02FFL-204

Automotive Ignition Transfer Efficiency

G. J. Rohwein
UHp, Inc.
9209 Evangeline NE
Albuquerque, NM 87111

L.S. Camilli
Combustion Technology Products Corp.
2301 Yale Blvd. SE A-6
Albuquerque, NM 87106

ABSTRACT

Measurement and analysis of typical automotive spark ignitions operating up to 30Kv and 30 to 100ma show the electrical-to-plasma (energy) transfer efficiency to be very low, significantly less than one-percent (1%).[1] The reason for this low energy transfer efficiency is high resistance in the driving circuit that is in series with the rather low resistance of the ignition spark. The largest components of resistance are in the ignition coil and the high voltage cables.

The latest evolution of ignition systems has been the elimination or severe shortening of the high voltage cable and the incorporation of one ignition coil attached directly to the individual spark plug. While this has eliminated much, and in some cases all, of the transfer losses attributed to the cables, the system as a whole is still very inefficient in the electrical-to-plasma conversion efficiency because the spark coil and spark plugs still have many times the resistance of the spark discharge channel, the "spark" between the electrodes.

These systems will therefore not meet the needs of future lean burn and alternative fuel engines requiring higher energy discharges to effectively ignite the fuel mixtures.[2, 3, 4, 5] A further complication is the present requirement to reduce the power consumption of the ignition system.

There are two basic approaches to increasing the electrical efficiency of ignition systems. The implementation of either will reduce power consumption of the ignition system. The first is to design the coil circuit with low resistance, which would require upgraded electrical components of the ignition to handle higher currents. The second and most practical, is to use a peaking capacitor between the coil output and the spark plug. With the second alternative, energy transfer efficiencies approaching 50% can be achieved.[1]

This paper will present a general analysis of distributor, distributor-less, and present coil-on-plug ignition systems and the data from measurements of an ignition system with a peaking capacitor. Recommendations for increasing general ignition efficiency and effectiveness will also be included.

INTRODUCTION

Power-enhanced ignitions have demonstrated an ability to extend the lean burn limits and transient response of spark ignition engines.[5, 6, 7] These ignitions have been of three types; plasma jet, double discharge, and low inductance peaking capacitors across the spark plug. Plasma jet and double discharge experiments date to the early 1970's and the peaking capacitor data was generated in the 1990's. Additional benefits resulting from the use of these types of ignitions include better starting and cold operation, and lower combustion pressure variability.[6, 7] In contrast to the plasma jet and double discharge types of ignition, the high-voltage peaking capacitors significantly increase the electrical-to-plasma conversion efficiency by delivering high current during the resistive phase of the spark discharge.[8, 9] This is critical as it is during this period, the resistive phase, in which the flame kernel is created.

Low-inductance, low-loss peaking capacitors have been developed by Combustion Technology Products Corp. with assistance in testing and electrical characterization provided by Sandia National Laboratories. BP Amoco Polymers also aided in the development process by designing the proprietary dielectric insulator and the materials processing technology for the capacitor design.

While the capacitors developed by Combustion Technology Products Corp. have only recently been available to the public, the concept of placing a peaking capacitor in parallel across a spark plug is not a novel idea as one of the earlier efforts dates back to 1915.[10] The very stringent electrical, mechanical, chemical, and physical requirements placed on the capacitor have prevented a practical application of the technology until recent design and materials breakthroughs.

Adaptation to any engine involves only the installation of non-resistor spark plugs with the peaking capacitors placed directly over and surrounding the spark plug insulator. This technique, as compared to other methods of increasing transfer efficiency, represents the simplest and most economical method of ignition enhancement.

