spark duration would work out at approximately 150 microseconds (the time base is 100 microseconds/div), but as the waveforms in photograph 2 demonstrate is somewhat longer in practice.

TABLE 1: ELECTRONIC IGNITION MODULE — COMPONENT LIST

C1 — Capacitor metallised polycarbonate 2.2 microfarad 100V D.C. working
C2 — Capacitor metallised polycarbonate 10 nanofarad 100V D.C. working
C3 — Capacitor metallised polycarbonate 0.1 microfarad 100V D.C. working
C4 — Capacitor metallised polycarbonate 10 nanofarad 100V D.C. working
C5 — Capacitor metallised polycarbonate 10 nanofarad 100V D.C. working
C6 — Capacitor metallised polycarbonate 0.1 microfarad 100V D.C. working
C7 — Capacitor metallised polycarbonate 0.1 microfarad 100V D.C. working
C8 — Capacitor ceramic 2.2 nanofarad 1KV D.C. working

D1 — Zener 9.1V 200 mW
D2 — 1N4001
D3 — 1N4001
D4 — 1N4148
D5 — Zener 15V 200 mW

Q1 — 2N2369
Q2 — 2N2369
Q3 — 2N2369
Q4 — 2N2369
Q5 — 2N2905

R1 — Resistor 100K 1/8W
R2 — Resistor 100K 1/8W
R3 — Resistor 39K 1/8W
R4 — Resistor 2K7 1/8W
R5 — Resistor 2K7 1/8W
R6 — Resistor 5K6 1/8W
R7 — Resistor 10K 1/8W
R8 — Resistor 820R 1/8W
R9 — Resistor 1K 1/8W

R10 — Resistor 5K6 1/8W
R11 — Resistor 10K 1/8W
R12 — 820R 1/8W
R13 — 12R 1/8W

IC1 — ICM 7556

S1 — Switch SPST

In photograph 2, the time base has been changed to 200 microseconds/div and the lower trace sensitivity to 200V/div. The upper trace sensitivity remains at 5 kV/div. The waveforms show the gap breaking down at approximately 9 kilovolts, while the arc sustaining voltage is approximately 2 kilovolts. From the lower trace it is evident that the spark duration is approximately 200 microseconds for a maintained battery voltage of 4.5 volts.

Photograph 3 shows the waveforms obtained with the bridgeable air gap set to 12 mm and the battery voltage set to 14 volts. This would be the minimum voltage during charging that would be seen as a typical condition in the car.

The HT waveforms appear on the upper trace (5 kV/div) while V_{DS} of Q6 is on the lower waveform (200 V/div). It can be seen that the gap breaks down at approximately 16 kilovolts while the arc is maintained for approximately 1 millisecond. The 500 V drain source spike is caused by the leakage inductance of the coil and plays no part in the spark generation. This is vividly demonstrated in photograph 4 where the time base speed has been increased to 1 microsecond/div.

It can be seen from photograph 4 that the HT voltage has only reached about 2 kilovolts by the time the leakage reactance spike starts to diminish. The magnitude of the leakage spike amply displays avalanche occurring in the HEXFET, and this avalanche capability will prevent the HT voltage from ever exceeding a nominal 22 kilovolts with an IRF741 for Q6. It is worth noting that the waveforms in all photographs were obtained at a frequency compatible with an engine RPM of

