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UNIFORM SPARK PLUGS POLARITY IN AUTOMOTIVE IGNITION CIRCUITS EQUIPPED WITH DOUBLE-ENDED IGNITION COILS

JEDNOLITA POLARYZACJA ŚWIEC W UKŁADACH ZAPŁONOWYCH WYPOSAŻONYCH W CEWKI DWUBIEGUNOWE

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Summary

Automobile ignition systems with double-ended coils are classified under the group of distributorless ignition systems (DIS) family, used in the majority of contemporary vehicles. The characteristic feature of this type of system is the opposite (positive and negative) polarity of the central electrodes of spark plugs, being the load of the secondary winding of the double-ended ignition coil. The consequence of this is the difference in the peak value of the avalanche breakdown voltage of the gap between the spark plug electrodes - higher in the case of a positively polarized center electrode. The subject of this article is a technical solution that provides uniform polarity of the center electrodes of all spark plugs that constitute the load of the double-ended coil of the DIS. The polarity of the spark plug electrodes of all cylinders is particularly important in terms of measuring the leakage current of the insulator due to the aforementioned differential peak value at the gap between the electrodes. Uniform polarity of high voltage pulses also allows for conducting a series of comparative studies of the spark discharge energy on the plugs of individual engine cylinders. Such tests may be helpful in the case of attempts to identify the malfunctioning of the ignition coil secondary circuit, often leading to ignition misfire or increased fuel consumption.

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Keywords: ignition system, spark-ignited combustion engine, spark plugs, automotive electrical engineering

Streszczenie

Samochodowe systemy zapłonu z cewkami dwubiegunowymi zaliczane są do grupy bezrozdzielaczowych układów zapłonowych wykorzystywanych w większości współcześnie użytkowanych pojazdów. Cechą charakterystyczną tego rodzaju układów jest przeciwna (dodatnia i ujemna) polaryzacja elektrod środkowych świec zapłonowych stanowiących obciążenie uzwojenia wtórnego dwubiegunowej cewki zapłonowej. Konsekwencją tego jest odmienna wartość szczytowa napięcia przebicia przestrzeni międzyelektrodowej świec zapłonowych – wyższa w przypadku elektrody środkowej spolaryzowanej dodatnio. Przedmiotem artykułu jest rozwiązanie techniczne zapewniające jednolitą polaryzację elektrod środkowych wszystkich świec stanowiących obciążenie cewki dwubiegunowej bezrozdzielaczowego układu zapłonowego. Biegunowość elektrod świec zapłonowych wszystkich cylindrów jest szczególnie ważna z punktu widzenia pomiaru natężenia prądu upływu izolatora ze względu na wspomnianą wyżej zróżnicowaną wartość szczytową napięcia przebicia przestrzeni międzyelektrodowej. Ujednolicenie polaryzacji impulsów wysokiego napięcia pozwala ponadto na przeprowadzenie serii badań porównawczych energii wyładowania iskrowego na świecach poszczególnych cylindrów silnika. Tego rodzaju badania mogą okazać się pomocne w przypadku prób identyfikacji nieprawidłowego działania obwodu wtórnego cewki zapłonowej, prowadzącego niejednokrotnie do wypadania zapłonów lub wzrostu zużycia paliwa.

Słowa kluczowe: układ zapłonowy, silnik spalinowy o zapłonie iskrowym, świece zapłonowe, elektrotechnika samochodowa

1. Introduction

Spark-ignited combustion engines are currently the most numerous among conventional and hybrid drive train units for motor vehicles. In the case of a spark-ignited engines, the ignition of the mixture is possible due to the phenomenon of electric discharge inside the combustion chamber, initiated at a strictly defined moment by high voltage appearing between the spark plug electrodes. One factor affecting the discharge voltage is the polarity of the central spark plug electrode in relation to the peripheral electrode, which is galvanically connected to the ground of the vehicle. For the overwhelming majority of cases, ignition system designers aim to provide a negative polarity of the center electrode in relation to the potential of the vehicle ground [3, 8, 15] due to the lower discharge voltage value, which is advantageous in terms of the ignition coil operating conditions. However, there are also technical solutions where a positive polarity of the center electrode of the spark plug is preferred [12]. Notwithstanding the issue of the varied wear ratios for spark plugs of different polarity, different polarity of the discharge voltage is not particularly important from the point of view of the vehicle user. However, it does matter in the case of the measurement of voltage, current and electrical discharge energy levels of the spark plug and testing the properties of ceramic insulators.