DISCUSSION

IGNITION CIRCUIT ANALYSIS

Prior analysis of the automotive ignition system circuit, from empirical measurements, shows it to have electrical-to-plasma transfer efficiencies of approximately 0.2%.[1] The circuit analysis was presented showing energy transfer efficiency of conventional and modified ignition systems as a function of their circuit parameters. Looking at the Circuit Analysis in Table 1 and referencing line 1 of Table 1, using a typical ignition coil of approximately 10KΩ (R_t), HV leads with transmission resistance (R_w) of 8KΩ, and a standard resistor spark plug with 5KΩ resistance (R_{sp}) results in an electrical-to-plasma transfer efficiency of approximately 0.15%. In line 5 of Table 1, using low resistance coil and HV cables, non-resistor spark plugs, and peaking capacitors increases transfer efficiency to approximately 56%. For all cases, it was assumed that the spark gap breakdown voltage occurred at the maximum excursion of the coil secondary voltage.

Here, energy transfer efficiency is defined as the percent of total energy supplied to the system that is dissipated in the resistance of the spark plug gap.

To be more specific, there are three phases of the spark event; (1) spark gap breakdown (Streamer Phase), (2) heating of the spark channel (Resistive Phase), and (3) the spark resident between the electrodes (Residual Phase). Here we are discussing phase three where a very small fraction of energy per pulse supplied to the primary side of the ignition is dissipated in the ignition spark, typically much less than 1%. This is due to the condition of a high resistance source (coil, HV lead, and resistor plug) driving a low resistance spark gap. In this condition very little energy can be dissipated in the spark.

By installing the peaking capacitor on and over a non-resistor spark plug, the assembly is isolated from the high resistance drive circuit and the low resistance capacitor is now driving the low resistance spark gap. The breakdown voltage (Phase 1) and spark duration (Phase 3) as well as ignition timing remain unchanged.

To summarize this analysis, conventional ignition systems, including the latest coil-on-plug types, have very high components of resistance throughout the circuits (> 10KΩ), particularly on the secondary side of the coil that feeds the spark plug. The spark resistance, whether operated in a very high current or standard low current mode, is very small by comparison (approximately 50-100Ω).

With the peaking capacitor technique, transfer efficiencies approaching 50% can be achieved even with the high circuit resistance components. Again, this assumes that the secondary energy store (peaking capacitor) is properly matched to the primary store (primary capacitor) and the peaking capacitor is allowed to reach maximum voltage before it is discharged.

In practice, however, the spark plug gap typically breaks over at voltage levels below the theoretical maximum, discharging the peaking capacitor and limiting higher transfer efficiencies associated with higher charge voltages. The residual energy in the ignition circuit subsequently flows through the system and supplies the long duration, low level current that sustains the ignition process during Phase 3 of the spark event. During idle and low-load conditions, break down (Phase 1) voltage levels are well under the theoretical maximum with smaller transfer efficiency but with peak current discharges of approximately 300-400 amps. Under heavy load conditions and breakdown voltages approaching theoretical maximum, the energy transfer efficiency approaches 50% with peak current discharges of over 1000 amps.

While higher transfer efficiencies would be possible with more complex and costly ignition circuits, it is clear that the simple addition of a peaking capacitor will increase present energy transfer efficiencies by at least an order of magnitude.

As a matter of interest, utilizing peaking capacitors in the form of pulse forming lines or networks is common practice in the pulsed-power field where high-energy particle accelerators, laser drivers, radar systems and pulsed RF generators are designed. In these applications the peaking stage typically acts as an impedance matching device and controls the duration of the discharge. Without the peaking stage, these machines would be exceedingly inefficient. The same principal applies to ignition systems.

