EXPERIMENTAL INVESTIGATION OF LEAKAGE CURRENT INFLUENCE ON AUTOMOTIVE SPARK PLUG VOLTAGE WAVEFORM

Bernard FRYŚKOWSKI

Faculty of Electrical Engineering, Warsaw University of Technology
Plac Politechniki 1, Warsaw, +48 22 621 98 25, bernard.fryskowski@ee.pw.edu.pl

Summary

The misfire effect in an automotive ignition circuits is caused by parasitic spark plug shunt resistance resulting in leakage current flow. The main explanation for leakage current flow through a spark plug insulator is insulator surface contamination or dielectric failure. Practical measurements show that the spark plug waveforms analysis could be used for diagnostic purposes to recognize the presence of shunt resistance in secondary ignition circuit. A novel method of leakage current simulation and a prototype of an adjustable ignition coil electric load able to operate at high – voltage were proposed. Energy dissipated by adjustable electric load, spark plug voltage and leakage current measurement results were presented. A change in the shape of spark plug voltage and current waveforms caused by leakage current was analyzed and discussed.

Keywords: ignition systems, spark plugs, spark ignition engine, vacuum tubes, car diagnostics

DOŚWIADCZALNE BADANIE WPŁYWU PRĄDU UPŁYWU NA PRZEBIEG NAPIĘCIA ŚWIECY ZAPŁONOWEJ

Streszczenie

Zjawisko wypadania zapłonu w samochodowych układach zapłonowych wywołane jest obecnością niepożądanej rezystancji bocznikującej, która wywołuje przepływ prądu upływu. Głównym powodem obecności prądu upływu izolatora jest zanieczyszczenie jego powierzchni lub degradacja właściwości izolacyjnych dielektryka. Wyniki pomiarów wykonywanych w praktyce dowodzą, że analiza przebiegu napięcia na świecy zapłonowej może być wykorzystana na potrzeby identyfikacji obecności rezystancji bocznikującej w obwodzie wtórnym cewki zapłonowej. W pracy zaproponowano nową metodę symulacji przepływu prądu upływu oraz prototyp regulowanego obciążenia obwodu wtórnego cewki zapłonowej mogącego funkcjonować w warunkach wysokiego napięcia. Przedstawiono wyniki pomiarów energii rozproszonej dzięki regulowanemu obciążeniu, napięcia na świecy zapłonowej oraz natężenia prądu upływu. Dokonano analizy wpływu obecności prądu upływu na kształt wykresów napięcia i prądu świecy zapłonowej.

Słowa kluczowe: układy zapłonowe, świece zapłonowe, silnik o zapłonie iskrowym, lampy elektronowe, diagnostyka samochodowa

1. INTRODUCTION

Automotive ignition coil's primary and secondary voltage measurements performed with an oscilloscope and high - voltage waveform analysis is a well-known method used by car–service staff to diagnose ignition circuit failures. Additionally, primary current measurements are useful to calculate electric energy stored in the magnetic field of ignition coil. The ignition coil efficiency calculation would be possible knowing product of instantaneous ignition coil's secondary voltage and current values. Unfortunately, electric current in the secondary winding is hardly ever taken into consideration because it is rather difficult to measure it. Therefore, spark plug current measurement results were published relatively seldom [1]. One of the most important factors affecting spark energy is spark plug failure resulting in misfire due to parasitic leakage current. The aim of this work is experimental investigation of leakage current influence on automotive spark plug voltage waveform. An apparatus being an electronic load of the secondary ignition coil winding was utilized for simulation and measurement purposes. The working principle of the electronic load able to act as an adjustable high-voltage shunt resistor of a spark plug was discussed in [2].

