

DIAGNOSTICS OF IGNITION SYSTEMS

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Abstract: Ignition systems even in its simplest form, represent electrical system which produce voltage waveforms in a form of pulses in complex shape. For the diagnosis of these systems is necessary to use such diagnostic systems, which allow to record these waveforms for next analysis. In the presented contribution we deal with possibilities of analysis and investigation of waveforms, primary and secondary circuit fully electronic ignition systems.

Key words: diagnostics, EFS ignition systems, DFS ignition systems, LabVIEW, high-voltage waveforms

1. Introduction

Distributorless ignition system (DIS) is ignition system which distribute high voltage to each spark plug without using mechanic distributor. High voltage shall be achieved to create a spark at the spark plug igniting the mixture through a high-voltage coil (transformer). High-voltage outlets in distributorless ignition system are directly applied to plugs, thus increasing the number of ignition coils. An immediate flash-over in the cylinders is necessary to determine by a separate switch controlling of transformer primary circuits. In practice are used two solutions which differ in the number of ignition coils.

2. The DFS ignition system

Ignition system with coils with dual secondary windings DFS (Doppelfulen Spule) is ignition system where high voltage is transported directly on spark plugs and flash-over occurs at a certain moment on the two plugs at the same time. Fig.1 shows simplified scheme of the DFS system.

At some point of flash-over on two spark plugs at the same time a pulse of high-voltage appears on the secondary winding of the transformer, space between electrodes of the spark plug ionizes the electrical strength of the space exceeded by high voltage and current discharge flows through a spark. The engine operating parameter signals enter into the control unit by which the control unit is creating control pulses for the final stages of ignition coils (Fig.1).

The operating signals are needed to calculate the specific moment in which the high-voltage pulse should occur. On the Fig.2 is an example of voltage waveforms (pulses) of the primary and secondary winding of the transformer.

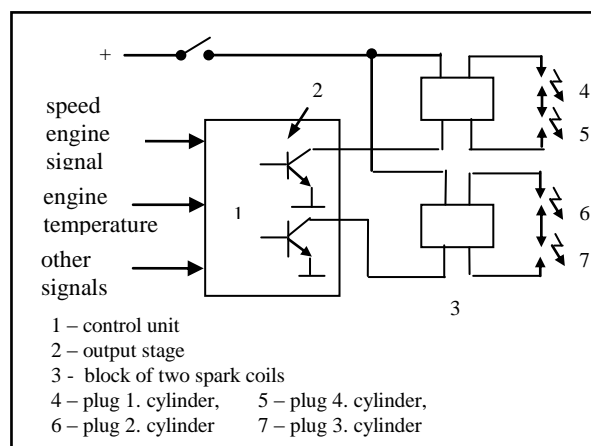


Fig.1. Simplified scheme of the ignition DFS

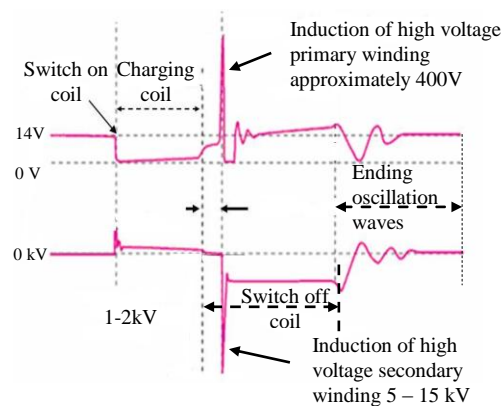


Fig.2. The voltage waveforms of the primary and secondary winding of the transformer

The spark has to flash over in cylinder near the top dead center in compression stroke for right engine running.

3. The EFS ignition system

In this type of ignition system are used coils which are creating only one spark for one spark plug at any given moment, thus that the number of ignition coils is corresponding with the number of engine cylinders Fig.3.

