Daniel KORENCIAK[1], Matej KUBIS[1], Milan SEBOK[1], Miroslav GUTTEN[1], Matej KUCERA[1]
University of Zilina, Slovakia (1)

doi:10.15199/48.2020.09.10

Analysis of Automotive Ignition Systems in Laboratory Conditions

***Abstract**. Paper presents basic principles and diagnostic analysis of automotive ignition system for various working and adverse states in laboratory conditions. In the first part of the paper it is examined description and importance of basic diagnostics of automotive ignition system. In the second part of paper they are described on basic principles and solution of spark plug model. In the next part of paper it is focused on proposed test laboratory device for fault simulation. In the finally, specialized measurements were made on the proposed measurement system by simulating faults by applying oil and gasoline between the electrodes and failing to make the ignition contact of the driver on the spark plug.*

Streszczenie.** Artykuł prezentuje laboratoryjną analizę diagnostyczną samochodowego systemu zapłonowego w różnych warunkach pracy. Dokonano przeglądu metod testowania i zaproponowano nowy system diagnostyczny. Przeprowadzono też symulację defektów. **Analiza samochodowego systemu zapłonowego w warunkach laboratoryjnych.

Keywords: Ignition systems, spark plug model, test laboratory device, diagnostics, failure simulation
Słowa kluczowe: system zapłonowy, diagnostyka, symulacja błędów

1. Introduction

Recent trends in the automotive industry lead to an increase in performance and a reduction in the production of pollutants contained in the exhaust gas, while also reducing fuel consumption. This is also associated with a huge development in the field of ignition systems of internal combustion engines. Ignition systems are among the most important in the field of engine management, so great emphasis is placed on the diagnostics itself and the determination of the exact failure [1].

The ignition system is equipped with an ignition module (high-voltage transformer), power electronics (transistors with protective circuits) and a spark plug. The ignition system is controlled by generating signals by the control unit which are led to the power module. On the basis of the signals, transistors are opened, thanks to which the current flows through the primary side of the ignition coil. When the transistor is closed, the energy is transferred from the primary side to the secondary side [2], [3].

Modelling of the spark plug during discharge of the ignition coil is problematic. The current passing between the electrodes is the dominant ignition current. The corresponding spark plug design is shown in Fig. 1 [4].

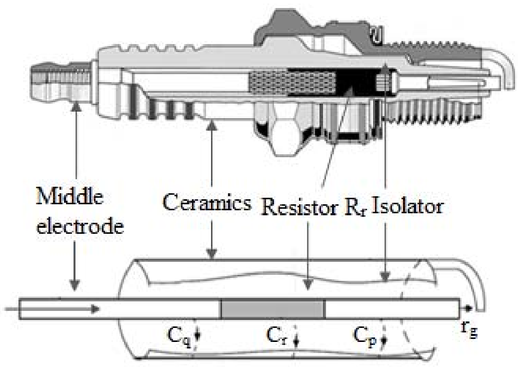

Fig. 1 The model of a spark plug

A replacement model of the ignition assembly constructed by using the Fig. 2 spark plug model, where R_r is a series resistance and its value depends on the design solution, r_g is the spark plug air gap resistance, and C_q, C_r and C_p are parasitic capacities between the middle electrode and the sheath.

The following equations can be derived from Fig. 2

$$C_4 = C_q + \frac{C_r}{2}, \quad (1)$$

$$C_5 = C_p + \frac{C_r}{2}, \quad (2)$$

$$C_3 = \frac{C_w}{2}. \quad (3)$$

DC power supply voltage is marked U_S. R_1 and R_2 are respectively primary and secondary winding resistances, L_1 and L_2 are respectively the primary and secondary winding inductance, R_w is the high-voltage conductor resistance and M is the mutual inductance coefficient between the primary and secondary sides, C_w is the parasitic capacitance between the high-voltage wire and the shell. It is obvious from the replacement ignition circuit that the transition from the steady state is associated with a change in the electromagnetic energy W (t) in the circuit [4], [5].