The subject of this publication is a presentation of a method allowing equal (negative or positive – depending on the requirements) polarity of the center electrodes of all spark plugs for a spark-ignited engine featuring double-ended (or double-spark) ignition coils. The proposed modification of the ignition system will be of importance mainly from the point of view of laboratory testing, where first and foremost the measurement of the energy supplied to the spark plugs of the individual cylinders and the leakage current on the insulator testing surface must be mentioned. Moreover, the modification will facilitate more accurate assessment of the fuel-air mixture combustion process and its effect on the functioning of the engine with omitting the polarity of the center electrodes of individual spark plugs as a factor determining the ignition voltage peak value.

2. The problem of polarity of the spark plug center electrode

The vehicle ignition coil is an electrical device of similar operating principles to a transformer or a buck-boosting autotransformer. Therefore, the design (direction of winding) and the connection of the ignition coil windings are the main factors that determine the polarity of the spark plug center electrode. The approximate instantaneous peak value of the secondary winding voltage u_{2max} of the ignition coil is defined by the following relation [10, 13]:

$$u_{2max} \approx I_{1m} \cdot \sqrt{\frac{L_1}{C_1\left(\frac{z_1}{z_2}\right)^2 + C_2}} \tag{1}$$

where:

I_1m – current flowing through the primary winding

L_1 – inductance of primary winding

C_1 and C_2 – capacitance at the primary and secondary circuit respectively

z_1 and z_2 – number of coils of primary and secondary windings respectively

The equation (1) does not take into account the dependence of the secondary ignition coil voltage on a number of other crucial factors, e.g. the shunt resistance of the spark plug electrode.

The results of studies and computer simulations which the authors of a number of publications [2, 3, 5, 9, 11, 15] refer to show the benefits of ensuring a negative polarity of the center electrode of the spark plug in relation to the ground potential of the vehicle. The primary advantage of this solution is that the ignition voltage value for the compressed air-fuel mixture is therefore decreased by approximately 10 % to 15 % comparing to a system featuring a positive center electrode [15]. This effect is particularly significant in the case of difficult ignition conditions in temperatures below zero, reduced electrical supply voltage (e.g. during the start of the engine) or due to an ignition system malfunction. Because of this, the conductive elements of the vehicle's body and chassis (ground) were initially connected to the positive pole of the voltage source, so that the potential difference between the negatively polarized center electrode and the peripheral electrode of the spark plug [13] could be further increased.

2.1 Systems featuring an electromechanical ignition device

Taking into account the increasingly widespread use of semiconductor based electronics, chiefly of the bipolar type n-p-n transistors, the combination of the vehicle ground with the positive polarity of the voltage source has lost its importance. However, practical applications continue to feature ignition systems with negative polarity of the spark plug center electrode in relation to the vehicle ground, resulting in a spark discharge in the conditions of lower voltage than in the case of reverse polarity. Firstly, when discussing these systems, some older solutions should be mentioned, characterized by the presence of an electro-mechanical ignition device featuring a cap and a rotating distributor cam (Fig. 1).