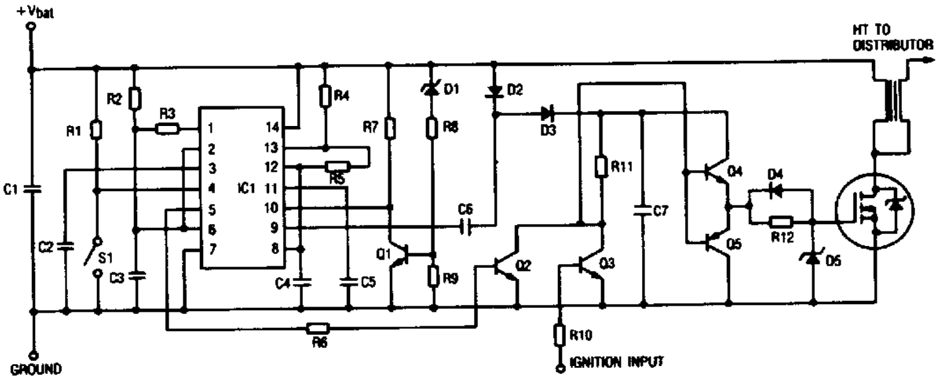

FIGURE .1 ELECTRONIC IGNITION MODULE

TABLE 2: PERFORMANCE OF STANDARD (6 mH NOMINAL 3.2 AMPERE) COIL SWITCHED BY IRF740

BATTERY VOLTS	EHT VOLTS (KILOVOLTS)	BRIDGEABLE AIR GAP HT TERMINAL OPEN (MM/INS)
4.5	11.0	5.0/0.197
6.0	14.0	8.5/0.335
12.0	23.5 (NOTE 1)	13.0/0.512 (NOTE 2)
14.0	26.0 (NOTE 1)	16.0/0.63 (NOTE 2)

NOTES:

1: Minimum measured value with stable oscilloscope trace.

2: Audible and visual (oscilloscope) Evidence of coil internal breakdown

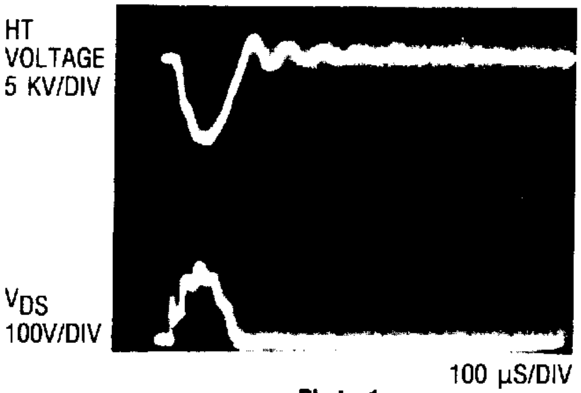

Photo 1

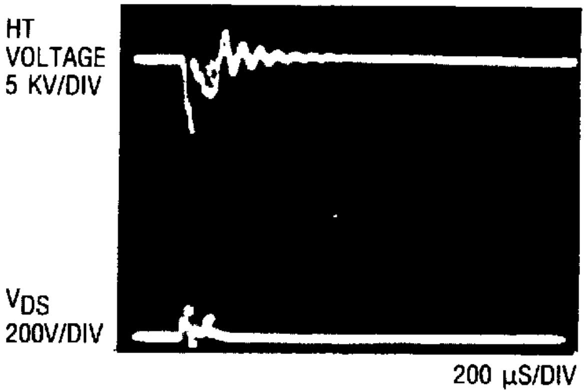

Photo 2

Photo 3

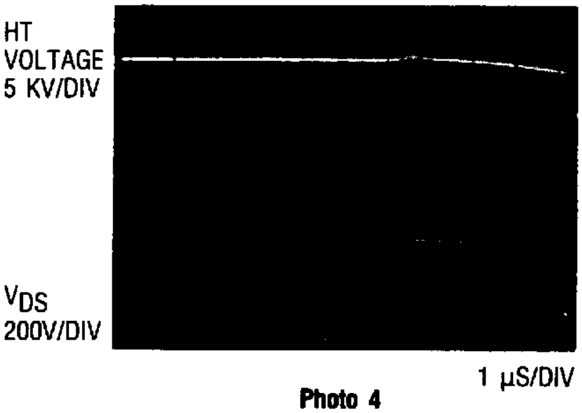

Photo 4

6000 for an 8 cylinder engine. At idle the increased dwell angle would certainly increase the magnitude of the HT aiming voltages of photographs 1 and 2.

The maximum power consumption measured at 800 RPM and 6000 RPM was 21.5 Watts and 16.8 Watts, respectively, and is in line with the design specification.

Conclusion

The ignition module of Figure 1 gives a performance similar to that of any of the better systems available today without any sacrifice in cost. It provides worthwhile savings in power consumption and generated heat, this last factor ultimately being a measure of reliability. □

References

(1) International Rectifier Application Note AN966: HEXFET III — A New Generation of Power MOSFETs.