The air-fuel mixture is compressed in the combustion chamber and ignited by a high-energy spark from a plug. The spark is a high - voltage discharge observed in the air gap of the plug. It is produced due to magnetic field energy stored in the ignition coil. Spark plug electrodes are insulated by a ceramic insulator typically made of sintered alumina. The typical electric energy transmission process from the ignition coil through high–voltage ignition cables to the spark plugs introduces energy losses because of secondary winding resistance connected in series with coil terminals and spark plug leads, voltage drops across ignition cables and noise suppressors implemented to reduce radio frequency interference caused by electrical discharges. On the other hand the parasitic spark plug shunt resistance causes leakage current flow. Parasitic currents have a negative influence on the automotive ignition system observed in case of spark plug fouling, insulator surface contamination or erosion, axial and radial cracks. The leakage current can flow through conductive insulator surface to the ground electrode. It is generally believed that leakage current causes spark energy dissipation resulting in sporadic ignition problems and even misfire. The spark plug fouling, analyzed in [3 - 5], occurs at low - temperature engine start. The commonly held opinion among technicians is that this effect might be negligible at temperatures higher than 500°C [6]. Nevertheless, the investigation results published in [7-10] draw attention to insulator size, it's geometry or fuel and electrodes quality as key factors that affect spark plug fouling.

The problem of leakage current flowing through contaminated ceramic insulators was discussed in papers [11, 12]. The mathematical models of this effect were presented in [13, 14]. The leakage current waveforms were discussed in [11] as measurement result performed with high-voltage probes and oscilloscope. However, the published data were applied to power energy insulators operating in other environmental conditions than automotive spark plug insulators. The mechanism of ceramic insulator degradation and erosion produced by pulsed high-current surface discharges was analyzed in [15]. It was stated that insulator degradation process involves complex thermochemical interactions between the arc channel, the ambient gas and the insulator material decomposition into conductive particles. Furthermore, quantitative assessment of the erosion process can be carried out taking into consideration decrease in the surface breakdown voltage and material's mass loss. Spark plug dielectric properties investigation can be realized by insulation conductivity measurements [10], local capacitance measurements [16] or high-voltage pulses application to the tested plugs samples [17 – 20]. Even assuming that the ceramic insulator is in good condition, the leakage current can be caused by wet or contaminated insulating silicone cover surrounding the spark plug. Summarizing the parasitic shunt resistance problem it is stated that the leakage current can increase due to some external factors such as ambient temperature, atmospheric pressure, absolute humidity etc.

2. THE EFFECT OF SHUNT RESISTANCE ON THE SPARKING PERFORMANCE

The total current in actual dielectrics equals the algebraic sum of resistive current, capacitive charging current and absorption rate flowing through the insulator volume and it's surface. The leakage current discussed in this work is represented by the resistive component. The air gap of a spark plug can be shunted due to insulator tip fouling, surface contamination, cracks and punctures. The equivalent circuit of a spark plug insulator considering parasitic shunts is shown in figure 1.

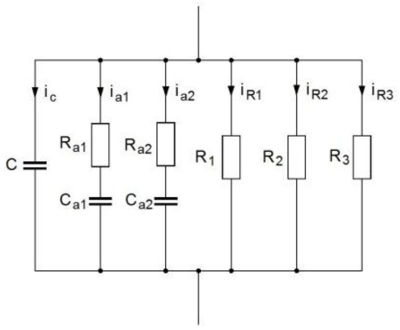

Fig. 1. Equivalent circuit of a spark plug insulator

The resistors R_1, R_2 and R_3 represent insulator conductivity, fouling effect and surface contamination respectively. The capacitive charging current i_c has no influence on the energy losses unlike the absorption currents i_{a1} and i_{a2} as well as leakage currents i_{R1}, i_{R2} and i_{R3}. The insulator tip fouling effect is observed at plug temperature below 500°C. The conductive carbonized particles deposited on the surface of the insulator shunt the plug electrodes but they are burned out at higher temperature. The ceramic material volume conductivity is relatively low and can be neglected, hence the most significant factor determining leakage current flow is the surface conductivity caused by contaminations. The leakage current can flow like in case of a purely resistive load or it can produce electric arc (Fig. 2).

