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Development of a hybrid gas and electrical installation for direct-injected engine vehicles

***Abstract**. The article will present the results of research and development works related to the development of electrical charging systems with the use of BLDC motors cooperating with the LPG installation adapted to work with gasoline direct injection engines. Three different motor vehicles (Audi A3, Volkswagen Touareg and Ford F-150) were adapted for the project and equipped with an electric drive and LPG system.*

Streszczenie.** W artykule przedstawione zostaną wyniki prac badawczo-rozwojowych związanych z opracowaniem dopędzającej instalacji elektrycznej z zastosowaniem silników BLDC współpracującej z instalacją LPG przystosowaną do pracy z benzynowymi jednostkami napędowymi z wtryskiem bezpośrednim. Na potrzeby projektu zaadoptowano trzy różne pojazdy samochodowe (Audi A3, Volkswagen Touareg oraz Ford F-150), które doposażono w napęd elektryczny oraz instalację LPG. (**Opracowanie hybrydowej instalacji służącej do gazowo–elektrycznego zasilania pojazdów samochodowych z wtryskiem bezpośrednim)

Keywords: electric vehicle, electric drive, ecology, LPG installation.
Słowa kluczowe: pojazd elektryczny, napęd elektryczny, ekologia, instalacja LPG.

Introduction

The main objective of the implemented project "Development of a Hybrid Gas-Electric Power Supply System for Motor Vehicles" co-financed by the EU is to develop technical solutions enabling the adaptation and retrofitting of motor vehicles with two additional cooperating power systems: LPG system and electrical (additional) system, thus creating a hybrid vehicle. The development and implementation of the above concept of a hybrid drive vehicle has many advantages and provides future users with specific technical solutions as well as additional functionality, e.g. the possibility of entering restricted zones or lower fees for entering the center of some Western European cities. In addition, the electric drive, through acceleration (starting) as well as during braking (energy recovery), is ideal for city traffic, especially during rush hours and traffic jams.

In such road conditions, higher efficiency of the electric drive translates into lower fuel consumption and lower emission of harmful substances to the environment (locally) in which it moves. It is generally said that vehicles with electric motors are environmentally friendly as they do not emit harmful products of combustion. However, taking into account the necessity and the method of energy storage in this type of vehicle (lithium-ion batteries), it has a negative impact on the environment due to the emission of harmful gases related to its production and the need of disposal (during replacement) due to the aging of the battery [1]. Another factor of great importance, in terms of ecology and the amount of CO_2 emissions to the atmosphere, is the method of generating electricity used to charge the battery of accumulators installed in the vehicle. When electricity is used from low-emission sources or from renewable energy sources, the carbon dioxide emissions of electric vehicles may be zero. Unfortunately, in Poland electric energy comes mainly from coal combustion, which in general is not favorable in terms of ecology [2]. Analysis of the results of the tests on the composition of exhaust emissions [3], [4] clearly shows that CO and NOx emissions are lower when the vehicle is fueled with LPG compared to the engine fueled with unleaded petrol. This result speaks in favor of the LPG system, as carbon oxides and nitrogen oxides are toxic components of exhaust gases and it is desirable to keep their content as low as possible. The continuous and dynamic development of the automotive industry [5], combined with the global trend related to the reduction of exhaust gas emissions that are harmful to the environment, makes internal combustion engines more and more advanced [6]. Even today, direct injection engines come as a standard, where efficiency improvements are sought by increasing boost pressure, injection pressure and compression ratio. All this, together with the unchanging market needs for alternative LPG fueling systems for internal combustion engines, forces the manufacturers of systems to introduce new solutions by constantly investing funds in research and development. The implemented project is in line with these trends through the planned research and development related to the development and implementation of a hybrid system, which includes components of the LPG system using modern technologies and standards, thus enabling trouble-free operation with internal combustion engines with direct fuel injection.

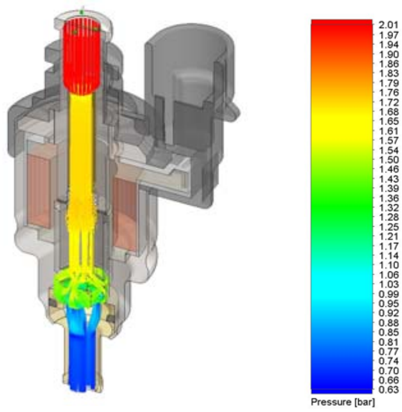

Fig.1. Gas flow trajectory through the injector (longitudinal section view)

Research methodology and the selection method of chosen components

The project was carried out in stages, which included activities in the field of creation of R&D facilities, development of virtual models with simulation tests, implementation of real models, laboratory tests and final testing of prototypes under real conditions. During the work related to the construction of virtual models necessary to conduct simulation studies, i.a. Solidworks Flow Simulation program was applied. The obtained simulation results made it possible to verify the design assumptions (validation), while allowing the detection of errors and thus the introduction of appropriate corrections. Selected elements of the LPG system were analyzed in detail, such as: injector, reducer with temperature control system and multivalve. Figure 1 shows an example of a spatial model that is the result of simulating a gas injector while working in the open state.

