http://dx.doi.org/10.5755/j01.eee.20.10.5666 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 20, NO. 10, 2014

Centralized Diagnostics of Ignition System

M. Okrouhly[1], J. Novak[1]
[1]*Faculty of Electrical Engineering, Czech Technical University in Prague, Technicka 2, CZ-16627 Prague, Czech Republic*
okroumil@fel.cvut.cz

***Abstract*—Current trends in the passenger car industry are focused on reduction of manufacturing costs and thus increasing competitiveness on the automotive market. This paper introduces a new approach to vehicle diagnostics, promising direct cost reduction of in-vehicle diagnostic subsystems. The new approach provides for an easy transition from currently used concept of decentralized diagnostic probes to a centralized concept, based on (in an ideal case) a single diagnostic probe. This concept is demonstrated in a case study, which is focused on vehicle ignition system diagnostics. Diagnostic signatures are measured in vehicle supply network, and classified using additional information acquired from internal vehicle communication network. Case study results are presented including the discussion of advantages and limits of the centralized diagnostics concept.**

***Index Terms*—Ignition fault diagnosis, signal processing, vehicle diagnostics, template matching.**

I. INTRODUCTION

Safety and reliability of passenger cars and their subsystems are discussed from the early beginning of the automotive industry [1]. Car manufacturers are forced to look for various ways of decreasing manufacturing costs [2], whereas the safety, reliability and passenger comfort are expected to grow. Using cheaper components is one possible way of cost reduction, but this approach often results in increasing requirements for materials and components inspection during the vehicle manufacturing and later its operation. To provide inspection during the vehicle operation the vehicle diagnostics is implemented. Current vehicle diagnostic concept is based on a set of decentralized diagnostic probes that are typically used to detect a particular fault. With raising number of modern (often safety critical) driver assistance systems the number (and the costs) of diagnostic probes increases simultaneously [3], [4]. We believe that the concept of centralized diagnostics allows decreasing the speed with which the diagnostics costs are raising.

Centralized diagnostics concept is based on measuring and evaluating of diagnostic signatures in a single point of vehicle power supply network. To detect particular fault states it is necessary to have available either the fault and faultless state signatures of components under diagnostics (CUDs) or their diagnostic models [5] As the diagnostics signatures are acquired from the supply network, the method covers only the electrical or electromechanical parts of the vehicle – simply those producing any signatures in the supply network. Other components and subsystems (like mechanical parts without any electrical excitation) cannot be evaluated. The case study in the second part of the paper is focused on a single but rather complex demonstration of centralized diagnostics concept principle – the ignition system of a spark-ignition engine.

Simplified description was already presented in [6]. In this paper, the particular faults are specified more precisely and more diagnostic methods are explained in detail and verified using measured data. Another example of ignition system diagnostics is described in [7].

II. CENTRALIZED VEHICLE DIAGNOSTICS PRINCIPLE

As stated above, today vehicles' diagnostics relies on decentralized concept with high number of dedicated sensors (diagnostics probes) covering particular components or even particular fault states of CUDs. This approach is rather cost-consuming, as each CUD requires its probes, accessories and computing power (usually less important factor). Several probes' outputs processing is often concentrated within a single unit (ECU – Electronic Control Unit) to reduce the costs [8]–[11].

The principal idea of the centralized diagnostics concept comes from the fact that all the state transitions of electromechanical or electrical components are accompanying with well-defined physical phenomena. If, for example, the CUD is powered from the ideal voltage source, its state transitions are visible by means of CUD consumed electric current.

By measuring the electric current in a vehicle power supply network it is therefore possible to observe the state transitions and generally the behaviour of any CUD. In an ideal case the single current probe placed between the power source and CUDs can be enough for all connected components diagnostics.

Additional information supporting especially localization (in time) of diagnostic signatures in the current signal and separation of overlapping signatures from particular CUDs can be found in vehicle information system (often a CAN – Controller Area Network is used).

The new methods using acoustic emission signals, predominantly based on Fourier Transform, are also a kind

Manuscript received November 13, 2013; accepted September 5, 2014.
This research was funded by a grant (No. SGS14/153/OHK3/2T/13) from the Grant Agency of the Czech Technical University in Prague, project name Systems of Data Processing and Fusion for Diagnostics and Measurement Applications, and project (# LO1311) from The Ministry of Education, Youth and Sports program NPU I (LO), project name Development of Vehicle Centre of Sustainable Mobility.

of centralized diagnostics [12].

III. IMPLEMENTATION OF CENTRALIZED VEHICLE DIAGNOSTICS

Centralized diagnostics method is based on measurement of the power supply current in existing power distribution cables, which reduces the diagnostics installation costs in vehicle. In the ideal case mentioned above the current is measured in a single point – the wire interconnecting the car battery and appliances (CUDs). Current probe output signal is then evaluated in a central diagnostic unit. The measured current carries information about the behaviour of all the CUDs, more or less including also the behaviour of their mechanical parts (e.g. windshield wiper, power windows or electro-hydraulic steering booster. In Fig. 1 the possible current probe placements (A, B, C a D) in vehicle power supply network are shown. In the ideal case the current is measured in the A point, where the total current delivered by alternator and battery and consumed by all appliances is measured and later used for diagnostics of all CUDs.

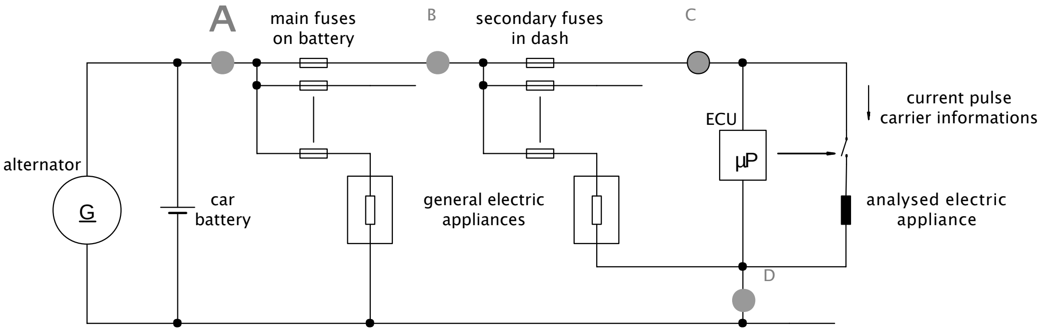


Fig. 1. Alternative current measurement points (A, B, C and D) in vehicle supply network.

Centralized diagnostics consists of three crucial parts. The first is data acquisition of signatures. Its quality depends on the dynamic range, sampling frequency and effective number of bits of the used acquisition hardware. The second is an algorithm for localization and separation of particular signatures and the third an algorithm for interpretation of signatures and classification of CUD states.

The number of simultaneously evaluated CUDs is determined by the quality of localization and signature separation algorithm. Localization and separation of signatures can be based e.g. on peak detection, correlation functions, band-pass filters or match filters. Important parameters used for localization and separation of signatures can be obtained from the related CAN bus carried signal or set of signals. The issue of the centralized concept is in localization and separation of signatures from low-power CUDs. It can partially be overcome by using more probes placed in B or even in C points instead of a single probe in point A (Fig. 1). The C point's measurement arrangement provides inherent separation of signatures from CUDs powered by various supply branches; the single A point measurement implementation is of course cheaper. The resulting arrangement should always be a compromise between usability and costs – from this point of view a C point probe can make sense for selected CUDs.

Results of signature interpretation and CUD state classification algorithm depends on an ability to describe the influence of the CUD state transition on the signature and on repeatability of signatures for the particular CUD transitions and states. For selected CUDs the algorithms can be developed that are even able to predict the time to CUD failure and critical component can thus be repaired or replaced without getting into the fault state.

All previously mentioned algorithms depend on quality of measured input signal. The dynamic range and sampling frequency are the determining parameters. The required dynamic range of measurement channel (current probe, amplifier, A/D converter) should be at least 80 dB but better 100 dB, sampling rate in order of MHz. This is especially true for the arrangement with single probe in point A, where the peak current value can reach 200 Amps and required resolution is 1 mA. In arrangements with more than one probe placed in B or even C points the requirements are proportionally lower. In real implementation a compromise has to be found between the single probe arrangement in point A (essentially the best case, but requiring high dynamic range of measurement channel and complex signature separation, which can be expensive) and higher number of probes in B or C points (lower dynamic range of the channel, more channels, but much simpler or no signature separation needed). To find the best compromise it is necessary to identify and evaluate the signatures of each potential CUD in its respective C point in order to find the measurement uncertainty, which is necessary for the further successful interpretation of the signature and classification of CUD state. The next step is to find whether the location and separation algorithm (selected for respective signature) can provide signatures of required quality from measurements in the points B or even in the point A.