Table 1. Circuit Configuration Parameters

CIRCUIT CONFIGURATION	PARAMETERS UNITS								
	Rp ohm	Lp mH	Ls H	Cpc pF	Rt ohm	Rw ohm	Rsp ohm	Rs ohm	Eff %
STD Coil, HiR Wire, Res Plug	1	3	30	0	10K	8K	5K	50	.15
STD Coil HiR Wire, Non-R Spark Plug	1	3	30	0	10K	8K	0	50	10.1
STD Coil HiR Wire, Non-R Plug Pk Cap	1	3	30	80	10K	8K	0	10	49
80:1 Lo R Coil, Lo R Wire, Res Plug	.005	.008	.05	0	12	100	5K	50	.38
80:1 Lo R Coil, Lo R Wire, Non-R Plug, Pk Cap	.005	.008	.05	80	12	100	0	10	56
50:1 Lo R Coil, Lo R Wire Non-R Plug, Pk Cap (Matched CKT)	.005	.008	.05	110	12	100	0	10	60
50:1 Lo R Coil, Lo R Wire, Res Plug	.005	.024	.062	0	8	100	5K	50	.38
50:1 Lo R Coil, Lo R Wire Non-R Plug, Pk Cap	.005	.024	.062	80	8	100	0	10	41.5
50:1 Lo R Coil, Lo R Wire Non-R Plug, Pk Cap (Matched CKT)	.005	.024	.062	360	8	100	0	10	78

For All Circuits: Cp=1microF, Ct=40pF, C_S=l0pF, L_{SP}=25nH

For reference, the circuit diagram and results of the analyses are included in Table 1 and Figure 1.

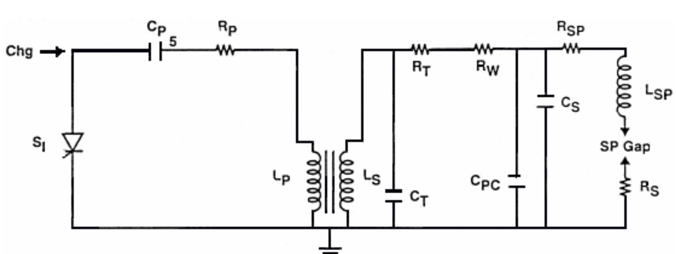

Figure 1. Capacitor Discharge Ignition System

The analysis was performed in 1996 from then currently available ignition systems. This analysis, however, is valid for even the very latest ignition offerings from the major automobile manufacturers. The coil-on-plug technique reduces or eliminates the transfer losses attributed to the high voltage cables but does not mitigate the losses caused by the coil and spark plug resistances. The coil used on the coil-on-plug applications still has over 10KΩ resistance of the secondary winding and the spark plug used in this method has approximately 5KΩ. With comparatively low primary side resistance and no capacitance in the secondary circuit, the transfer efficiency may be approximated by:

$$\eta \approx \text{Rspark} / \text{Rcoil} + \text{Rsparkplug}$$

By replacing the resistor spark plug with a non-resistor type, the transfer efficiency of present day ignition systems increases to about 10% due to the 10pF capacitance of the spark plug discharging directly into the spark. This simple exchange of components illustrates the function of a peaking capacitor. By increasing the capacitance to 90pF, the transfer efficiency increases to nearly 50%.[1]

The original function of the resistor in the spark plug was suppression of radio frequency (RFI), which causes severe static on the radio. Early attempts to shield the “noise” can be seen on mid-60’s corvettes where a grounded stainless steel shroud was placed surrounding the distributor. European vehicles were delivered with metal shrouds covering the spark plug at the end of spark plug boot, grounding to the engine block and effectively eliminating the RFI. In today’s vehicles, RFI can cause engine ECU malfunction resulting in poor or failed engine operation, increasing the need for suppression. The peaking capacitors duplicate the European method of suppression by shunting the noise to ground and eliminating any feedback RFI to the ECU.

CURRENT ANALYSIS

The current discharged by the peaking capacitor during the resistive phase of the arc is significant as compared to current levels of present ignition systems. While the charge level of the peaking capacitor is not optimized due to the varying levels of voltage required to break down the spark gap during typical operation of the engine, the current discharge is orders of magnitude higher than that of conventional ignition. As seen in Figure 2, a 90 pF capacitor charged to 18 KV produces a max current of 1020 A to the spark. This is visible on the left in Figure 3, as compared to the standard resistor spark plug on the right side of the figure.