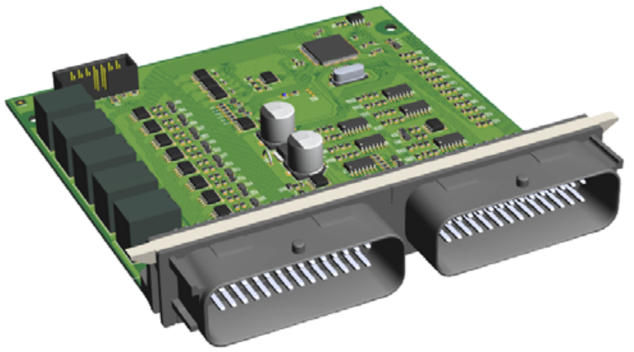

Fig.2. Visualization of the main controller board

After completion of simulation studies, 3D modeling and determination of technological solutions, the first version of the technical documentation of the hybrid system was developed, in particular: gas controller plates, main controller plates (Fig. 2), injectors, reducer, electrical harnesses and a multivalve. Based on the developed functional assumptions and block diagrams, the operating modes of all elements of the system were determined.

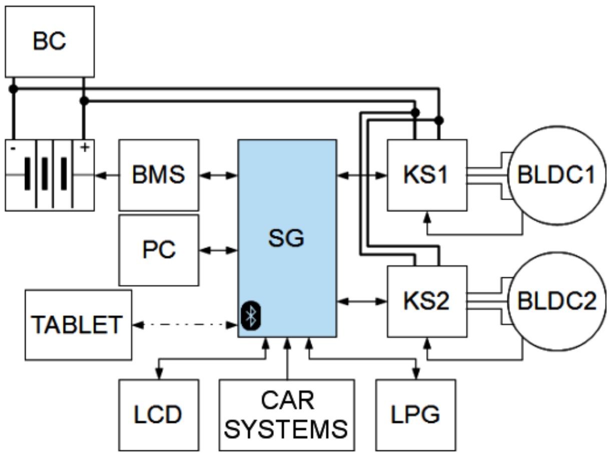

Fig.3. Block diagram of the control structure of a hybrid system

The main controller (SG), which is the central part of the system (Fig. 3), is the decision system of the highest priority. Its task is to analyze all signals from individual systems and controllers, and to supervise the correct sequence of switching between the available power sources, ensuring the correct operation and operation of the car powered by a given fuel source (petrol, LPG or electric drive). The user is informed, on ongoing basis, about the current mode and operating parameters of the system via an application with a graphical user interface. The application not only serves as a visualization of system data, but also allows you to set driving parameters with the option of switching between a given drive system. A necessary condition for all operating modes is the correct charge level of the primary battery (starting battery for the internal combustion engine). It is the primary power source for the internal combustion engine controller, gas controller, main controller (SG) and most of the measuring circuits installed as standard in the vehicle. Despite the fact that both power supply circuits available in the vehicle (12V battery - starting battery and battery bank - energy source for electric drive) are not connected with each other with their negative poles, they work independently. This means that under normal operating conditions, they cannot "complement" each other and supply selected circuits simultaneously. This method of operation, e.g. for technical reasons (different voltage levels), is safer, less invasive for the vehicle and cheaper (no voltage converters are required). In addition, such a division will be more advantageous in terms of resistance to any disturbances in measurement signals that may be induced or conducted during dynamic states (regenerative braking, acceleration, etc.).

Selection of vehicles used in the project on the hybrid system

Another important factor, having a significant impact on the timeliness and correct course of subsequent stages of the planned activities, is the acquisition of input data necessary to define the functional assumptions and requirements necessary for the proper operation of individual elements of the system. For this purpose, three vehicles were rented: Audi A3, Volkswagen Touareg and Ford F-150, equipped with gasoline engines with direct injection, the basic details of which are presented in the Table 1.