When compared with the today used decentralized concept the centralized diagnostics method shows several advantages. It can bring costs reduction, as it requires less diagnostic probes (only one in the best case), implemented using dedicated hardware. In many cases it is able to classify the state of CUD better than currently used approach, because many probes provide only binary output information. The signatures evaluation can provide prediction of future failures and thus avoid occurrence of potentially dangerous fault states. The centralized approach also provides higher flexibility of diagnostic subsystem - to support a new CUD only the firmware update with new separation, interpretation and classification algorithms is necessary. On the other hand, simpler hardware requires more complex processing of acquired signatures and uncertainty of CUD state classification is generally higher than for the decentralized concept. To decrease it the results should be evaluated using statistical data processing.

IV. Ignition System

Ignition system is an important part of the spark-ignition engine. High voltage discharges between contacts of a spark plug ignite the mixture of fuel and air in the engine cylinders and expansion of gases arising by the mixture combustion generates mechanical energy [13] and [14]. Ignition system failure directly influences engine functionality.

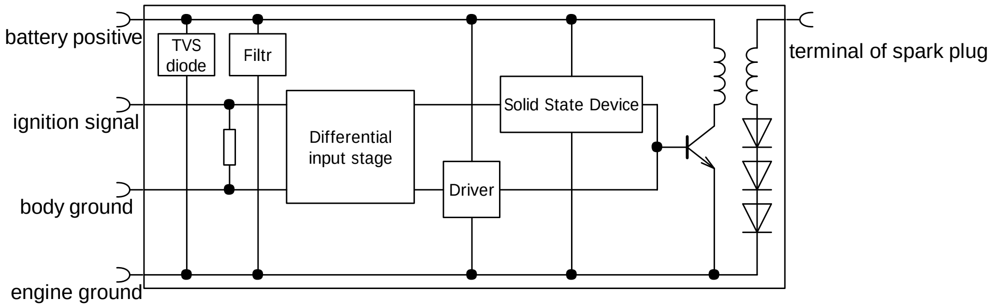


Fig. 2. Block diagram of a single ignition coil module.

At cheaper engine variant a double ignition coil (DIC) is often used; in four cylinder engine two spark plugs are activated simultaneously. Nowadays a single ignition coil (SIC) arrangement is preferred with dedicated high-voltage transformer for each spark plug. Primary voltage switching is provided by semiconductor switches directly integrated in the SIC transformer, as shown in Fig. 2.

A. Current Concept of Decentralized Diagnostics of Ignition System

Diagnostics of ignition system of spark-ignition engine relies on indirect evaluation of actual functional state of particular cylinders. There are three main approaches to find fail-state cylinder (the ignition coil, spark plug or injection valve can fail).

The most common approach is lambda probe signal processing. In case of unexpected oxygen ratio in exhausts the engine ECU successively switches off injection into particular cylinders. Changes (or no change) in a lambda probe output signal are used for failure localization (which cylinder). The method is not able to distinguish between the failures in ignition or injection systems.

The second method is based on measurement of ignition coil primary current, similarly as the centralized diagnostics approach described by this paper. It requires a measurement probe (or probes) dedicated for this purpose and provides only binary (failure / no failure) information. The method is able to distinguish between the failures in ignition or injection systems.

The third diagnostics method is evaluating output of the crankshaft revolution sensor. The sensor output signal is of a sawtooth type. Changes in a distance between the teeth correspond with acceleration or deceleration of the crankshaft, so a cylinder failure can be detected. Again, the method is not able to distinguish between the faults in ignition or injection systems.

There can be a large number of different ignition system faults – spark plug failure, high or low voltage cable breakdown or break, ignition coil failure, primary side switch failure and so on. The detailed information allowing such a deep localization or even the prediction of the failure is not available during today vehicles operation and can only be acquired using special diagnostics equipment in service stations. Methods attempting to localize the fault more precisely in the current diagnostics concept are described in [15] and [16].

B. New Concept of Centralized Diagnostics of Ignition System

As already discussed above in the general description of centralized diagnostics concept in Fig. 1, the behaviour of all electrical devices in vehicle can be observed at measurement point A. To diagnose the spark-ignition engine we have to focus on its electrical or electromechanical parts – the ignition system and the injection system. Further in this chapter the analysis and implementation of ignition system diagnostics is described.

1) Acquisition and Description of Diagnostic Signatures

The goal of the centralized vehicle diagnostics concept is to cover maximum number of electrical devices in vehicle. The diagnostics signatures are measured at the vehicle supply network, additional information is acquired from the vehicle information network (usually the CAN). In an ideal case a single current probe is used at the power supply source (point A in Fig. 1), what satisfies the requirement on maximum coverage (the supply current of all appliances flows via this point).

The advantage of full coverage brings simultaneously an important disadvantage – as the current measured in point A is a sum of supply currents of all appliances, the signature belonging to a single appliance should be localized and separated from other signatures first. This issue is demonstrated in Fig. 3 that presents the signal measured in point B as shown in Fig. 1 at engine idle speed. All presented measurements come from the Skoda Fabia II Sport vehicle with 1,4 l, 16 V, 63 kW spark ignition engine with single ignition coil system, produced in 2007. Measurements were done using oscilloscope Tektronix TDS 7104, current probe amplifier TCPA300 and current probe TCP303. All measurement were done on other vehicles of the same type (Skoda Fabia) with the SIC and also the DIC ignition systems and the measured signatures were very similar. In further discussion only the signals measured at the vehicle mentioned above are presented.

Figure 3 shows the steady state when engine is idle. There are visible signatures from at least four sources after the engine is started.

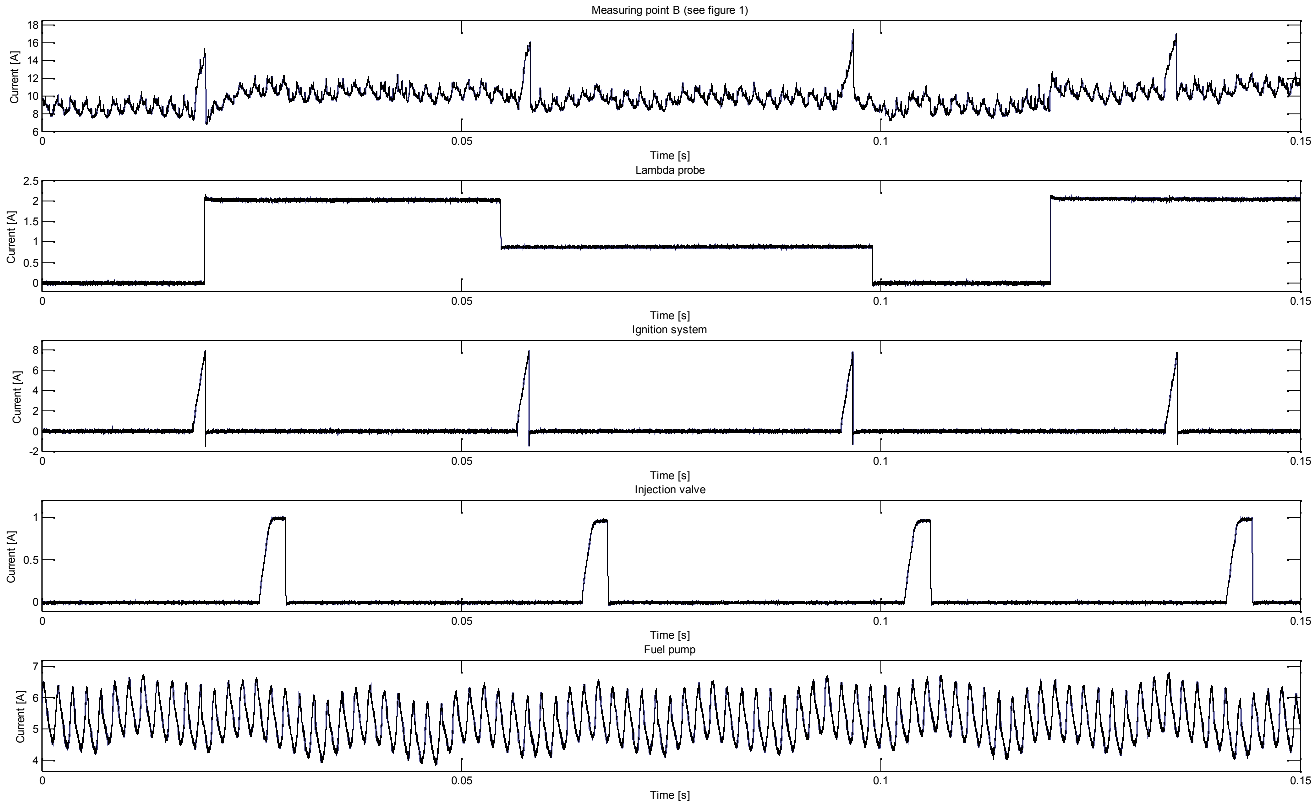


Fig. 3. Current consumption in measurement point B at engine idle.