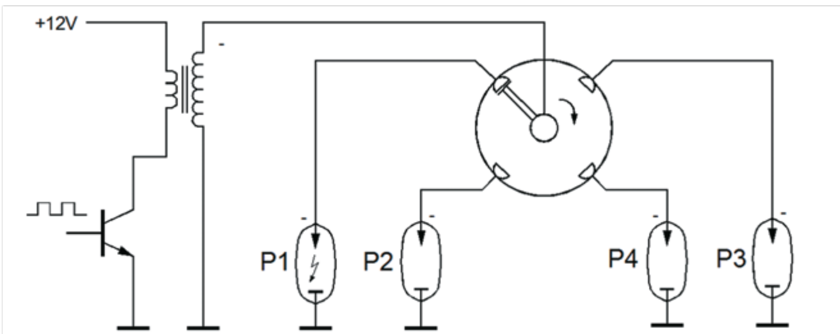

Fig. 1. Ignition system with a distrcibutor mechanism

This type of ignition system enabled the generation of high voltage pulses by means of a single ignition coil, and subsequently was responsible for directing them to the consecutive spark plugs of the individual cylinders. Due to the direction of the secondary winding and the way the coil windings are connected, the polarity of all the pulses was uniform (according to the designers' intentions - usually negative). A change into positive polarity could occur if the primary winding terminals were juxtaposed. Typically, this type of connection is referred to in the literature as incorrect, substantially considering the fact that the secondary voltage of the coil necessary to initiate the discharge between the spark plug electrodes [3] is increased.

2.2 Ignition systems featuring a single-spark coil (pencil coil)

Manufacturers of ignition systems for contemporary engines predominantly decide to use a separate ignition coil (a single-spark coil) for each individual cylinder. A section of a diagram for this ignition system type is shown in Fig. 2.

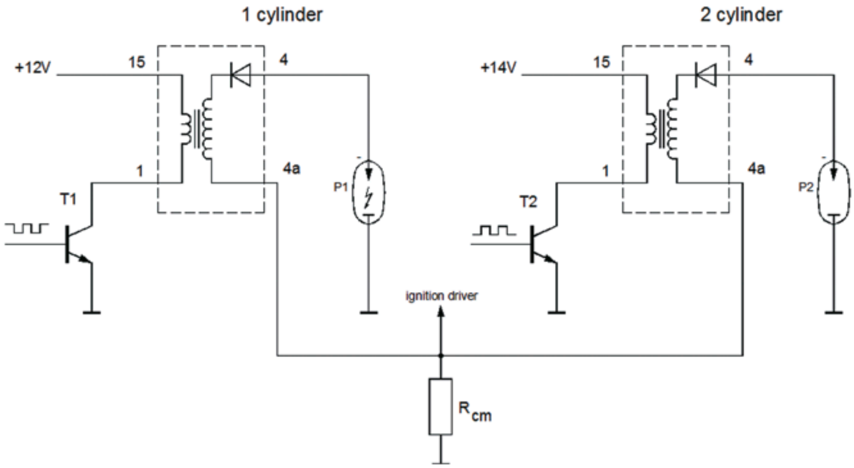

Fig. 2. Ignition system featuring single-spark coils

The single-spark coil system does not feature the ignition device. Thanks to the appropriate connection it was possible to connect the spark plugs to the terminals of the coil's secondary winding without the use of an ignition distributor. This solution significantly improved the reliability of the ignition systems. This was due to the fact that their several typical defects have been eliminated, including the burning of breaker contacts and damaging the elements mating with the rotating distributor cam. The polarity of the center electrodes of all spark plugs is negative. The R_{cm} resistor shown in Fig. 2 allows to control the secondary winding current, which is important for monitoring the occurrence of misfiring. Due to the presence of a HV diode connected in series in the secondary circuit of the ignition coil, reversing the polarity of the terminals of the primary winding of the coil is unacceptable.

The introduction of distributorless systems has significantly improved the accuracy of ignition timing adjustment. Calculations of this parameter are carried out by the motor microcontroller of the motor control unit, based on the signals received from relevant sensors which cooperate with it. The mixture ignition process controlled in this way may also be of significance for the operation of other systems such as ABS and ASR [4]. In the case of older solutions (systems featuring a mechanical breaker and ignition distributor), the effective adjustment of the ignition timing value required a number of additional components and operations [7].