The engine operating parameter signals input into the control unit. EFS is not sufficient just with crank

speed signals because each ignition coil receives one control pulse for two turns of crank but from the signal reference mark the control unit don't know whether the piston of cylinder is at top dead center compression stroke or at exhaust stroke. It is not possible to decide whether the spark-over is conducted in the 1st or 4th cylinder and therefore another synchronization pulse is needed, which is a control pulse cam Fig.7.

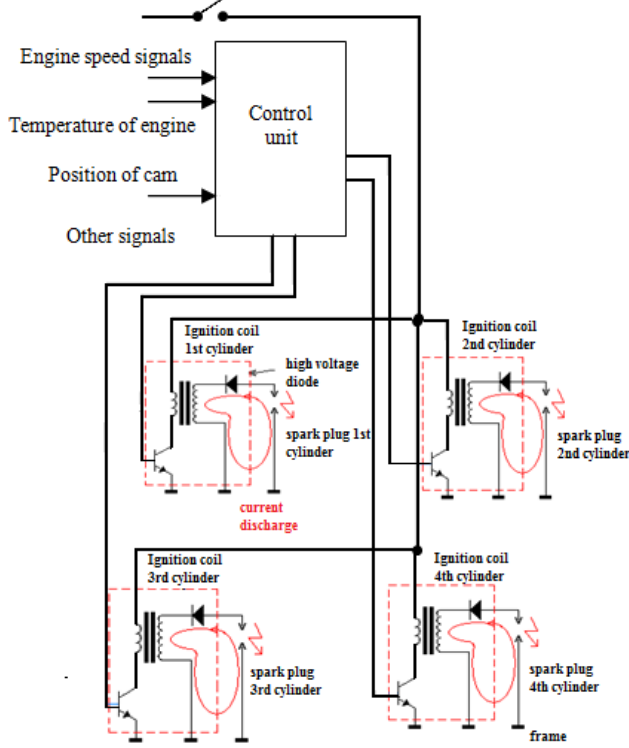


Fig.3. Simplified scheme of the ignition EFS

4. Analysis of equivalent circuit of the ignition

In the analysis of ignition circuit, based on analysis of behavior linear circuits in time between two steady-states. Circuit is getting from the steady state into a new due to active element parameter changes i.e. connecting or disconnecting the voltage source or current.

From the equivalent circuit of the ignition on Fig.4 is obvious, that change in steady-state to another is associated with a change of electromagnetic energy $W(t)$ of circuit.

This can be distributed into electric field energy accumulated in the capacitor circuit and magnetic field energy accumulated in inductors.

$$W(t) = \sum_{k=1}^{n_1} W_{ek}(t) + \sum_{k=1}^{n_2} W_{mk} \quad (1)$$

where n_1 is the number of capacitors and n_2 is the number of inductors.

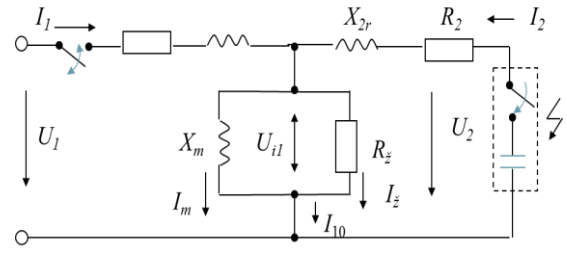


Fig.4. Equivalent circuit of the ignition

If we analyze the ignition circuit of fully electronic ignition we can replace switching of direct current by switch and ignition coil by capacitor.