The first component is a square signal (PWM – pulse width modulation) introduced by the lambda probe heating. Its basic frequency is constant but the duty cycle and amplitude of pulses are variable according to the required heating power. Second current component is generated by a fuel pump. Its current spikes frequency is proportional to the pump speed and its amplitude depends on the fuel pipe internal pressure. Two remaining components belong to the injection and ignition systems. Their frequency is (from the engine principle) the same (or the ratio is an integer number – for 16 valves it is 4) and their phase relation is constant.

It can be seen that for ignition system diagnostics the localization and separation of appropriate signatures is necessary.

2) Localization and Separation of Ignition Signatures

Signature localization and separation algorithm is one of three basic elements of centralized diagnostics. It allows finding the time window, in which the CUD signatures should be observed, and then the separation of signature from the sum of signatures generated by all appliances supplied via the point of measurement. Implementation of such algorithm differs according to the signature attributes – for some signatures (ignition) a simple peek detection can be used, for others the frequency filtering (pass-band or match filters), FFT or time domain transient analysis can be used.

For the signature localization the supporting information from vehicle information system can be used. In case of ignition system of Skoda Fabia car the CAN network communication was monitored and such information was taken. Unfortunately the ignition time events (for particular spark plugs) that could be used for exact signature localization are not directly visible on the CAN bus. The only suitable information is the engine speed (revolutions per minute), that can be used to verify the period of ignition system signatures.

Time domain algorithm detecting the typical signal peaks with fast edges was used to localize the ignition signatures. These peaks are generated by opening of SSD switch in primary ignition coil winding. Localization algorithm uses the information about the engine speed to define the period of ignition signatures. The length of the ignition signature time window was determined empirically at 250 μs. This window length covers both the faultless as well as faulty ignition system signatures. Distinguishing of signatures in case of simultaneously occurring faults is discussed in [17] and [18].

V. Ignition System Faultless State

First the correct functionality of the ignition should be described. At the beginning of an ignition cycle the switch controlled by an engine ECU is switched on (see the block diagram in Fig. 2). The primary coil current raises and energy is accumulated into the transformer magnetic core. Then the switch is opened and magnetic flux in the core changes its direction, as there are permanent magnets present at both ends of iron core, generating the magnetic flux of opposite direction to that generated by primary coil. This change induces the voltage spike into both primary and secondary coils. As the primary coil has about 200 and the secondary about 15 000 turns of wire, secondary voltage is much higher – it reaches more than 30 kV. Such high voltage is necessary to generate the spark between the spark plug electrodes reliably.

When the spark is ignited in the secondary circuit, another magnetic flux change is generated by the secondary current, inducing the primary coil voltage peak. To reduce its voltage the primary switch is temporarily switched on and the part of accumulated energy is returned. This can be measured by the current probe and the delay from the first opening of the switch can be evaluated as an important signature attribute, describing the functional status of the spark plug. Nevertheless this delay depends on many other conditions, as explained later in this chapter.

Generally the primary coil induced voltage is unwanted – it generates disturbance in the vehicle supply network. To suppress the remaining interference the transient voltage suppressors as well as analogue low pass filters are used within the primary switch electronic circuitry. Part of the energy accumulated in the ignition coil core is therefore wasted in primary circuit.

Figure 4 shows the current measured in faultless state. The record was measured in the measurement point C (Fig. 1), providing inherent separation of ignition signatures from signatures of other appliances. Due to the low oscilloscope resolution (8 bits) the zoomed details were measured in sequence; little differences in particular graphs can therefore be observed.

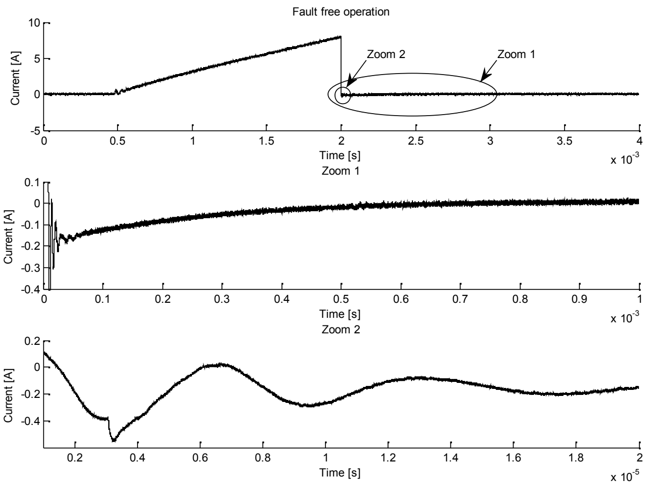


Fig. 4. Supply network current after the ignition.

After the ignition in the faultless state the fast primary current fall transition can be observed (Fig. 4). The transition is followed by damped oscillations that converge to zero. Within the oscillations a negative current spike can be observed, indicating the spark between the spark plug electrodes (see the lowest trace in Fig. 4). The voltage induced in the secondary coil circuit should be high enough to generate a spark between the spark plug electrodes. There is a mixture of air and fuel in the space between electrodes, which defines its electric strength and together with the distance between the electrodes the minimum voltage required to ignite the spark. As the secondary voltage increases in time from the point when primary switch is switched off, the time lag between this point and the spark ignition increases with increasing secondary voltage required for ignition.

The time lag of this spike (from the opening of the primary coil switch) can be used for classification of the spark plug functional status; it however depends on several parameters.

A. Spark Time Lag Dependence on Particular Spark Plug

TABLE I. MEAN VALUE AND VARIANCE OF THE TIME LAG.

Spark plug No.	1	2	3	4	5	6	7	8	9
Spark plug type	Bosch FR7HC+			Brisk DOX15LE-1			Brisk DOR15YS-1		
Mean time lag [μs]	9.79	11.47	10.76	9.32	9.55	10.13	9.55	9.66	9.65
Time lag variance [μs]	0.07	0.55	0.18	0.03	0.12	0.15	0.20	0.21	0.10

The time lag between the opening of the primary coil switch (indicating by the fast falling transient of primary current) and the spike indicating the secondary circuit spark was measured for nine spark plugs – three different types, three pieces for each of them. Bosch FR7HC+ (nominal distance between electrodes is 0.90 mm), Brisk DOX15LE-1 (nominal distance between electrodes is 1.05 mm) and Brisk DOR15YS-1 (nominal distance between electrodes is 1.00 mm) spark plugs were used. 90 measurements were performed for each spark plug, which are presented in Table I and Fig. 5.

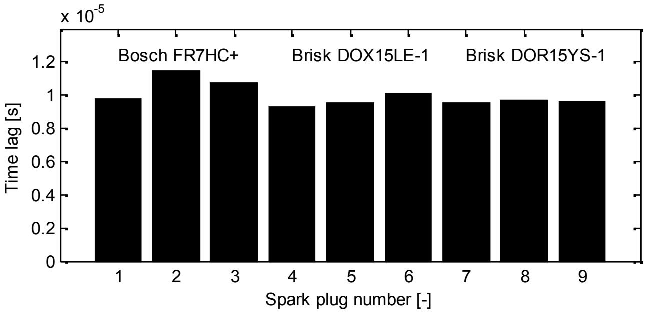


Fig. 5. Mean value of time lags for 9 different spark plugs.

The time lag value can easily be evaluated for a particular spark plug in the faultless state, but other conditions should be taken into account.