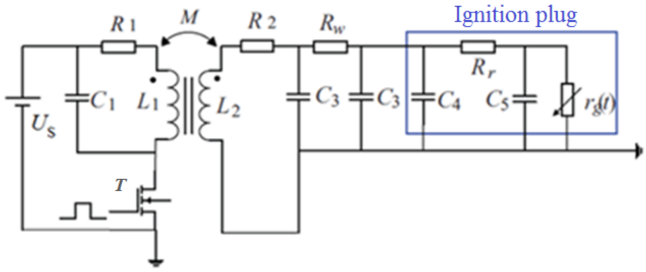

Fig. 2 A replacement model of the ignition assembly

2. Proposed Test Laboratory Device

In order to evaluate the correct operation of the ignition system, it is necessary to check the time course of the voltage and current of the high-voltage module by measuring. By measuring and evaluating the characteristics, it is possible to determine the state of the ignition system and to determine the reduced functionality.

A device has been created to obtain the necessary signals. The device allows creating fault states and monitoring changes in output characteristics. Fig. 3 shows a wiring diagram of a test device that includes a control signal generator, power module, high voltage module, and spark plugs. The diagram also contains measuring points for direct connection of oscilloscope and capacitive probe.

The signal generator replaces the motor control unit in a simplified form. It is a programmed 8-bit microprocessor DC9S08QE. With the help of the buttons it is possible to activate the generator and change the time intervals during which the energy accumulates on the primary side of the ignition coils.

For information on the set signal generation mode, the generator also includes an LCD display. The signal generator allows generating a switch-on time t_{on} ranging from 0 to 9ms and a switch-off time t_{off} between 10 and 500ms in 1ms steps. Generation is performed for five channels. The display unit shows the mentioned times, the generator activation status and the estimated four-stroke engine speed. The generator produces 5 volts voltage levels. Output circuits contain optocouplers for galvanic isolation. The power module converts the low-power 5 volts voltage signals to power. It is powered from a 12 volts power supply. The component contains a charging current limitation, which can also be seen in the current characteristics.

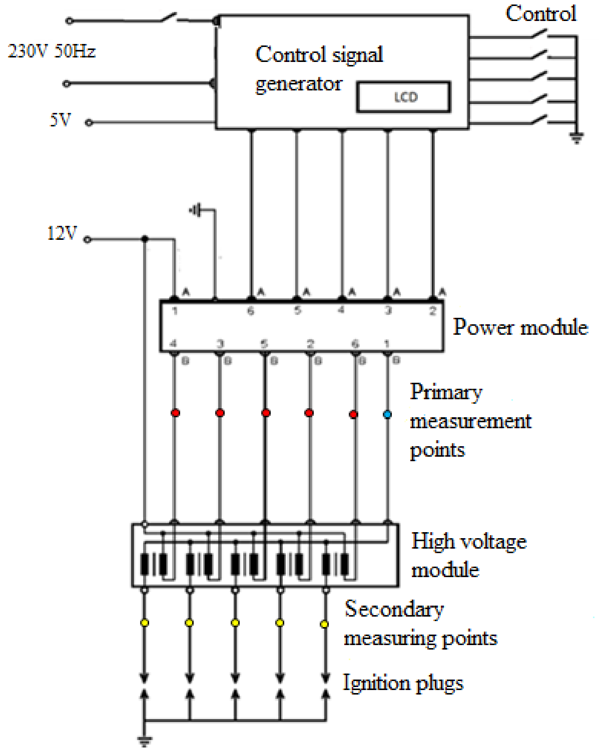

Fig. 3 Ignition system wiring diagram

The current limitation is to prevent the ignition coil from being supersaturated. The high voltage module is a block containing high voltage ignition coils. They are voltage transformers whose primary tents resistance is approximately 1.5Ω and secondary 5-10kΩ. The primary sides of the coils are connected all together to the 12V voltage and by means of transistors the connection is made to ground (vehicle ground).