Table 1. Basic technical data of vehicles

Vehicle brand	Audi	Volkswagen	Ford
Model	A3	Touareg	F-150
Production year	2015	2014	2015
Car body	Sedan	SUV	Pickup
Type of engine	1.8L L4 DOHC 16V	3.6L VR6 DOHC 24V	5.0L Ti-VCT DOHC
Engine power	180 hp (132 kW)	280 hp (206 kW)	390 hp (287 kW)
Maximum torque	250 Nm	360 Nm	525 Nm

The Audi A3 was chosen due to the fact that the design solutions used in it are commonly used and found on our roads. This includes items of suspension and drive, brake and steering systems found in cars: VW Golf, Skoda Octavia or Seat Leon. In addition, 1.8 TFSI combustion engines are available in the offer of other VW AG car models. The applied solution with a transaxle drive system, in which its main elements are combined into one compact unit, therefore this type of design has many advantages and is used in most currently produced and operated passenger cars. Ford F-150 is a Pick-up truck, the design solutions of which are often used in light commercial vehicles. The vehicle is distinguished by a frame structure, a classic drive system with a longitudinally positioned engine and a drive axle suspended on two leaf springs. The Volkswagen Touareg is a fairly popular SUV that was developed in cooperation with Porsche. The Touareg was built on a floor plate shared with, among others, Porsche Cayenne III and Audi Q8. The development of structural elements of the hybrid system intended for installation in the Touareg will also be compatible with the above-mentioned models. Moreover, the popularity of this type of an off-road vehicle is constantly growing. The above-mentioned features of various designs, combined with a large market of potential buyers interested in the purchase and installation of a hybrid system for their vehicles, are particularly significant with regard to economic and implementation issues. Each vehicle on the dynamometer was used to collect measurement data using measuring instruments. A series of measurements was carried out during the steady-state operation of combustion engines (constant rotational speed and load) as well as in transient states (variable loads and/or rotational speed).

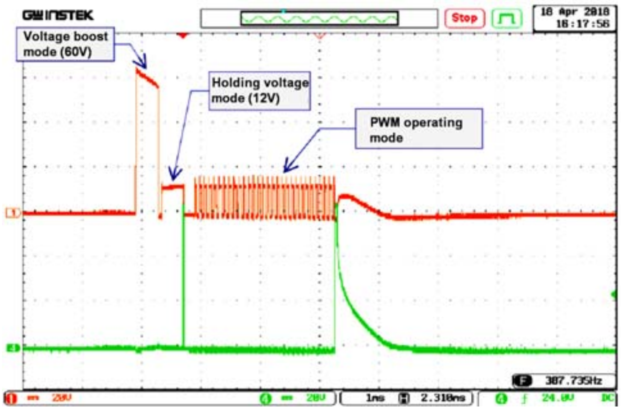

Fig.4. Time courses of voltages on (transistor drain) controlling the operation of the injector in the Audi A3 vehicle

The obtained data was thoroughly analyzed and the measurement results with a detailed description were included in the reports, thus creating the technical documentation. The measurement data contained in the reports, calculations with conclusions and recommendations made it possible to determine the technical parameters of the system components, e.g. the speed and efficiency of LPG injectors, the pressure and temperature stability of the reducer, as well as the performance requirements of the gas multivalve (gas intake pipe opening diameters, channel between the pipe and the outlet, shut-off valve and solenoid valve). Figure 4 shows an exemplary oscillogram with a commentary on the individual fuel injector control times with high voltage (60V) and low voltage (12V) in the Audi A3 vehicle.

Fig.5. Kelly Controller KLS72701-8080I (72V, 700A)

Components of the hybrid system, boosting system with BLDC motors

The power of the engines installed in each of the vehicles provided for in the project was selected individually. The selection of electrical machines has been divided into several stages. In the first step, electric motors were selected on the basis of parameters such as the torque on the propeller shaft, drive shaft and the wheel hub of the vehicle. The selection was made assuming the maximum speed in the first or second gear (driving-up), taking into account the possible maximum revolutions, speed and weight of the vehicle. In the next step, mechanical measurements were carried out and spatial models were made using a 3D scanner of areas and places enabling the installation of electric drives. Having the dimensions of the available electric machines and their 3D models in combination with the data obtained in the scanning process, allowed virtual modeling in order to select the optimal configuration possible for installation of individual structural elements of the drive transmission and electric motors.

Fig.6. The way of mounting the BLDC drive in the rear wheel hub - Audi A3

Fig.7. View of the test stand: with a BLDC motor (HPM-20 kW) powered from the converter