B. Spark Time Lag Value Dependence on Pressure in Cylinder

Electric strength of the air/fuel mixture depends not only on the air/fuel ratio but especially on the pressure. Measurement presented in Fig. 6 was performed in the test vehicle (standard ignition coil and spark plug) but without presence of the fuel. It shows that the electric strength and therefore the time lag value increase with increasing pressure in the cylinder.

Internal cylinder pressure varies during the working cycle as shown in Fig. 7. The pressure at the time of ignition also strongly depends on actual engine speed.

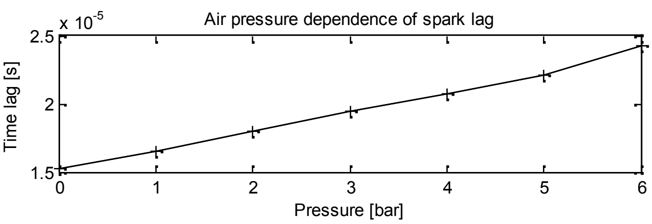


Fig. 6. Time lag value dependence on the cylinder pressure.

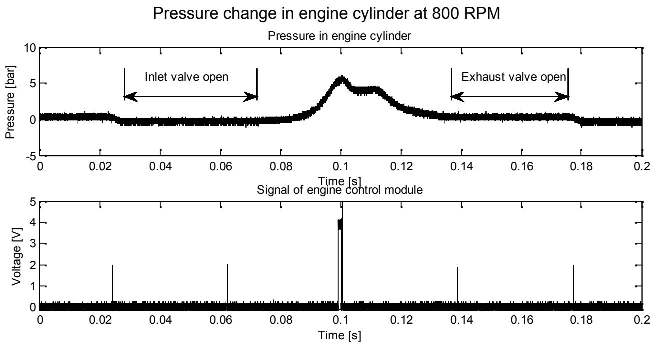


Fig. 7. Cylinder internal pressure during the working cycle at 800 rpm.

This dependence is introduced by variable ignition timing – at higher engine speed the ignition is triggered earlier and the pressure in the cylinder at the ignition time is lower (see values in Table II). The pressure values are related to the minimum cylinder pressure when the suction valve is opened.

TABLE II. CYLINDER PRESSURE AT THE IGNITION TIME.

RPM	800	1500	2500	3500	4500
Max. pressure [bar]	6,2	6	8,9	11,9	15,1
Pressure at ignition [bar]	5,6	5,2	2	1,2	1,4

C. Spark Time Lag Value Dependence on Distance of Electrodes

The time lag between the opening of the primary coil switch and the spike indicating the secondary circuit spark depends on the distance between spark plug electrodes too. Larger distance results in higher required voltage, which in turn requires larger.

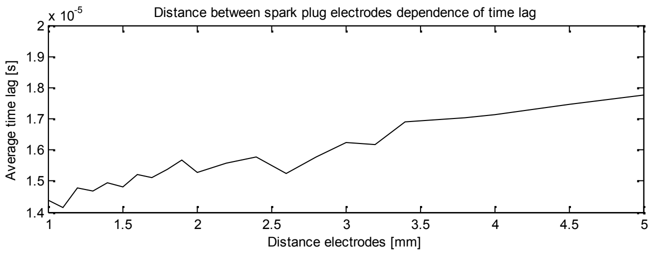


Fig. 8. Time lag value dependence on distance of spark plug electrodes.

Figure 8 shows the measured dependence of the spark time lag on the distance between spark plug electrodes (for BRISK DOX15LE-1 spark plug). The values are averages of 90 measurements.

VI. SYMPTOMS OF FAILURES

All the failures that can be distinguished in the vehicle ignition system by means of measuring the primary coil current are identified in phase of the dissipation of energy accumulated in the transformer core.

Typical ignition system faults possibly leading to the engine or vehicle failure were consulted with certified Skoda repairers. Primary coil semiconductor switch failure, secondary coil insulation breakdown, large distance between spark plug electrodes (at end of life), and dirty spark plug electrodes were identified as the most common.

A. Primary Coil Switch Failure

Figure 9 shows the record of the current consumed by four ignition coils from the vehicle battery measured on a four cylinder engine idling. The semiconductor switch in the ignition coil primary circuit (Fig 4.) is broken (permanent disconnect). The record was measured at the respective C point (Fig. 1), thus the signature separation is not necessary.

The failure classification is very easy, only the result of separation algorithm detecting the regular presence of the current spikes with frequency corresponding with the engine speed (taken from the CAN bus) is enough.

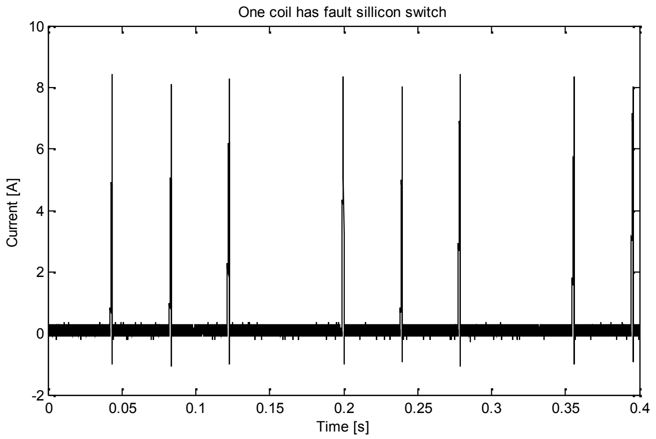


Fig. 9. Current consumption of ignition system with a failure of one switch.

B. Large Distance between Spark Plug Electrodes

The influence of the extremely large distance between the spark plug electrodes is shown in Fig. 10. The larger distance as well as partially dirty electrodes increase the voltage required for spark and ignition is thus delayed, as already explained above. The negative current spike time lag is therefore increasing as already explained in Fig. 8. Increasing time lag is proportional to the distance between spark plug electrodes and therefore to the degree of spark plug wear.

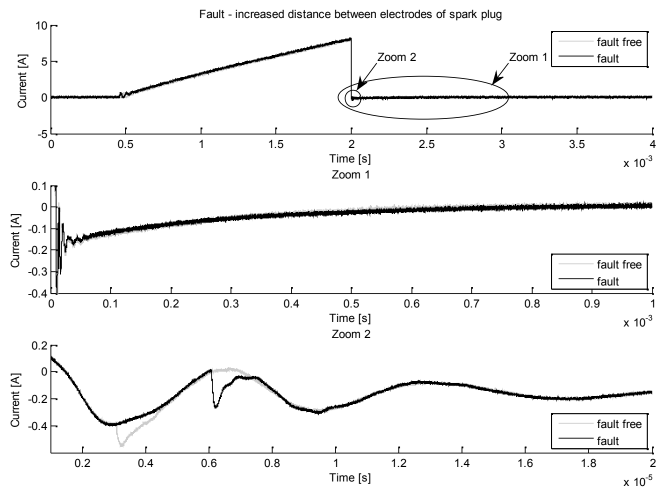


Fig. 10. Primary coil current for variable distance between spark plug electrodes.

C. Short Connection of the Spark Plug Electrodes

Primary coil current for this failure is shown in Fig. 11. When compared with faultless state, the negative current spike normally visible in damped oscillations has disappeared.

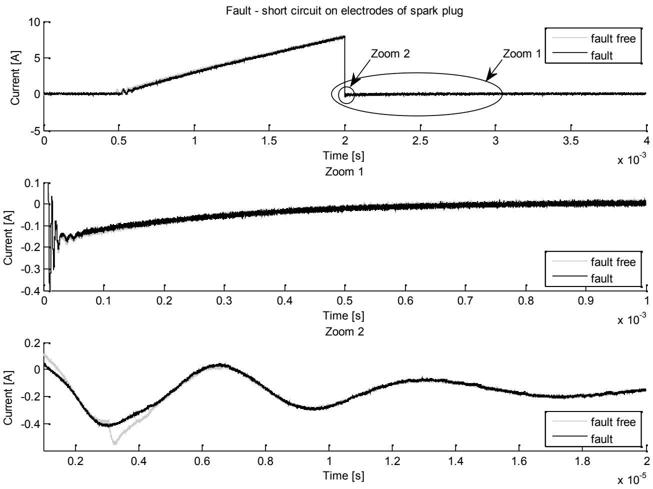


Fig. 11. Primary coil current for short circuit of spark plug electrodes.