From equivalent scheme of particular circuit model is evident that after switching the power on the secondary side of the transformer (high voltage coil) generates voltage

$$U = L \frac{di}{dt} + Ri + \frac{1}{C} + u_c(0) \quad (2)$$

Derived equation gives an equation of the second order with constant coefficients

$$L \frac{d^2 i}{dt^2} + R \frac{di}{dt} + \frac{1}{C} i = 0 \quad (3)$$

The roots of the characteristic equation is

$$L\lambda^2 + R\lambda + \frac{1}{C} = 0 \quad (4)$$

where
$$\lambda_{1,2} = -\frac{R}{2L} \pm \sqrt{\frac{R^2}{4L^2} + \frac{1}{LC}} \quad (5)$$

From the equation for calculation of roots of the characteristic equation shows that there may be three cases: roots λ_1 and λ_2 are real and various, roots are identical and roots are comprehensive. Each of these cases corresponds with the different character of current and voltage. If the roots are real thus the discriminant is positive, then

$$R > 2\sqrt{\frac{L}{C}} = R_{krit} \quad (6)$$

Therefore the circuit resistance is greater than R_{krit} and for the current in the circuit is valid

$$i(t) = \frac{U}{2\sqrt{\frac{R}{4L^2} - \frac{1}{LC}}} (e^{\lambda_1 t} - e^{\lambda_2 t}) = I_0 (e^{-\frac{t}{\tau_1}} - e^{-\frac{t}{\tau_2}}) \quad (7)$$

where:

$$\tau_1 = -\frac{1}{\lambda_1} = \frac{1}{\frac{R}{2L} - \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}}$$

$$\tau_2 = -\frac{1}{\lambda_2} = \frac{1}{\frac{R}{2L} + \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}} \quad (8)$$

From the above equations, is clear that the current $i(t)$ increases to its maximum value as first, and then decreases monotonously. Voltage is approaching to their settled value and takes the value

$$u_L(t) = L \frac{di}{dt} = \frac{U}{2\sqrt{\frac{R}{4L} - \frac{1}{LC}}} \left(\frac{1}{\tau_2} e^{-\frac{t}{\tau_2}} - \frac{1}{\tau_1} e^{-\frac{t}{\tau_1}} \right) \quad (9)$$

If the roots are λ_1 a λ_2 complex conjugate so for the discriminant is valid

$$\frac{R^2}{4L^2} < \frac{1}{LC} = R < 2\sqrt{\frac{L}{C}} = R_{krit} \quad (10)$$

Then the roots of the characteristic equation can be written in the form

$$\lambda_1 = -\delta + j\omega_0, \quad \lambda_2 = -\delta - j\omega_0$$

where
$$\omega_0 = \sqrt{\omega_r^2 - \delta^2} \quad (11)$$

If we substitute the roots into the general solution of the mathematical model to obtain a current response

$$i(t) = e^{-\delta t} (B_1 e^{j\omega_0 t} - B_2 e^{-j\omega_0 t}) = I_0 (e^{-\delta t} \sin \omega_0 t)$$

where
$$I_0 = \frac{U}{\omega_0 L} \quad (12)$$

Current responses corresponds with the smooth development (quasi periodic course), but the amplitude is not constant but decreases exponentially i.e. is damped by factor $\delta = R/2L$.

As in the case of aperiodic character responses can also be derived from current response to the voltage response the circuit elements.

$$u_L(t) = L \frac{di}{dt} = \frac{\omega_r}{\omega_0} U \sin(\omega_0 t + \frac{\pi}{2} + \beta) \quad (13)$$

$$u_c(t) = U + \frac{\omega_r}{\omega_0} U e^{-\delta t} \sin(\omega_0 t - \frac{\pi}{2} - \beta)$$

On theoretical waveform of voltage Fig.12 switching on at the primary side of the transformer and also for discharging the secondary coil at discharge.

Discharging the secondary coil side can be observed as discharge the capacitor through the resistor and inductor in time t_2 this unstable situation can be analyzed similarly as at the previous state. Response of $i(t)$, $u_R(t)$ a $u_L(t)$ are similar for aperiodic and quasi periodic action except the capacitor voltage response to aperiodic state takes its values

$$u_c(t) = -\frac{U_0}{2\beta} \left(\frac{1}{\tau_1} e^{-\frac{t}{\tau_1}} - \frac{1}{\tau_2} e^{-\frac{t}{\tau_2}} \right) \quad (14)$$

and for the quasi periodic case

$$u_c(t) = \frac{\omega_r}{\omega_0} U e^{-\delta t} \sin(\omega_0 t - \frac{\pi}{2} - \beta) \quad (15)$$

In the case where the circuit resistance $R = 0$ and also the damping factor is zero ($\delta=0$) all responses as current and voltage have harmonic waveform.