2.3 Ignition systems featuring double-ended coils

There is a group of ignition systems, used mainly in engines featuring an even number of cylinders, where the discharge between spark plug electrodes occurs both under negative and positive voltage. These are double-ended coil circuits. Figure 3 shows a diagram of a distributorless ignition system of a four-cylinder engine featuring a double-ended coil, each section of which has been loaded with two spark plugs.

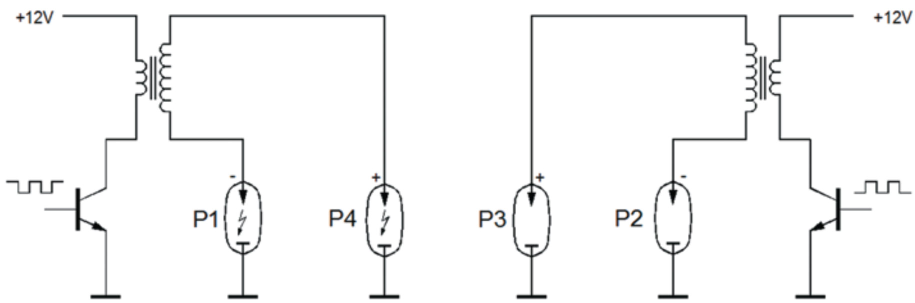

Fig. 3. Distributorless ignition system of a four-cylinder engine featuring a double-ended coil

For some double-ended ignition coils, the driver transistor, which is responsible for controlling the primary winding current, would be located inside the coil housing, although it was usually located on the microprocessor board of the motor control unit. This transistor heats up excessively during operation, so changing its location was a favorable solution.

The characteristic feature of ignition systems featuring double-ended coils is the simultaneous occurrence of spark discharge on both spark plugs connected to the terminals of the secondary winding of a given coil section, irrespective for which of the two cylinders the ignition of the compressed mixture was to be initiated at the given moment. The electric discharge at one of these spark plugs (during the exhaust stroke) did not therefore lead to ignition, consequently in the English literature such systems are referred to as *waste spark ignition systems* [14, 16]. In addition, the positive and negative polarity of spark plugs being the load of a single section of the double-ended coil are always present. This means a different peak value of the discharge voltage at the spark plugs, whilst assuming similar conditions in the combustion chambers of both cylinders in the final phase of the compression stroke. Therefore, in practice, a varied degree of wear of the central and peripheral spark plug electrodes was observed depending on the polarity, especially so in the case of electrodes made of older generation materials [16].

3. The significance of the polarity of the center electrode of the spark plug

The different polarity of spark plug center electrodes is not of significance if the testing is performed with respect to ignition and engine parameters that do not depend on the peak voltage at the secondary winding terminal of the ignition coil. Otherwise, it is recommended to standardize the polarity of the spark plug electrodes. The increased discharge voltage at the positive polarity of the center electrode may be of practical relevance from the point of view of tasting the dirt discharge and leakage current flowing on the outside surface of a damp or contaminated insulator. Increasing the voltage on the central electrode is a phenomenon enhancing such undesirable discharges. When measuring the energy of the spark discharge, particularly for intensively operated spark plugs, it is reasonable to limit the impact of leakage currents and dirt discharges by ensuring uniform (negative) polarity of the spark plug center electrodes of all cylinders.

3.1 Double-ended coil system ensuring uniform polarity of central spark plug electrodes

Research laboratories used by the manufacturers of vehicle ignition system components continue to make use of engines featuring double-ended ignition coils with integrated drive transistors (such as engines of Daewoo vehicles). This type of ignition can also be found in newer vehicles, such as the Skoda Octavia II equipped with a 1.6-liter, 102- hp engine. The problem of ensuring the uniform polarity of the central spark plug electrodes of all cylinders can be solved by modifying the ignition system and replacing the double-ended coil with individual coils. However, this solution is costly because of the need to introduce significant changes in the structure of the ignition system, which involves the selection procedure of individual coils with regard to the appropriate dimensions and electrical properties. In addition, it is necessary to ensure the proper operation of the control process of these coils, which involves alterations in the design of the existing electronic systems of the motor control unit or the necessity to upgrade them.