D. *Secondary Coil Insulation Breakdown*

If this failure occurs, the energy accumulated in the magnetic core is released in the secondary coil and no spark is ignited. Failure signature is the same as for the short connection between the spark plug electrodes.

E. *Dirty Spark Plug Electrodes*

Carbon sediments are most often found on the spark plug electrodes. The piston rings leakage can lead to the presence of an oil film on the electrodes, which has similar influence. The oil film was also used for the next measurement, demonstrating the signature of dirty electrodes in Fig. 12.

When compared with the faultless state one can identify a sequence of negative current spikes superimposed on damped oscillations. They are caused by primary coil safety circuit which temporarily switches on the primary coil switch when the voltage induced in primary coil reaches the limit.

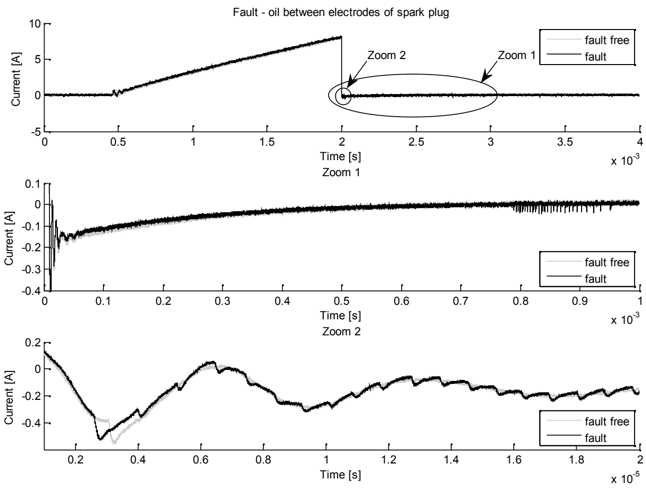
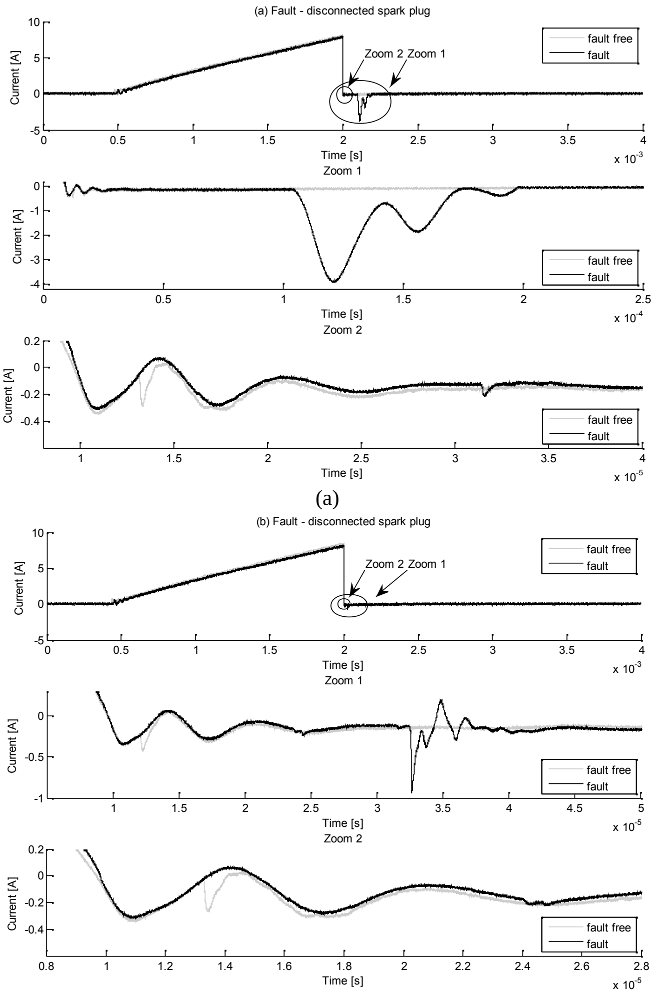


Fig. 12. Primary coil current with dirty spark plug electrodes.

F. *Spark Plug Disconnected (or High Voltage Cable Break)*

Figure 13 presents the primary coil measured current when the spark plug is disconnected. Two typical signatures were identified for this failure, there occurrence depends on secondary circuit discharge type. The signature in Fig. 13(a) is observed approximately in 80 % of all measurements for this fault type, in remaining 20 % the discharge characteristics as well as its signature (look at Fig. 13(b)) are different.



(a)

(b)

Fig. 13. Primary coil current for disconnected spark plug.

For the SIC (single ignition coil) system this failure is extremely rare, it can nevertheless happen in DIC (double ignition coil) system, where the ignition coil and spark plug are connected via high voltage cable. The signatures for both system types are nearly the same and they can be evaluated irrespective of the ignition system type.

VII. Algorithms for Separation and Classification of Ignition System Signatures

After the signature is localized the classification algorithms are applied to evaluate the functional state of the CUD. Template matching method extended with two methods for signature separation is used to classify the ignition.

A. *Template Matching*

Template matching is well known on the field of digital image processing. Here it is successfully applied to look for the specific signatures in measured signals. This method looks for the specific shape (template) in the measured signal. The template can be of an arbitrary shape and length. Usually the template is obtained by measurement on real CUD, which is in required functional state. Alternatively it can be received using a CUD diagnostics model with active required failure condition.

The principle of template matching method is visible from (1)

$$SAD(x) = \sum_{i=0}^{N} \left| t(i) - s(x+i) \right|, \quad (1)$$

where the t (template) signal is the expected signature we are looking for and the s is actually measured signal on CUD, N is a number of template samples.

Maximum level of similarity between the template and evaluated signal is indicated by the minimum value of SAD(x). If the value falls below the defined threshold, the similarity is high enough. The template matching method is described in detail in [19], [20].

Signature classification finally depends on the threshold value that is chosen using the SAD values from the large set of measurements on the CUD in the known functional state.

Advantage of the method is a simple implementation that doesn't require high computing power.

B. Template Matching with Signature Separation

For application of template matching in ignition system diagnostics the basic algorithm was modified to provide also the separation of ignition system signatures from signatures of other appliances, which is necessary for signals measured in B and A points. Fortunately the frequency spectrum of ignition system signatures lies much higher than the spectra of other appliances. This fact together with relatively short length of templates allows modelling the influence of the other signatures as an additive DC current. Without the separation this offset would modify the SAD values, the decision threshold could be reached even for false signatures and classification would fail. This effect was removed by simple subtraction of a mean value from both the template and the measured signal according to (2)

$$SAD(x) = \\ = \sum_{i=1}^{N} \left| \left(t(i) - \frac{1}{N}\sum_{j=1}^{N} t(j) \right) - \left(s(x+i) - \frac{1}{N}\sum_{j=1}^{N} s(x+j) \right) \right|, \quad (2)$$

where t is an expected signature (template), s is a measured signal and N is a number of template samples.

C. Fast Edge Detector

Evaluation of the time delay between the ignitron process start and actual ignition event is necessary to classify the distance between the spark plug electrodes. The time of an ignition event can easily be evaluated using algorithm for detection of fast edges in the measured signal. Such pulse with a fast falling edge is generated by the primary coil switch electronics to prevent the overshots in the power supply network – it is shown in Fig. 2.

Template matching algorithm cannot be applied here as the pulse mentioned above is superimposed on the varying current signal with much higher value and the shape of the template thus depends on the measured time delay, as demonstrated in Fig. 14.

The edge detector looks for the fastest edge of the predefined length, as defined by (3)

$$h = \max_{k=1}^{N-T} \left(s(k) - \min_{l=k}^{k+T} \left(s(l) \right) \right), \quad (3)$$

where s is the measured signature, N is number of signature samples and T is expected length of the edge.