5. Analysis and measurement of high-voltage waveforms of ignition

Taking into consideration four-cylinder engine and if the piston of 1st cylinder is at top dead center of compression stroke and in the same time is the piston of 4th cylinder at top dead center but of exhaust stroke and in the same time is the piston of 2nd cylinder in the bottom dead center and piston of 3rd cylinder in the bottom dead center entering into compression stroke. In figure.5th we can see that the waveforms of high-voltage pulses on pistons of 1st and 4th cylinder are together in one position and with every turn are working with each rotation and they are alternating compression and exhaust stroke. In 2nd and 3rd cylinder is happening the same action but they are just time-shifted by 180 degrees of crank rotation.

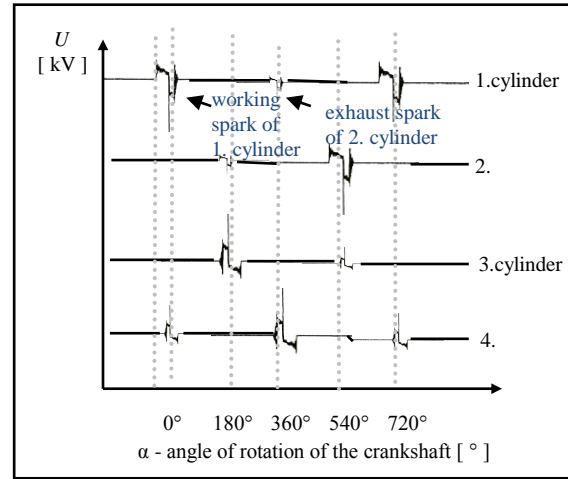


Fig.5. Waveforms of voltage pulses on spark plugs for each cylinder.

The high-voltage discharge (spark) Fig.6 occurs in different atmospheres on different cylinders. If is in the 1st cylinder of compression stroke between the electrodes of 1st plug high pressure and the corresponding with high flashover voltage. On the 4th cylinder at the same time the exhaust stroke and the spark flashover to a relatively low fuel pressure.

Spark flashover voltage is low and has the opposite polarity than working spark.

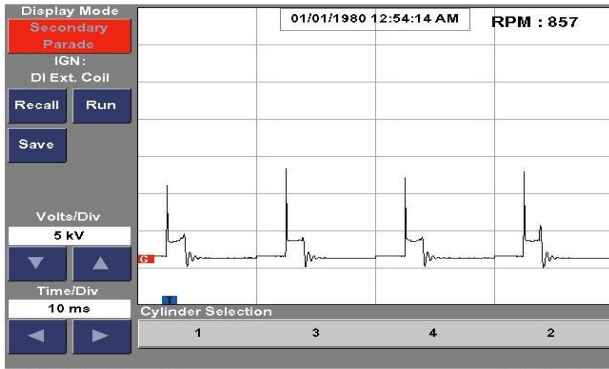


Fig.6. Ignition pulses of cylinders in the DFS system

The sides of primary coils are powered by the pulse voltage and switching by output stages to frame, or the ending degrees are integrated into module of coils. The control unit controls the switching and injection, and each coil is switched once per one cycle of the motor by control pulses (Fig.7.).