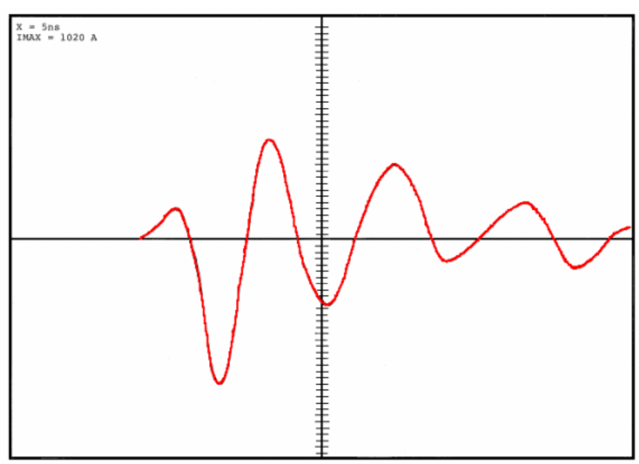

Figure 2. Peaking Capacitor Ringdown Current, 10ns

Figure 3. Spark Comparison

The secondary peak current of present day conventional ignitions ranges between 25 and 50 milliamps. For a comparison of peak spark power, consider the formula:

$$\text{Peak Power (Watts)} = I^2 \text{(amps)}\ R \text{(ohms)}$$

<u>Conventional Ignition</u>

Peak Power (Watts) = I^2 (amps) R (ohms)
Watts = $(.05 \text{ amps})^2 \times (50\Omega)$
Watts = .0025 X 50
Watts = **.125 Watts** peak power

<u>Peaking Capacitor</u>

Peak Power (Watts) = I^2 (amps) R (ohms)
Watts = $(1020 \text{ A})^2 \times (5\Omega)$
Watts = 1,040,400 X 5
Watts = **5.2 MW** peak power

The resistance of 50Ω for the first example is taken as the nominal resistance of a long-duration, low-current spark. The resistance of 5Ω for the second example was calculated from the Ristic-Sorensen formula[9] for resistive phase of a spark in the nano-second regime.

This comparison illustrates the difference in peak spark power with and without the use of a peaking capacitor. Dissipating more energy through the spark results in creating a larger and more consistent (relative to crank angle) flame kernel.

ELECTRODE EROSION

The high initial current produced by the peaking capacitors invariably raises concern over excessive erosion of the spark plug electrodes. However, observations and measurements made during a period of over ten (10) years have established that the erosion rate with the peaking capacitors is very close to that of normal ignition.

The discussion of electrode erosion, therefore, will be limited to the power transfer issue alone and not contemplate spark gap electrode erosion due to improper timing or heat related issues. The use of special alloys such as thoriated-tungsten, platinum, silver or iridium, which are more resistant to erosion and corrosion, have been the utilized to mitigate the erosion problem. Also used to alleviate erosion is the increased surface area of multiple electrodes. These electrode erosion solution options also will not be addressed here.

The installation of the peaking capacitor includes a spark gap of no more than .045” and operates on a principal of high energy density (hard discharge) as opposed to the large spark gaps more commonly found in the original equipment high energy systems. Over years of studying electrode erosion on non-resistor spark plugs equipped with peaking capacitors from 50pF to over 100pF with voltage levels from 5KV to 20KV, we have observed no more or no less erosion than expected from the particular electrode alloy.

Figure 4. Non-Resistor Spark Plug After 56,000 Miles

However, as seen in Figures 4 and 5, the trend is toward improved resistance to electrode erosion. Figure 4 is a close-up view of the spark gap from a Bosch non-resistor spark plug removed from a 1997 Ford ¾ ton 4-wheel drive pick-up with the 5.4L engine and coil-on-plug ignition after 56,000 miles of operation. Figure 5 is a close-up view of the spark gap from an Accel non-resistor spark plug removed from a 1996 GM Yukon 4X4 SUV with the 5.7L engine with standard ignition after 97,000 miles of operation.