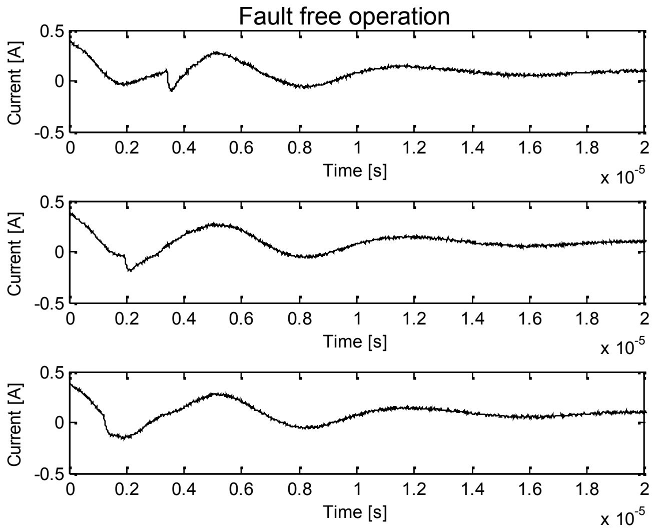


Fig. 14. Faultless ignition system state with varying ignition delay.

This algorithm can either be used without separation, if the underlying signal edges are much slower than the edge of interest, or a separation algorithm described in the next chapter can be applied.

D. Signature Separation by Deviation from Approximation

Deviation from approximation method is more general extension of the previous approach. It allows to separate high frequency detail of the signature that is superimposed on lower frequency part. This time domain method uses the approximation polynomial of a limited degree to approximate the low frequency part of the measured signal. This approximation is then subtracted from the original signal and the resulting signal is classified by the template matching algorithm. An example is shown in Fig. 15.

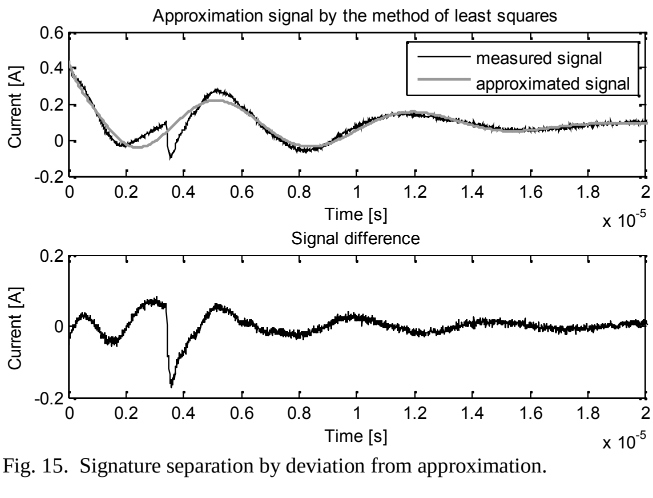


Fig. 15. Signature separation by deviation from approximation.

VIII. IMPLEMENTATION AND DISCUSSION OF RESULTS

A. Spark Plug Disconnected (or High Voltage Cable Break)

This failure is the only one where signatures comply with requirements for template matching based classification (they keep the shape and scale of the signature). It is indicated by two different signatures that appear in 1:4 ratio depending on the actual parasitic spark type. The more often observed signature (referred as type 1) is shown in Fig. 13(a), the less often observed one (type 2) in Fig. 13(b).

Templates for both signature types were measured at point C by averaging of 1000 measurements in the fault state, as shown in Fig. 16 (type 1 template is in (a), type 2 template is in (b)).

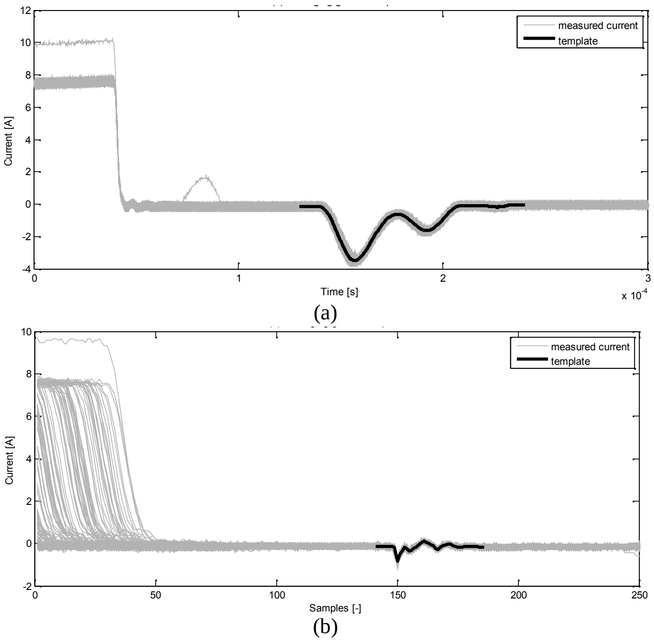


Fig. 16. Templates for disconnected spark plug failure: a) Averaging gained template type 1; b) Averaging gained template type 2.

For the signatures measured in point C (and thus separated from other appliances) the template matching method provides high success rate for both signature types (Fig. 17 (a) for type 1 signature). The signature of type 1 can even be successfully identified in signal measured in point B (Fig. 17 (b)) without separation.

Signature of type 2 measured in point B is unfortunately undetectable using the template matching, as the signal to noise ratio is too low. Nevertheless it can successfully be identified in signal measured in point C (Fig. 18) and ignition system state can thus be classified correctly.

The method was evaluated statistically using 1000 measurements for each ignition coil (4 cylinder engine) under the various conditions (especially the engine temperature). The signature signals were measured simultaneously in B and C points for both faulty and faultless states. Ignition system state classification threshold was defined using the histograms of the minimum SAD values for particular measurements (Fig. 19).

Absolute values of SAD depend on the template length (number of samples) and scale of the amplitude. Two templates (X and Z) were prepared for classification of states according to the Fig. 17 (template X) and Fig. 18 (template Z). Their parameters are specified in Table III.

TABLE III. TEMPLATES PARAMETERS.

Template	X	Z
Number of samples	2751	151
Sampling frequency f_{vz} *[MHz]*	25	25

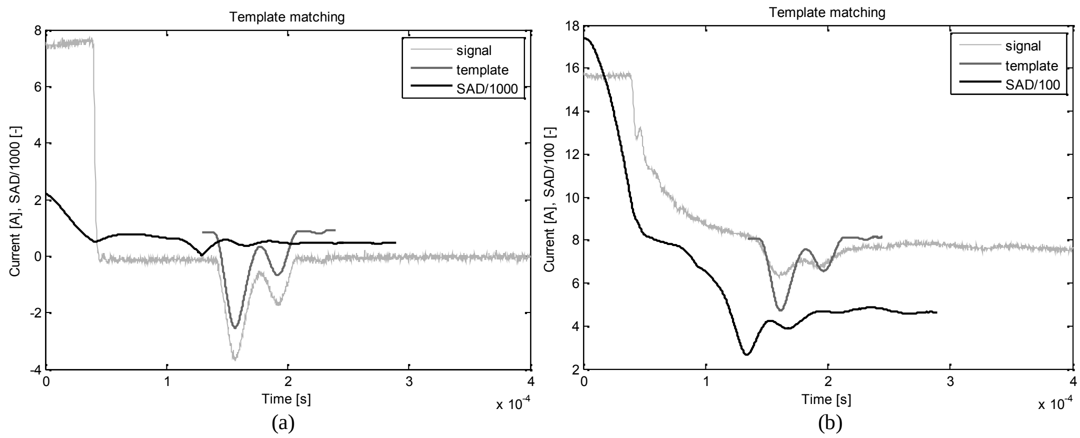


Fig. 17. Template matching for type 1 signature measured in points C, B.

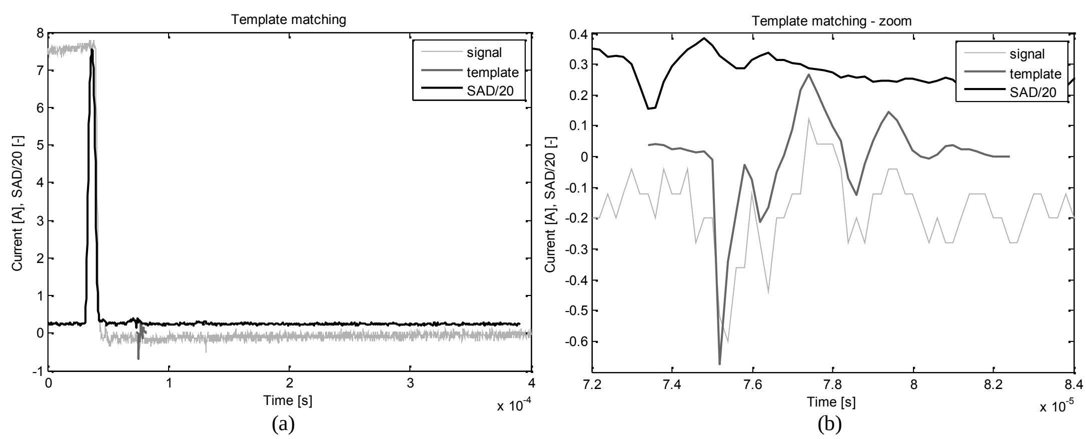


Fig. 18. Template matching for type 2 signature measured in point C.