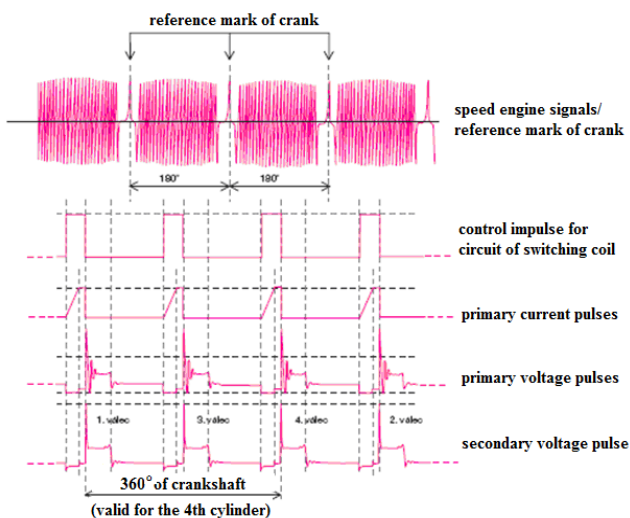


Fig.7. Synchronization of switching and the emergence of high-voltage pulses

Synchronization of switching is taken away from the crank speed. Obviously for the synchronization are needed another signals for adaptation of the ignition immediate operating conditions (engine load signal, temperature and the intake air quantity, throttle position etc.). [4]

To the control unit are entering signals of engine operating variables. Ignition with EFS is not sufficient just with crank speed signals because each ignition coil receives one control pulse for two turns of crank but from the signal reference mark the control unit do not know whether the piston of cylinder is at the top dead center compression stroke or at exhaust stroke. It is not possible to decide whether the spark-over is conducted in the 1st or 4th cylinder and therefore is needed synchronization pulse which is a control pulse cam

Fig.8. On the basis of cam and crank signals the control unit is creating control pulses for final stages of each ignition coil Fig.7.

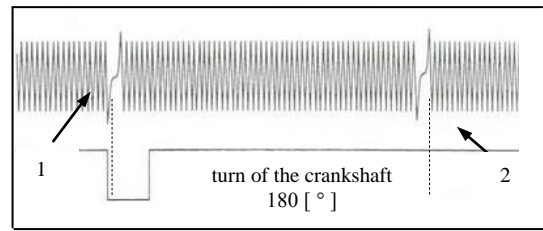


Fig.8. Speed engine signal / reference mark of crank (1) and cam position signal (2).

In the secondary circuit coils is high-voltage diode connected. For each of the cylinders in the moment of switching the primary winding on the secondary side there is a high voltage pulse (1-2kV). In ignition systems with distributor and the cylinder located outside circuit is disconnected. This voltage do not shift air gap between the plug electrodes and thus undesirable spark on the spark plug does not skip. [4]

In DFS system high voltage pulse of secondary circuit breaks dielectric area on the distance given by the sum of the distances of the electrodes connected distance given by the sum of the distances of the electrodes connected in series spark plugs in series and therefore there is no discharge. If the primary circuit switch off it incurred substantially higher voltage which breaks through the area between two electrodes of spark plug and that results in a spark.

EFS systems have diode in secondary circuit of ignition coil that prevents creation of unwanted sparks when switching the primary winding and conversely transmits high voltage for the creation of sparks in its disconnection Fig.9.

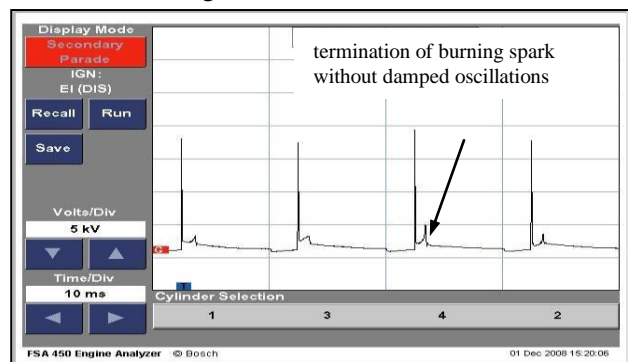


Fig.9. Ignition impulses in EFS

Diagnostic of high-voltage (secondary) circuit of ignition is affected by the presence of high-voltage diode.