Figure 5. Non-Resistor Spark Plug After 97,000 Miles

COMBUSTION INITIATION

The question of how the combustion process is enhanced by the discharge of the peaking capacitor at the beginning of the initiation period can be understood by observing that the high current delivered for a short duration produces a larger than normal and higher temperature ignition kernel that initiates combustion faster and in a larger volume.[6] The measured result of the prompt high current initiation period is that the pressure level reached in the cylinder is more uniform on a pulse to pulse basis than with conventional low current initiation.[6]

Following the high current combustion initiation stage (Resistive Phase of the spark), which has a total duration of about 35 ns, low level current (milliamps) continues to flow through the spark zone for tens to hundreds of microseconds (Residual Phase) depending upon the circuit parameters. This long duration, low current period appears to be necessary to achieve optimum combustion, although the reasons for its contribution are rather obscure from a theoretical standpoint.

CONCLUSION

The use of coil-on-plug ignition does not increase the electric-to-plasma conversion efficiency of the system. While there may be benefits derived from this strategy such as signal control and clarity, system packaging, or reduction in cable corona, the power dissipated through the spark is effectively unchanged as compared to the distributor or distributor-less ignition systems.

Adding a peaking capacitor across a non-resistor spark plug gap increases transfer efficiency to approximately 50%. The increased hard current discharge initiates a larger than normal flame kernel and begins the combustion process more consistently relative to crank angle than conventional ignition. The larger flame front propagates through the fuel charge more completely and in a shorter period of time.

Operational benefits attributed to the enhanced ignition process include better cold starting, increased torque, reduction in ignition delay, and improved fuel economy. Transient operations are also improved. In addition, there is evidence that exhaust emissions can be reduced not only as a result of lower fuel consumption, but also due to a more complete burn of hydrocarbons. Some of these benefits are derived directly from the reduction in cycle-to-cycle variations in combustion pressures.

Field experience with peaking capacitors clearly demonstrates a reduction in fuel consumption across all types and vintages of internal combustion engines ranging from 2-cycle lawn mowers to 2002 luxury vehicles.

By installing the peaking capacitor, which increases electric-to-plasma conversion efficiency, power draw from the electrical system can be significantly reduced while still dissipating more power across the spark gap.

REFERENCES

1. G.J. Rohwein, "An Efficient, Power Enhanced Ignition System", IEEE Transactions on Plasma Science, Vol. 25, No. 2, April 1997.
2. G.F.W. Ziegler, R.R. Maly and E.P Wagner, "Effects of Ignition System Design on Flammability Requirements On Ultra-Lean Turbulent Mixtures", I. Mech. E., paper no. C47/83, 1983.
3. R. Maly, B. Saggau, E. Wagner and G. Ziegler, "Prospects of Ignition Enhancement", SAE Paper 830478, Feb. 1983.
4. R.W. Anderson, "The Effects of Ignition System Power On Fast-Burn Engine Combustion", SAE paper 870549, Feb. 1987.
5. R.W. Anderson and J.R. Asik, "Lean Air-Fuel Ignition System Comparison In a Fast-Burn Engine", SAE paper 850076, Feb. 1985.
6. G.A. Ball and J.V. Gross, "Evaluation Of a Hard Discharge Ignition System", Advance Powerplant Engineering, Chrysler Corporation Mar. 1986.
7. R. Maly, "Spark Ignition: Its Physics and effects on the Internal Combustion Process", Published in: Fuel Economy in Road Vehicles Powered By Spark Ignition Engines, Hilliard, J.C. and Springer, G.S. (Ed.) Plenum, New York, 1984.
8. J.C. Martin, "Duration of the Resistive Phase and Inductance of Spark Channels", AFWL Switching Note 9, 1965.
9. T.P. Sorensen and V.M. Ristic, "Rise Time and Time-Dependant Spark-Gap Resistance in Nitrogen and Helium", J. Appl. Phys., V. 48, No. 1, pp. 114-117, 1977.
10. V. Lux, "Sparking Plug", USPTO Patent No. 1,148,106, Jul. 1915