Spark plugs must be designed to withstand the aggressive working environment of the combustion chamber and to ignite the mixture. Ignition of the fuel mixture is accomplished by creating an electric arc between the contacts. Connection between high voltage module and spark plugs is made with high voltage conductors with increased resistance from 5 to 10kΩ.

Spark plugs also have an increased resistance and are 3-6kΩ depending on design type. As the temperature rises, the candle resistance decreases. The measuring points are placed in such a way that important signals can be detected, which give us information about the state of the ignition system. The constructed device is shown in the Fig. 4.

The device allows creating fault states in individual blocks, which also affects the change of electrical quantities, which can be subsequently measured and evaluated.

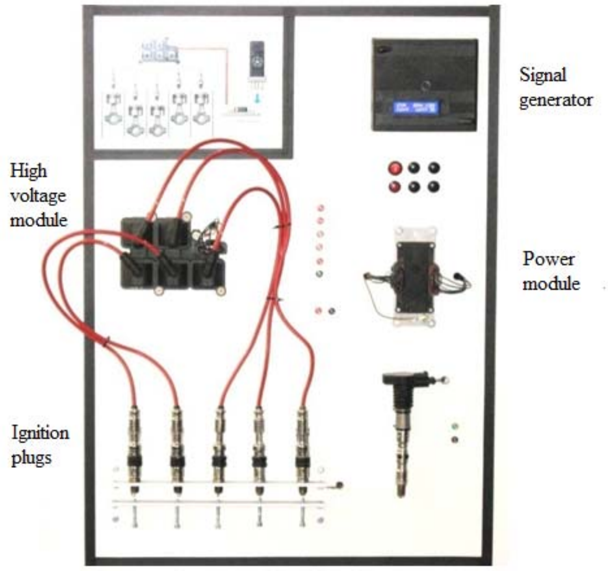

Fig. 4 Ignition system test equipment

3. Processing of results

Let us consider that we have a time course of measurable quantity. If we then compare this signal with the desired signal, we can evaluate the residue based on the difference. Failure assessment using a residual assessor not only allows us to detect component failures but can provide us with information about component degradation. The best solution for detecting a failure and possibly making a component prognosis is to monitor the course of the arc burning on the spark plug. By measuring the voltage on the primary or secondary side we get information about the arc burning or eventually the inactivity of the ignition system. Fig. 5 shows the current and voltage waveforms on the primary side of the ignition module for the set interval t_{on}=3ms. The voltage characteristic shows the influence of the secondary side, where it is possible to observe the initial impulse for arc formation and burning time in our case of approximately 2ms.

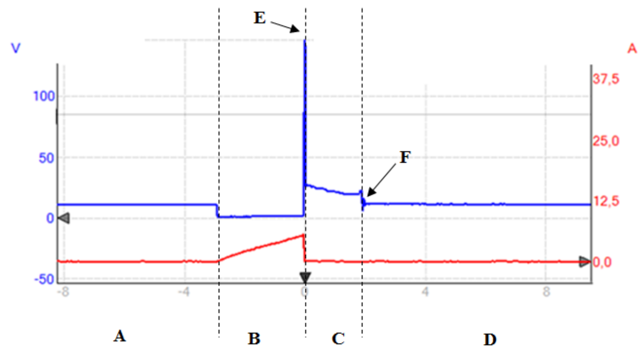

Fig. 5 Current and voltage waveform on the primary side of the ignition module:
A- ignition module inactivity, B- energy storage interval, C- arc burning time, D- ignition module inactivity, E- Initialization of arc burning, F- ignition coil oscillations.