The solution proposed in this publication allows to retain the original engine ignition system, as designed by the manufacturer, to ensure the negative polarity of the center spark plug electrodes for two of the four engine cylinders. The negative polarity of the remaining two spark plugs will be possible through the upgrade of the ignition system by using a second dual double-ended ignition coil of parameters identical to the original one. As a result, the generation of negative ignition pulses of the parameters provided by the original engine designer will be ensured, whilst using the factory-built ignition coils mating with the engine control unit, which will not require any alterations of its design. The diagram of the modified ignition coil system featuring double-spark coils ensures the uniform polarity of the central electrodes of all spark plugs, as shown in Figure 4.

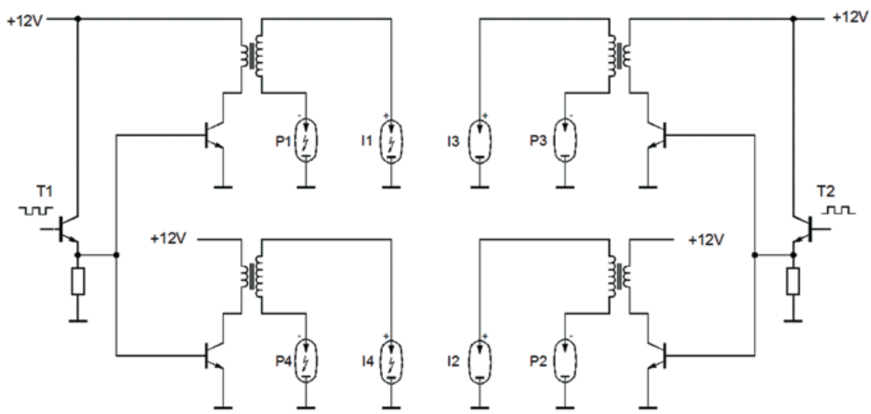

Fig. 4. The solution to the issue of ensuring uniform polarity of central spark plug electrodes in a circuit featuring double-ended coils

This solution consists in introducing two additional transistor control stages – T1 and T2 – which are responsible for controlling the primary winding current of two double-ended coils, each of which handles a pair of spark plugs for cylinders 1-4 (P1 and P4 spark plugs) and 2-3 (P2 and P3 spark plugs) respectively. Ideograms of the engine control units or specifications for electronic components are usually not published by the manufacturers of vehicle electronics. Therefore, it is assumed that the permissible power loss of the terminal stage transistor of the control unit responsible for controlling the drive transistors integrated into the ignition coil primary winding circuit is unknown. To limit the load at the output stage of the motor control unit, the two additional transistor stages T1 and T2 operate in a common collector system (so called emitter follower system). The characteristic feature of this system is a voltage gain of approximately 1 and a significant input impedance value (of tens or hundreds of kilohms), thanks to which there is no threat of overload to the control unit's terminal stage. Taking into account the dependence between the emitter current and the repeater base current, expressed by the following equation [1]:

$$I_E = (\beta + 1) I_B \tag{2}$$

where: β – the current gain factor of the transistor, the input impedance Z_i and the transistor stages T1 and T2 are described by the following formula:

$$Z_i = (\beta + 1) R_E + \frac{U_{BE}}{I_B} \tag{3}$$

where: U_{BE} – the voltage between the base and the emitter (equal to about 0.7 V in active state), R_E – emitter circuit resistance.

With spark plugs I1, I2, I3 and I4, located outside the cylinder combustion chambers, the electrical circuits of the secondary windings of the individual coils are closed and the load of the individual coil sections is approximate to the rated load. These spark plugs, in a sense, act as auxiliary spark gaps that do not participate in the ignition process of the mixture directly. Therefore, the ignition system shown in Figure 4 will ensure the generation of negative ignition pulses of the parameters provided by the original engine designer at spark plugs P1 – P4 whilst using the factory-built ignition coils mating with the engine control unit. The electronics of this control unit will not require any modifications.