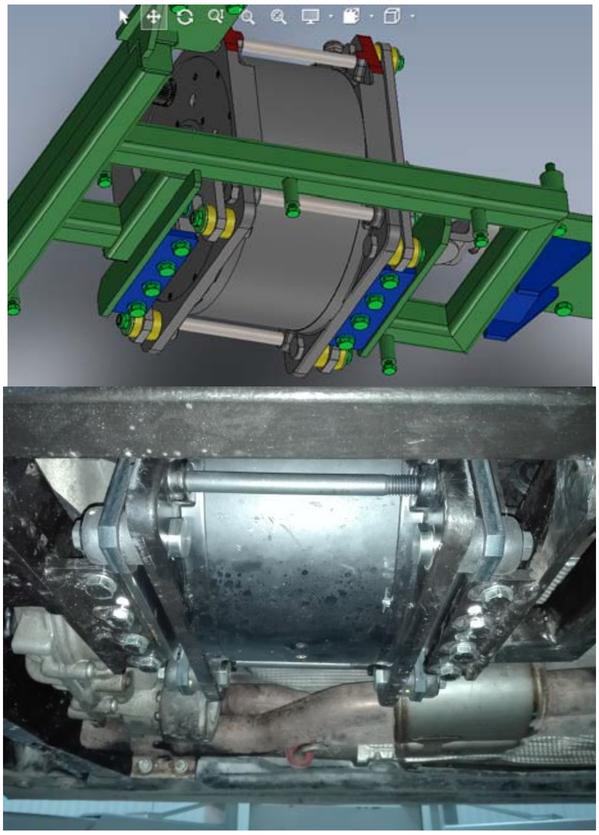

Fig.8. Design (3D model) of the drive mounting in the VW Touareg and below the final result of the work in a mechanical workshop

Ultimately, electric motors with controllers were purchased, being a compromise between the required power and the permissible dimensions, while ensuring the boost function. Controllers were used to power BLDC motors (Brushless DC Motor) (Fig. 5), in which the FOC (Field Oriented Control) control method with the SVPWM (Space Vector Pulse Width Modulation) modulator was implemented. These controllers belong to the family of galvanically insulated controllers. In this type of solution, the high-current part is separated from the control part of the controller. Therefore, it requires two types of power supply. The high-current part is powered by a battery, while the control part is powered from a separate voltage source, usually a lead-acid battery. Two models of electric motors were used in the project. The first one, marked: QS 8000W 273 (50H) E-car Export / V2, was installed in the wheel hubs of the rear axle of the Audi A3 car (Fig. 6). The second drive model: Golden Motor HPM-20 kW (Fig. 7) was installed in the remaining vehicles on the rear propeller shaft. One engine in VW Touareg and two engines working in parallel on a common shaft (Ford F-150).

Battery of accumulators prototype

The prototype of the battery of accumulators has been designed and made based on popular and easily available individual 18650 cells with a capacity of 2500mAh each. The complete battery of accumulators installed e.g. in an Audi A3 vehicle is designed as a series connection of 20 modules with rated voltage of 3.64V. Each of the 20 modules is a parallel connection of 40 18650 cells placed in plastic holders. Elements connecting the negative and positive poles are made of aluminum sheet with additional copper connectors minimizing voltage drops.

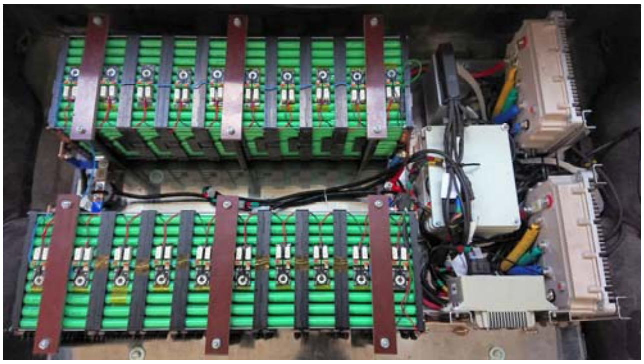

Fig.9. The battery pack installed in the vehicle with engine controllers

Conclusions

The article presents selected results of research and development related to the research and development project being carried out regarding the development and integration of hybrid systems with the use of electric drive and LPG systems in motor vehicles. The article presents only a part of the results of the work and the general concept without a detailed analysis of the research results due to the fact that the project was still in progress. The conducted research and data acquisition in real road conditions will allow comparative assessment, thus revealing the advantages and disadvantages of a given solution. The project focused on the modularity and repeatability of the developed system elements. At the stage of selecting electric motors with converters cooperating with them, the same value of the rated voltage, supplying the power circuits, was determined at 72V. This approach was justified both from the economic and technical point of view - lower total costs of the system materials and standardization of individual elements (battery module, BMS modules and electrical harnesses). On the other hand, over time, it turned out to be suboptimal in terms of the efficiency of the hybrid systems (significant currents, power losses and the level of generated disturbances). The combination of an electric hybrid system and an LPG system intended for direct fuel injection engines significantly reduces the costs of vehicle operation, with lower and lower costs related to the modernization and purchase of the described solution. LPG fuel is also much safer for the environment than other fossil fuels. It may be one of the alternatives to purely electric vehicles, which are currently relatively expensive and are confronted with lack of adequate infrastructure. This system is a response to the needs of the automotive industry, which is currently being won by engines with direct fuel injection and electric hybrid drive.

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