By using the ADC converter of the engine control unit to monitor the signals on the primary side of the ignition module and then applying a suitable algorithm, it is possible to increase the diagnostics of the ignition system. If we observe the signal in the interval A (or D) we can evaluate whether the primary winding of the ignition module is damaged by interruption or whether the supply voltage has been disconnected. During the energy storage period B, the transistor in the power module opens. At this interval, the voltage is equal to the voltage drop across the transistor. The current increases depending on the parameters of the ignition coil. By evaluating the current increase and the maximum value, it is possible to determine the short in the winding, which would result in a change in inductance and a decrease in series resistance.

The interval C is essential for determining the arc burning condition. If there was a significant failure during A and B, there would be no burning interval. In this mode, the transistor is closed, and the energy stored on the primary side of the ignition coil is transferred to the secondary part. Voltage is greater than 10kV and is required for the initial combustion of the arc in the combustion chamber. This voltage is more than a hundred volts on the primary side. Each diagnostic system works by evaluating the measured signals in certain modes and comparing them with the desired signals. [6], [7]

Voltage simulation was created in LabVIEW environment (Fig. 7), where individual time periods are described, which are described by mathematical functions.

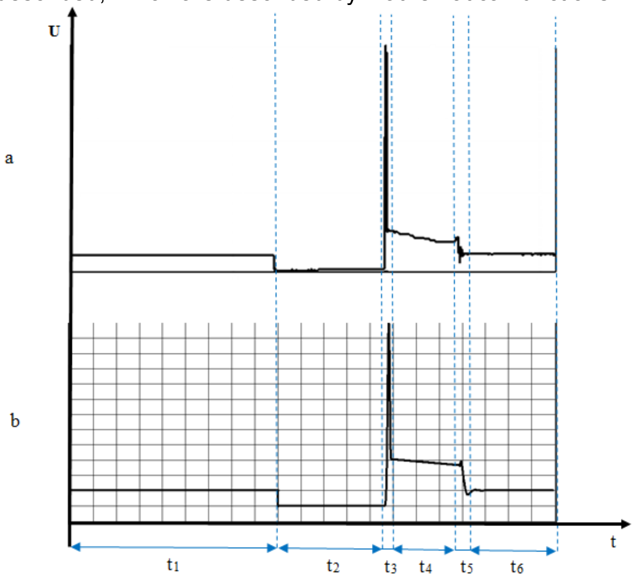

Fig. 6 Voltage waveform on the primary side of the ignition module: a - real, b - simulated

LabVIEW lets you export the simulated waveform to a spreadsheet program. Thus, the waveform can be used as a reference for signal testing. If we can determine the reference course of combustion, we can further introduce tolerance zones to detect partial and permanent failure. [8]

The first tolerance band may be for detecting a partial fault (Fig. 8 green).

The second tolerance zone (orange color) is intended to determine the inactivity of the ignition system. At least two measurements should be made during the intervals depicting the arc burning. The length of arc burning is almost 2ms. In time about 0.5 and 1.5 ms for the built-in online diagnostics, a test cycle would also have to be created, allowing for example to be checked only after the car has warmed up to operating temperature and partially loaded at medium engine speed with a minimum of 5 test cycles over 10 minutes.

Fig. 9 illustrates the sampling of arc burning that must be performed from time t_0. It is possible to realize only one measurement at time t_{z2}, which is sufficient for us to evaluate arc burning.