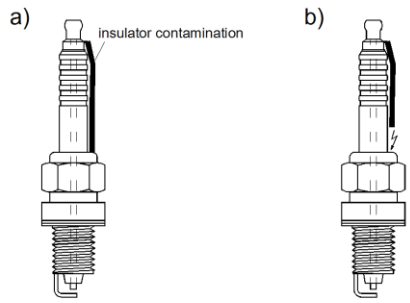

Fig. 2. Leakage current flow: (a) insulator contamination acting as resistive load, (b) electric arc forming

The external insulator surface of a spark plug is glazed to protect the insulator from contamination and moisture. The ribs located on the top impede leakage current flow. Persisting arcing observed on the insulator surface can damage the glaze layer revealing alumina core (Fig. 3).

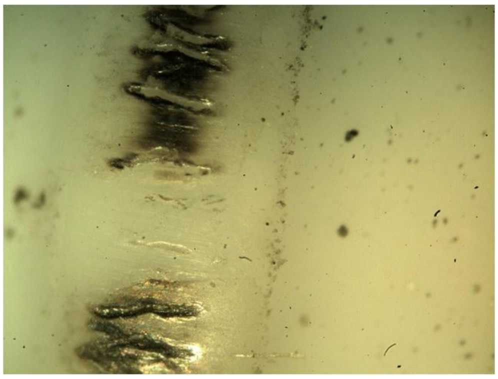

Fig. 3. Insulator surface damage caused by arcing

The carbonized particles visible on the insulator surface decrease the resistance, hence the surface conductivity becomes higher. On the other hand the alumina sinter permittivity can rise due to moisture absorption causing insulator axial cracks or punctures.

3. EXPERIMENTAL SETUP

The igntion citcuits of today's cars can produce enough energy to ignite the air–fuel mixture even for starting engines in cold weather or in case of energy losses. An interesting topic is minimal energy able to ignite the air–fuel mixture and avoid misfire. This energy can be evaluated using two methods – primary winding voltage lowering or variable load of the secondary winding. The first method is less suitable because it decreases the ignition circuit efficiency. The other method based on high-voltage resistors, igniters or Zener diodes chain is recommended in standards [21, 22]. The main disadvantage of discussed method is that the variable load of the secondary winding can be achieved stepwise only. This work introduces the concept of adjustable electronic load based on vacuum tubes. The electric diagram explaining the idea is shown in figure 4.

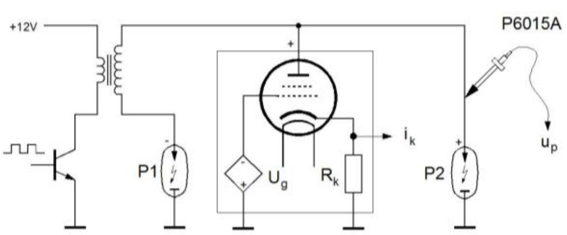

Fig. 4. Adjustable electronic load concept suitable for ignition circuits

The current probe for automotive ignition circuits described in [2] acting as an adjustable electronic load was used. In Figure 4, a high-voltage tetrode is shown as an electronic load in a cathode-follower connection. The vacuum tube dissipates a part of spark energy acting as an adjustable shunt controlled by grid bias voltage U_g. The tetrode is connected in parallel to the positive polarized spark plug P2.

The action of a tetrode can be described according to Child – Langmuir law [23]:

$$I_p = G\left(U_g + \frac{U_p}{\mu}\right)^{\frac{3}{2}} \quad (1)$$

where I_p is the plate current, G – perveance (depending on geometrical factors of the tube), U_p – plate voltage, U_g – grid voltage and μ - amplification factor.