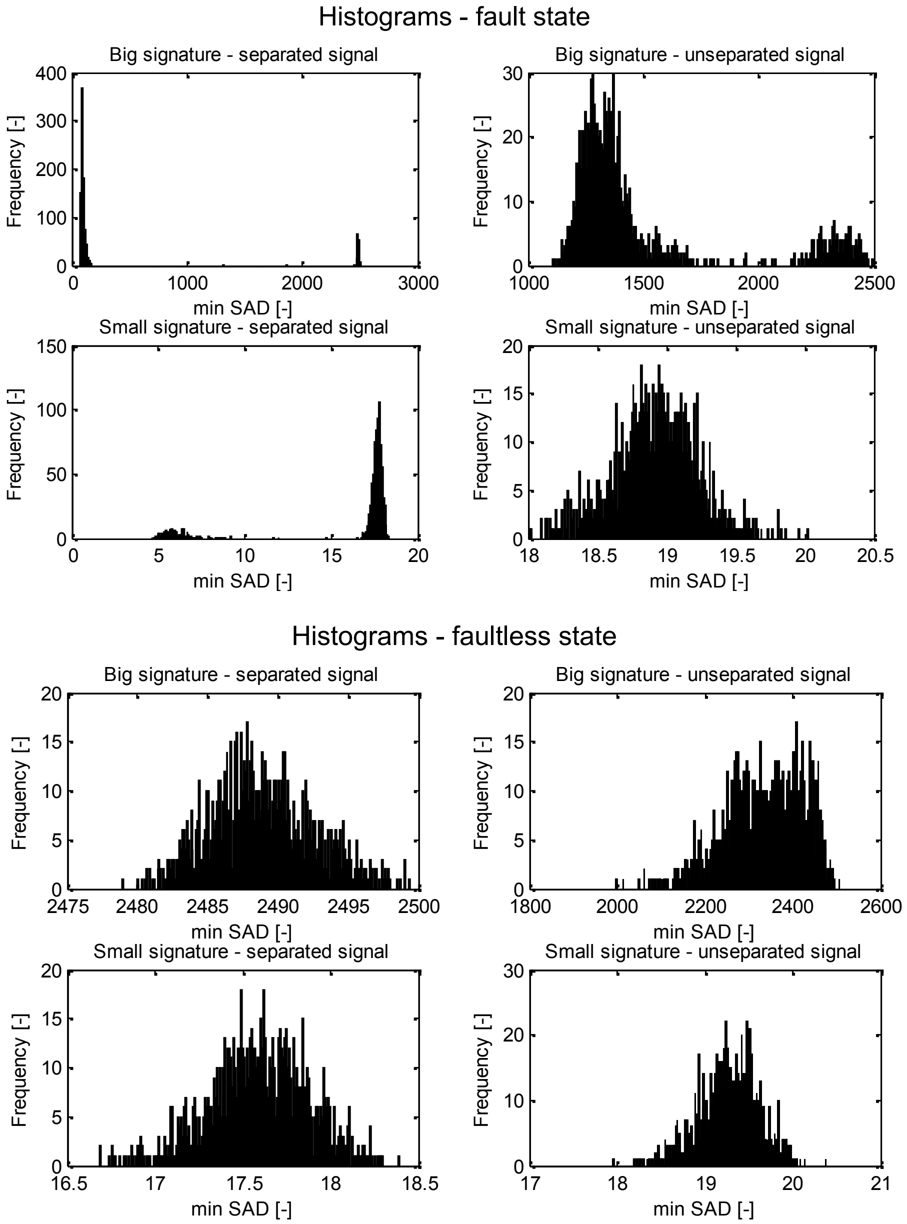


Fig. 19. Histograms of the minimum SAD values.

SAD threshold values were defined using the histograms in Fig. 19, the values can be found in Table IV.

TABLE IV. CLASSIFICATION THRESHOLDS.

Expected signature	X	Z
Separated signal	300	2000
Non-separated signal	10	18.5

TABLE V. RESULTS OF 1000 CLASSIFICATION ATTEMPTS IN FAULT STATE.

Description	**X template found**	**Z template found**	Both X and Z templates found	No template found
in separated signal	**853**	**143**	0	4
in non-separated signal	**854**	**90**	87	143
simultaneously in both separated and non-separated signals	852	3		
found in non-separated but not in separated signal	2	87		

The values above were used to classify the unknown ignition system state. In case of faulty state the results are summarized in Table V. The classification was correct for 996 from 1000 attempts for the separated signatures; only 4 samples were not classified.

For the faultless state the classification results are summarized in Table VI.

TABLE VI. RESULTS OF 1000 CLASSIFICATION ATTEMPTS IN FAULTLESS STATE.

Description	**X template found**	**Z template found**	Both X and Z templates found	No template found
in separated signal	**0**	**0**	0	1000
in non-separated signal	**1**	**20**	0	979
simultaneously in both separated and non-separated signals	0	0		
found in non-separated but not in separated signal	1	20		

Results presented in Table V and Table VI show that the particular failure types can be successfully identified only in the separated signatures. The results received by evaluation of non-separated signatures provide, nevertheless, enough reliable information about the fault or faultless state of the ignition. False positive results are below 3 % and true positive results are above 85 % on non-separated signal.

B. Failures at Spark Plug Electrodes

All remaining ignition system failure types fall into this category. They can be classified by the evaluation of the time lag between the primary coil switch-off event and the actual ignition time. Switch-off event time can be identified easily (Fig. 9), the actual ignition time can be found using fast edge detection algorithm described in 5.3. Before the edge detection the separation based on the deviation from approximation (see VII. *D.*) should be applied. Degree of an interpolation polynomial was found empirically (value 15).

Expected edge length and pulse amplitude for the fast edge detection algorithm were defined as 0,2 µs (T in (3)) and 70 mA. The algorithm was evaluated using three types of spark plugs (Bosch FR7HC+, Brisk DOX15LE-1 and Brisk DOR15YS-1). Three samples of each spark plug type were evaluated.

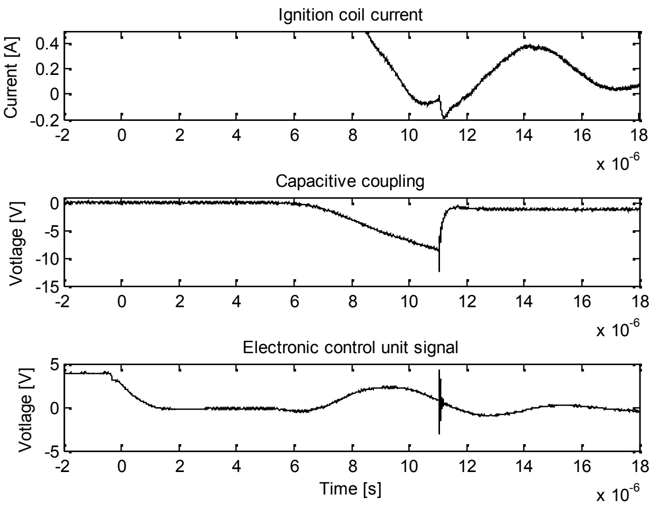


Fig. 20. Fast edge detection algorithm evaluation.

90 signatures were taken for each spark plug, it means together 810 signatures. The reference was taken using the capacitive coupled signal from the secondary winding (Fig. 20). The measured time lag was correctly identified in all cases.

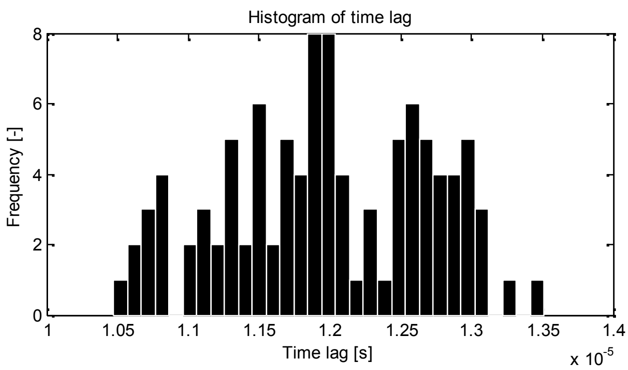


Fig. 21. Histogram of 100 measured time lag values.