In practice are individual ignitions coils recessed into the cavity in the cylinder head and there are mounted directly on the spark plug with short cables.

By implementing capacitive sensors on these wires it can be obtained waveforms of high-voltage discharges. We scan voltage on these coils just behind the high voltage diode which ultimately distorts the image resulting voltage.

6. Simulation waveforms in LabVIEW

For a deeper analysis can be used simulation by programming environment Labview, where you can set up through the mathematical model of such operations during the subsequent simulation of error conditions spark pulses Fig.10.

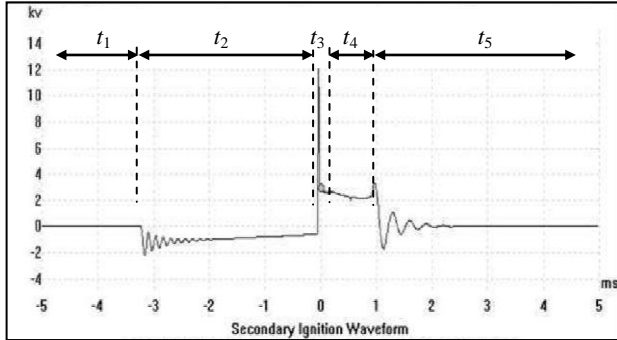


Fig.10. Model of ignition voltage waveform

According to Fig.10 we can be divided into waveform for five periods, which we then mathematically spread (interval t1 until t5):

Interval t_1 : $u(t) = 0$

Interval t_2 : $u(t) = l \cdot \cos(n \cdot t) e^{-d \cdot t}$

l – the voltage in the steady state is voltage constant,

n – determines the number of amplitudes,

k – amplitude, d – specifies the attenuation

Interval t_3 : $u(t) = a \cdot t + c_1$

a – is constant of inclination of the line, c_1 – determines the initial state (final state in the interval t_2).

Interval t_4 : $u(t) = \frac{1}{b\sqrt{\pi}} \cdot e^{-t^2/b^2} + c_2$

b – amplitude constant, c_2 – determines the initial state (final state in the interval t_3).

Interval $t_{5.1}$: $u(t) = -m \cdot t + c_3$

m – is constant of inclination of the line, c_3 – determines the initial state (final state in the interval t_4)

Interval $t_{5.2}$: $u(t) = k \cdot \cos(n \cdot t - h) e^{-d \cdot t} + c_4$

n – determines the number of amplitude, d – specifies the attenuation, h – shift of course, c_4 – determines the initial state (final state in the interval t_5).

Fig.11 is presented by sequence program of high

voltage waveform ignition model EFS with a faulty diode and simulation graph on Fig.12 which shows the comparison of malfunctioning ignition coil – sinusoidal course with decreasing amplitude at switching on primary side of transformer and switching off secondary side of transformer the shut down transformer (faulty diode) and graph with the end of burning sparkle without damped oscillations (correct operation of the ignition coil).