One example of the practical application of the uniform electrode polarity system is the procedure for measuring the spark discharge energy. Figure 5 shows a schematic diagram of an energy measurement system for spark discharge of a negatively polarized spark plug.

The spark discharges between the electrodes of the respective spark plugs P1 and P4, as well as P2 and P3 should coincide (see Fig. 3). The emitter follower does not invert the control signal phase at its input, so the control of the individual sections of the double-ended coils proceeds without significant delays in relation to the original circuit.

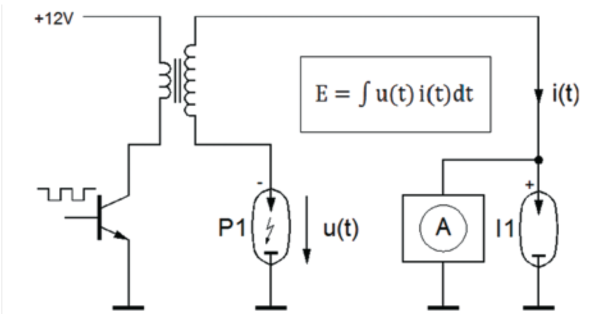

Fig. 5. Schematic diagram of measuring the spark discharge energy of a spark plug featuring a negative polarity electrode

The method of measuring the spark discharge energy, the apparatus and the results of the exemplary testing are described in detail in publication [6]. Thanks to the uniform electrode polarization system shown in Figure 4, similar simultaneous measurement can be carried out for spark discharge on the remaining spark plugs.

4. Conclusions

Distributorless ignition control systems are currently the most commonly used practical solution for ensuring precise ignition timing and the timing of activation of the primary coil winding by the means of the cooperation with microprocessor engine control units. These systems include no mechanical moving parts such as a breaker or an ignition system crank shaft, which has significantly improved their reliability compared to older solutions.

Using double-ended ignition coils reduces the cost of the ignition system, but a significant difference in relation to the distributorless systems featuring individual ignition coils is the opposite polarity of the center electrodes of spark plugs connected to the terminals of the secondary winding of an individual section of the double-ended coil section. From the perspective of the vehicle user, it is not important whether the ignition of the mixture occurred as a result of electric discharge incited by a positive or negative high voltage pulse. However, it should be borne in mind that the polarity of the center electrode is one of the factors that determines the peak value of the compressed mixture ignition voltage. Both the instantaneous voltage value and the polarity of the pulse that leads to the discharge at the gap between the electrodes are relevant for the laboratory tests of spark plugs. This in particular applies to the observation of the dirt discharge phenomenon on the outer surface of the insulator and the spark plug shunting effect (leakage current), since the increase in the voltage on the central electrode is a phenomenon favorable to such parasitic discharges. The need for considering the polarity of the center electrode of the spark plug is also taken into account when measuring the energy of the spark discharge [6] and the degree of electrode wear [12]. When carrying out comparative studies of the spark discharge energy to spark plugs on individual cylinders, particularly for spark plugs under intensive use, it is reasonable to limit the impact of leakage currents and dirt discharges by ensuring uniform (negative) polarity of the center spark plug electrodes of all cylinders.

The paper presents a simple method to ensure a uniform polarity of the center electrodes of the spark plugs for all cylinders. This method is applicable to the even-numbered cylinder engines, i.e. those whose ignition systems may be equipped with double-ended coils. The use of another ignition coil, identical to the original, controlled with the use of an ignition driver transistor responsible for the operation of the original coil guarantees ensuring the appropriate (compliant with the engine manufacturer's requirements) electrical parameters of the component. These parameters, which determine the operating conditions of the ignition coil, include the resistance and inductance of both windings, the peak value of secondary winding voltage, the energy and efficiency.

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