The adjustable plate resistance R_p is defined at constant grid voltage U_g by following formula [23]:

$$R_p = \frac{dU_p}{dI_p} \quad (2)$$

The cathode current can be calculated as the sum of the plate current I_p and DC components of grid currents I_{g1} and I_{g2} (usually neglected). The instantaneous cathode current i_k may be found from equation (3) [2].

$$i_k = \frac{u_p + \mu U_g + g_m U_{g2}}{R_p + R_k} + I_g + I_{g2} \quad (3)$$

where: u_p – instantaneous plate voltage, μ - amplification factor, g_m – mutual conductance, U_g - control grid bias voltage, U_{g2} –screen grid voltage.

The output waveform representing simulated leakage current is taken across R_k resistor. According to the Joule's low the dissipated component of the spark energy E_d can be calculated as shown in equation (4).

$$E_d = \int_{t_0}^{t_f} u_p\, i_k dt \quad (4)$$

where: t_0 and t_f – initial and final values of time, t – spark duration.

The E_d energy does not take part in air-fuel mixture ignition process. If the shunt resistance is low enough, the spark plug P2 is not fired causing misfire effect in the combustion chamber. It is important to note that the electronic load shown in Fig. 4 can be applied for ignition systems equipped with double–ended ignition coils only because of positive vacuum tube plate polarity.

4. LEAKAGE CURRENT INFLUENCE ON SPARK PLUGS OPERATION – EXPERIMENTAL RESULTS

The experiments were performed on Daewoo 1.6-litre, 4-cylinder engine fueled with petrol 95 RON. The ignition system was equipped with GM Opel Daewoo double–ended four-spark ignition coil and four BKR6E-11 spark plugs (internal resistance 16.3 kΩ) with standard 1.1 mm air gap. The ignition cable resistance was 3.9 kΩ. Spark plug and plate voltages were measured using passive voltage probe Tektronix P6015A. The engine operating point was selected at 1200 rpm. Measurements were taken at variable secondary winding load depending on vacuum tube grid bias voltage.

The experimental results are discussed referring to the correct spark plug voltage waveform at no load condition captured by Tektronix TDS2004B oscilloscope (sampling rate 1GS/s) stored in reference waveform memory Ref C. Figure 5 shows the spark plug voltage (channel 1) at high plate resistance of the tetrode.

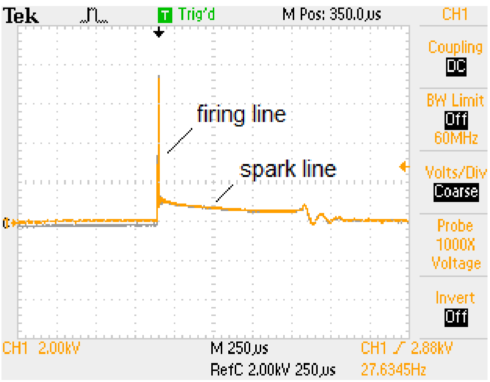

Fig. 5. Spark plug voltage (channel 1) at -5,5V grid bias voltage compared with spark plug voltage stored in Ref C at no load

Generally, a spark plug voltage waveform consists of three segments – firing line observed at breakdown voltage, spark line representing the voltage level at which the ionization turns to plasma and the oscillations at the end of the spark duration. The tetrode grid bias voltage resulting in high plate resistance of the tetrode was -5,5V. As a matter of fact no energy is dissipated in the vacuum tube, hence the observed spark plug voltage does not significantly differ from the correct spark plug voltage waveform stored in Ref C.

The spark plug voltage waveform recorded at tetrode grid bias voltage 0V is shown in figure 6.