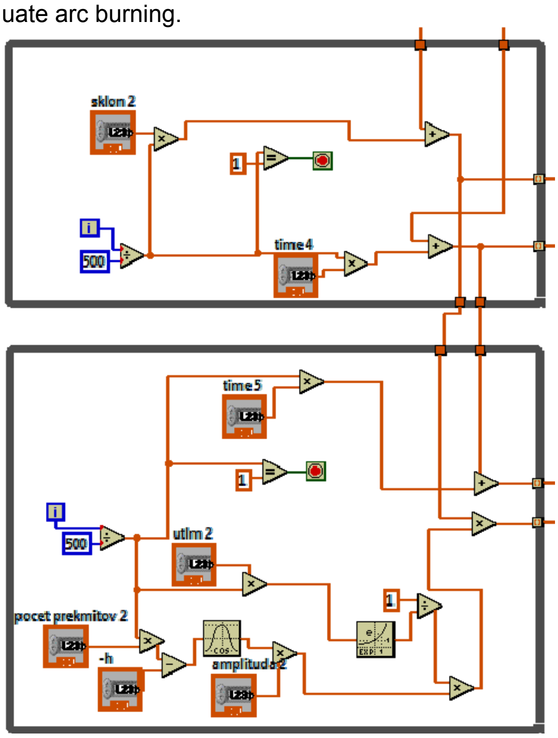

Fig.7 Part of the block diagram from LabVIEW to simulate intervals t_4, t_5 a t_6

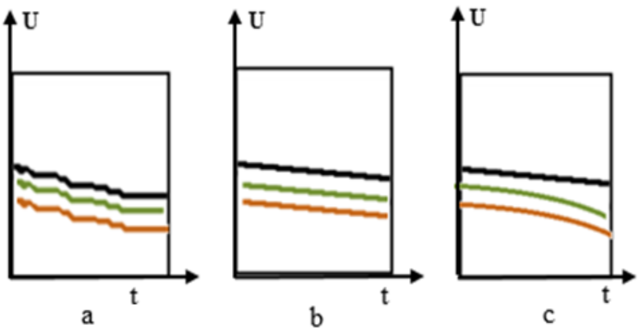

Fig. 8 Arc burning interval t_4 with tolerance zones: a- real, b- simulated, c- simulated with adjusted tolerance zones.

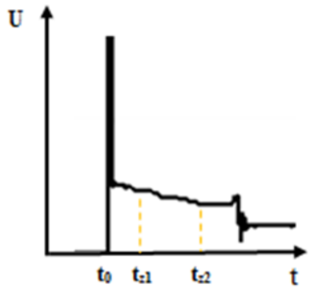

Fig. 9 Arc burning interval with two sampling points

4. Measured results with simulated faults

The measurement was performed at atmospheric pressure and on a four-electrode spark plug. The oscilloscope sampling was set to 100kS/s (time between samples is 10μs). The transformer charging phase was set to 6ms. The measurement was repeated and recorded five times. Fig. 10 is a characteristic showing the voltage on the primary side of the ignition module.

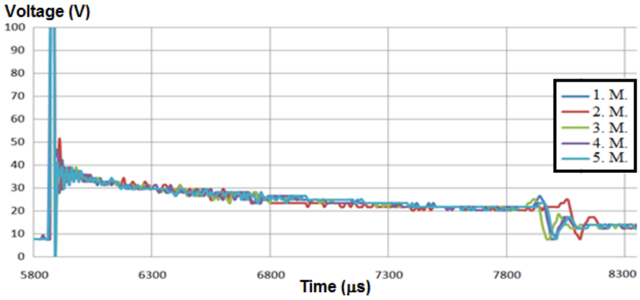

Fig. 10 The course of voltage during arc burning

By applying a small amount of gasoline to the spark plug, the arc fading scattering occurred (Fig. 11). Petrol changed the air gap properties between the electrodes.

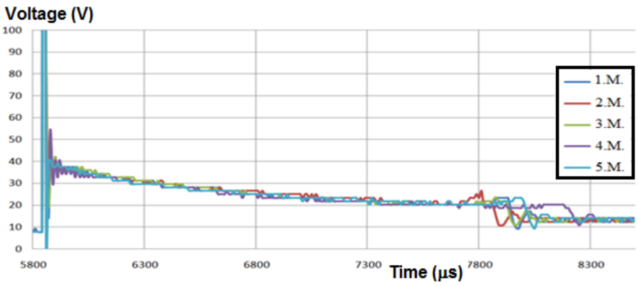

Fig. 11 The course of voltage during arc burning by applying gasoline

The oil was more radical in the characteristic (Figure 12). The reverberation of the arc burn was more oscillated, and the burn time was also reduced by 250 ± 100 µs.