The measured time lag (or its difference compared to expected value) is then used for the classification. As the measured time lag values are varying around the average value (Fig. 21), the mean value is obtained using the exponential moving average algorithm defined by (4).

$$EMA_k = EMA_{k-1} + \sim \left(D_k - EMA_{k-1}\right), \qquad (4)$$

where EMA_k is the moving average value evaluated in step k, D_k is the k^{th} time lag value and coefficient α represents a degree of weight (value between 0 and 1).

Filtered time lag value can now easily be used for the ignition system state classification using the known faultless state value. The classification thresholds nevertheless differ for each particular spark plug type. Examples of these thresholds for the Brisk DR15YS spark plug are shown in Table VII.

TABLE VII. CLASSIFICATION THRESHOLDS FOR BRISK DR15YS SPARK PLUG.

Failure	Description
Short connection between electrodes	Expected edge not found
No failure	Filtered time lag value < 11 µs
Electrodes distance too large	Filtered time lag value > 11 µs & just single edge found
Dirty electrodes	Filtered time lag value > 11 µs & more edges found

Method evaluation was done using 1500 current signatures for all described kinds of failures as well as for the faultless state. The classification was correct in 100 % cases, no false classification was encountered.

As the described classification is based on identification of the low current pulse, it can be applied only on separated signatures measured in point C (Fig. 1). In measurement point B and A this pulse is invisible, as the current flows mostly from the active ignition coil into the filter capacitors in remaining three coils. For the centralized diagnostics concept this approach therefore cannot be used.

Finally it should be emphasized that all the signature measurements used for the classification should be done at engine idle to ensure the reference conditions.

IX. CONCLUSIONS

The paper describes the concept of centralized vehicle diagnostics based on the limited number (only one in optimal configuration) of diagnostic probes used to identify high number of faults of vehicle electronic subsystems.

Results of the case study presented above can be summarized in following statement. Described classification algorithms provide very high success rate in classification of signatures measured at point C (separated ignition supply current (Fig. 1)). For the ignition coil break/disconnect fault the fault state classification is successful in more than 99 % of cases. For the large gap/dirty electrodes fault the classification was 100 % successful.

In point B (partially separated supply) the classification is only partially successful. For the ignition coil break/disconnect fault the false positive results are below 3 % and true positive results are above 85 %. For the large gap/dirty electrodes fault the classification is not successful.

In point A (non-separated vehicle supply) the classification is not successful at all.

These results show the limits of the centralized diagnostic concept and point out its limited applicability for low power appliances as well for appliances grouped in clusters.

REFERENCES

[1] M. Borner, H. Straky, T. Weispfenning, R. Isermann, "Model based fault detection of vehicle suspension and hydraulic brake systems", *Mechatronics*, vol. 12, no. 8, pp. 999–1010, 2002. [Online]. Available: http://dx.doi.org/10.1016/S0957-4158(02)00008-9

[2] A. O'Connor, "Tata Nano–world's cheapest new car is unveiled in India", *The Times*, vol. 11, 2008.

[3] J. Crossman, H. Guo, Y. Murphey, J. Cardillo, "Automotive signal fault diagnostics - part I: signal fault analysis, signal segmentation, feature extraction and quasi-optimal feature selection", *IEEE Trans. Vehicular Technology*, vol. 52, no. 4, pp. 1063–1075, 2003. [Online]. Available: http://dx.doi.org/10.1109/TVT.2002.807635

[4] Y. Murphey, J. Crossman, Z. Chen, J. Cardillo, "Automotive fault diagnosis - part II: a distributed agent diagnostic system", *IEEE Trans. Vehicular Technology*, vol. 52, no. 4, pp. 1076–1098, 2003. [Online]. Available: http://dx.doi.org/10.1109/TVT.2003.814236

[5] M. A. Rizvi, A. I. Bhatti, "Hybrid model for early detection of misfire fault in SI engines", *IEEE 13th Int. Multitopic Conf. (INMIC 2009)*, pp. 1–6.

[6] M. Okrouhly, J. Novak, "Centralized vehicle diagnostics", *IEEE 7th Int. Conf. Intelligent Data Acquisition and Advanced Computing Systems (IDAACS)*, 2013, vol. 1, pp. 353–357.

[7] Liu Zhenyong, Cheng Xin, Ren Shiwei, "Study on monitoring and fault diagnosis for ignition system of engines", *First Int. Workshop on Education Technology and Computer Science, (ETCS 2009)*, 2009, vol. 1, pp. 895–899.

[8] O. Gusikhin, N. Rychtyckyj, D. Filev, "Intelligent systems in the automotive industry: applications and trends", *Knowledge and Information Systems*, vol. 12, no. 2, pp. 147–168, 2007. [Online]. Available: http://dx.doi.org/10.1007/s10115-006-0063-1

[9] A. Alessandri, M. Caccia, G. Veruggio, "Fault detection of actuator faults in unmanned underwater vehicles", *Control Engineering Practice*, vol. 7, no. 3, pp. 357–368, 1999. [Online]. Available: http://dx.doi.org/10.1016/S0967-0661(98)00169-5

[10] G. Mauer, "On-line performance diagnostics for internal combustion engines", in *Proc. Int. Conf. Industrial Electronics, Control, Instrumentation, and Automation, Power Electronics and Motion Control*, 1992, vol. 3, pp. 1460–1465.

[11] J. Walter, S. Buller, E. Karden, F. Gronwald, S. Schroder, R. De Doncker, "Useful Noise: battery-diagnostics using existing noise and impedance spectroscopy", *VDI BERICHTE*, pp. 619–630, 2001.

[12] H. Ghaderi, P. Kabiri, "Fourier transform and correlation-based feature selection for fault detection of automobile engines", *16th CSI Int. Symposium on Artificial Intelligence and Signal Processing (AISP)*, 2012, pp. 514–519. [Online]. Available: http://dx.doi.org/10.1109/AISP.2012.6313801

[13] V. Patel, M. Steffka, "Vehicular spark ignition systems radiated emissions and reception performance", *Int. Symposium on Electromagnetic Compatibility, (EMC 2005)*, 2005, vol. 1, pp. 19–23.

[14] F. Soldera, F. Mucklich, K. Hrastnik, T. Kaiser, "Description of the discharge process in spark plugs and its correlation with the electrode erosion patterns", *IEEE Trans. Vehicular Technology*, vol. 53, no. 4, pp. 1257–1265, 2004. [Online]. Available: http://dx.doi.org/10.1109/TVT.2004.830977

[15] Zhang Lili, Chu Jiangwei, Zou Bencun, "Study of automobile electric controlled system fault diagnosis based on classification pattern recognition", *IEEE Int. Conf. Information and Automation (ICIA)*, 2010, pp. 2076–2081.

[16] Cheng Wang, Shan-zhen Xu, Chuan-sheng Si, "Study on vehicle remote test and diagnosis technology", *5th Int. Conf. Computer Science and Education (ICCSE)*, pp. 116–119, 2010.

[17] Chi-Man Vong, Pak-Kin Wong, Weng-Fai Ip, "Simultaneous faults diagnosis for automotive ignition patterns", *Int. Conf. Machine Learning and Cybernetics (ICMLC)*, 2011, vol. 3, pp. 1324–1330.

[18] Tan Derong, Yan Xinping, Gao Song, Liu Zhenglin, "Fault diagnosis for spark ignition engine based on multi-sensor data fusion", *IEEE Int. Conf. Vehicular Electronics and Safety*, 2005, pp. 311–314.

[19] D. Friedman, *Detection of signals by template matching*. Baltimore, MD: Johns Hopkins Press, 1969.

[20] Zhixiong Li, Xinping Yan, Zhiwei Guo, Yuelei Zhang, Chengqing Yuan, Z. Peng, "Condition Monitoring and Fault Diagnosis for Marine Diesel Engines using Information Fusion Techniques", *Elektronika ir Elektrotechnika*, no. 7, pp. 109–112, 2012. [Online]. Available: http://dx.doi.org/10.5755/j01.eee.123.7.2387