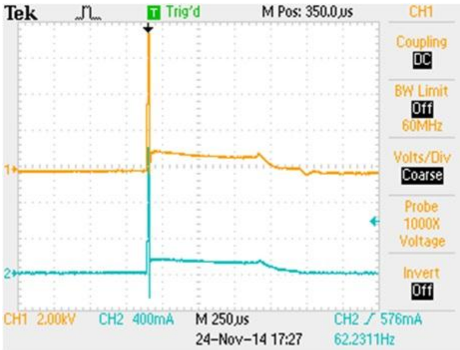

Fig. 6. Spark plug voltage (channel 1) and shunt current (channel 2) at 0V grid bias voltage

The shunt current adequate to the cathode i_k is represented by the waveform observed on channel 2. Spark energy loss calculated according to equation 4 was 2,51mJ. The spark plug voltage waveform at 0V grid bias voltage compared with spark plug voltage stored in Ref C at no load is presented in figure 7.

Fig. 7. Spark plug voltage (channel 1) at 0V grid bias voltage compared with spark plug voltage stored in Ref C at no load

Once an amount of energy produced by ignition coil is dissipated in the tetrode circuit oscillation suppression and significant spark line shortening are observed.

The oscilloscope trace of figure 8 shows spark plug voltage and shunt current recorded at 2,5V grid bias voltage.

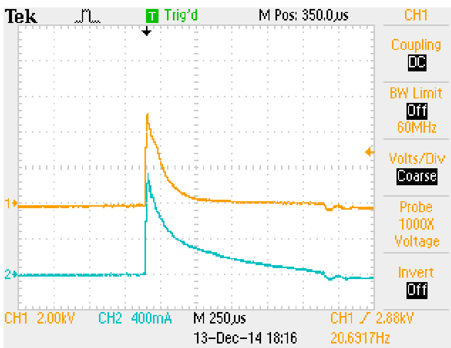

Fig. 8. Spark plug voltage (channel 1) and shunt current (channel 2) at 2,5V grid bias voltage

The amplitude of spark plug voltage representing firing line decreases causing misfire effect. This also leads to a change in the shape of the voltage and current waveforms, whereby the spark line is not observed (compared to the figures 5, 6 and 7). The spark plug P2 shown in Fig. 4 is not fired, therefore the total energy generated by ignition coil is dissipated in the tetrode circuit.

The spark energy calculated according formula (4), dissipated by shunt circuit is given in Table 1.

Table 1. Spark energy versus control grid voltage

Grid voltage (V)	Spark energy (mJ)	% of total energy stored
-0,5	1,63	16,1
0	2,51	24,8
0,5	3,68	36,4
1	5,63	55,7
1,5	7,10	70,3
2	8,97	88,8
2,5	9,91	98

The total spark energy measured in the ignition circuit was 10,1mJ.

5. CONCLUSIONS

The misfire effect in an automotive ignition circuit can occur for a number of reasons. One of them is parasitic shunt resistance connected in parallel to the spark plug. The parasitic resistance presence results in spark energy decrease. High–voltage waveforms captured by an oscilloscope connected to secondary winding of ignition coil are useful for ignition circuit troubleshooting. Variable length of ignition line observed along with controlled shunt resistance change is an evidence that precise spark voltage analysis allows to predict the leakage current causing misfire effect related to ignition problems (a weak spark or spark missing) or even failure in a catalytic converter in the future. In this paper leakage current influence on automotive spark plug voltage waveform was investigated. A novel method of leakage current flow simulation based on high–voltage vacuum tubes was delineated. More detailed experimental analysis of spark plug voltage affected by leakage current was realized due to vacuum tube plate resistance control. Taking into consideration spark plug voltage and leakage current measurement results the dissipated component of the spark energy could be calculated. Practical measurement shows that the spark plug waveforms analysis could be used for diagnostic purposes to recognize the presence of shunt resistance in secondary ignition circuit.

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Bernard FRYŚKOWSKI, PhD – lecturer and postdoctoral researcher at Faculty of Electrical Engineering, Warsaw University of Technology. Areas of research expertise – automotive electrical systems, electronics, car diagnostics, combustion engines, ignition systems, in-vehicle data transmission networks.