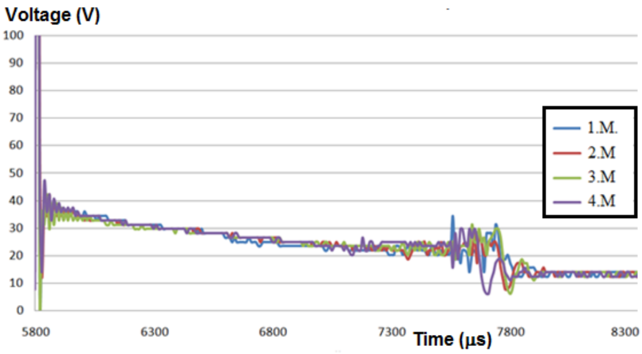

Fig. 12 The course of voltage during the arc burning by applying oil

Fig. 13 shows a simulated failure of the ignition contact of the driver to the spark plug. The gap distance was 400 ±100 µm. Burning time was reduced by 750 ± 150 µs. During burning, the voltage was about 10 V higher. Higher overshoot was also reflected in the decay of the arc.

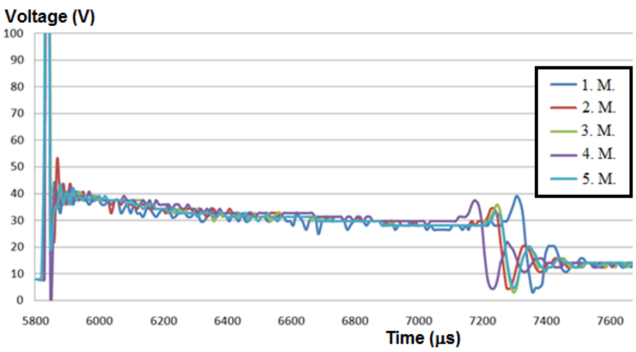

Fig. 13 The course of voltage during the arc burning with failure

5. Conclusion

Diagnostics of ignition systems by diagnostic systems allows measurement of primary and secondary high-voltage waveforms. Programming environment of Labview allows adequately evaluate the waveforms to obtain a comprehensive overview of the examined system based on the simulation analysis.

Ignition system with dual spark coils represent simple variant without mechanical distribution of ignition. The negative aspect is the limitation of time adjustment because of exhaust sparks.

We have designed a device on which we can test individual components of the ignition systems, monitor their functionality and measure the influence of the ignition arc on different components. Based on this device, it is possible to physically simulate possible faults, copy them to a database and compare them with the actual ones in the car on the basis of files.

Measurements have elucidated the phenomena and effects that affect the arc burning. After the application of oil and gasoline between the electrodes and the failure of the spark plug connection, the time characteristics of the voltage differed from the base. The most significant differences were found during the arc burning with failure.

In the abovementioned analysis voltage waveform when burns out spark are evident that finishing phase of burning sparks is missing and instead of damped oscillations course gradually declined. This effect is caused by high-voltage diode. If a spark goes off the current stops flowing in secondary circuit and diode closes than electrically disconnects section of secondary circuit.

This work was partially supported by the Grant Agency VEGA from the Ministry of Education of Slovak Republic under contract 1/0471/20.

Authors: *Assoc. Prof. Daniel Korenčiak, PhD.; Ing. Matej Kubiš; Ing. Milan Šebok, PhD.; Prof. Miroslav Gutten, PhD.; Ing. Matej Kučera; Faculty of Electrical Engineering and Information Technology of the University of Žilina Department of Measurement and Applied Electrical Engineering, Univerzitná 1, 010 26 Žilina, Slovak Republic, E-mail:gutten@fel.uniza.sk.*

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