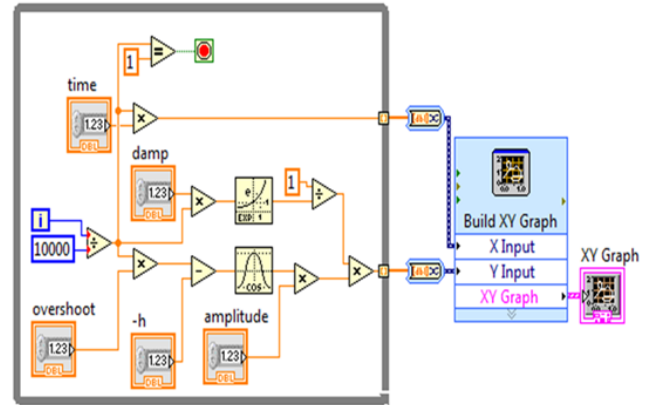


Fig.11. The sequence of program in Labview

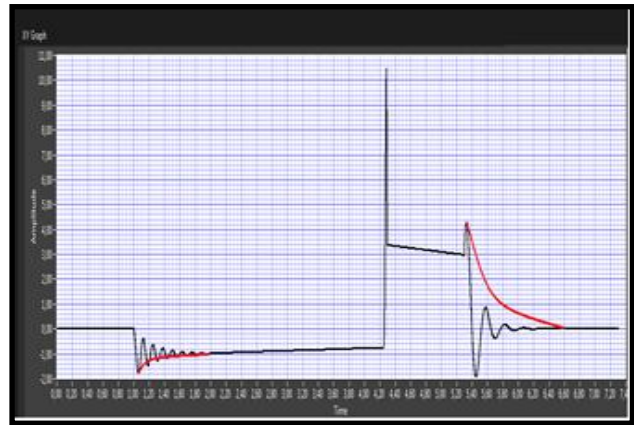


Fig.12. Simulating spark waveforms during correct and incorrect operation

7. 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.

High-voltage parts of ignition of two cylinders create serial circuit where in damaged conditions of circuit (high voltage lines), or the 1st plug of cylinder will also affect 4th cylinder. Interruption of high voltage circuit of one coil means failure of two cylinders. Fault

in the primary circuit of one coil results in failure of two cylinders. This method is only available for cars with an even number of cylinders.

EFS systems are demanding that every coil is excited by control pulse thus that works only once per two turns, or arise only work sparks and there are no exhaust sparks. In determining the choice we can choose large for inflammation - spark of the expansion time. Operational reliability of EFS ignition systems is greater than in two coil systems because a fail in circuits whether in primary or secondary circuit omits only one cylinder. These systems can be applied even in engines with an odd number of cylinders in the engine.

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.

In Fig.13 is recorded real and simulated process EFS ignition system with faulty diode.

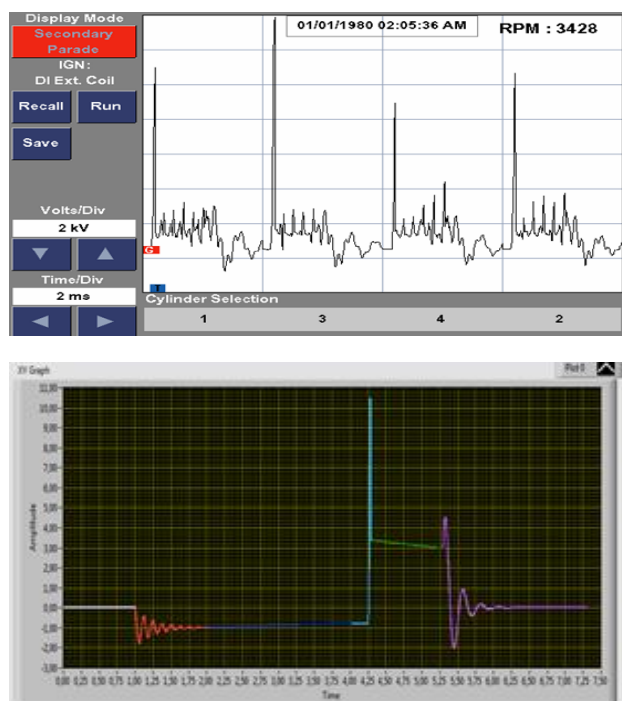


Fig.13. Real and simulated waveform with faulty diode in the EFS ignition

Simulation of ignition coil waveforms allows us to implement the various states of high voltage ignition coil waveforms based on mathematical analysis and solve problems in the ignition system.

Diode in this manner distorts the course of the measured high voltage. The voltage level can vary above or below the zero level, what can be affected by the accuracy of the analysis and the burning time of flashover voltage sparks. [3]

Pulse section length, burning time of spark, amplitude size of flashover voltage and amplitude of burning are important parameters in the analysis of high-voltage waveforms.

Acknowledgments

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