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Series plug-in hybrid powertrain system - an experimental setup

Streszczenie. *W artykule opisano układ laboratoryjny do badania algorytmów sterowania w szeregowych hybrydowych układach napędowych dla pojazdów typu plug-in (ang. PHEV = Plug-in Hybrid Electric Vehicle). Motywacją do jego budowy było wciąż rosnące wśród producentów zainteresowanie pojazdami elektrycznymi, w tym pojazdami typu szeregowy PHEV, w których problem ograniczonego zasięgu pojazdu o napędzie czysto elektrycznym (ang. BEV = Battery Electric Vehicle) rozwiązuje się dodając drugie źródło energii elektrycznej w postaci generatora napędzanego silnikiem spalinowym. (**Szeregowy hybrydowy układ napędowy typu plug-in – laboratoryjne stanowisko badawcze**).*

Abstract. *This paper presents an experimental setup designed for testing control systems for plug-in hybrid electric vehicles (PHEV). Our primary motivation was to meet polish industry half-way with its continuously growing interest in the development of electric and hybrid electric vehicles, incl. series plug-in hybrids that solve problem of limited range of a battery electric vehicle (BEV) by including into a powertrain additional electric power generator driven by a combustion engine.*

Słowa kluczowe: pojazd elektryczny, hybrydowy układ napędowy typu *plug-in*, prostownik aktywny, napęd z maszyną PMSM.
Keywords: electric vehicle, plug-in hybrid powertrain, active rectifier, PMSM motor drive.

Introduction

Hybrid drivetrain systems become more and more popular in concept passenger cars. An ongoing research focuses on delivering solutions that will replace traditional internal combustion engine based drivetrains. Almost every car manufacturer invests in developing hybrid or electric cars. Some of these cars are already available on the market. An electric car has its long history. Electric cars outsold combustion engine powered cars at the beginning of XX century. In those days, lack of effective speed controllers for electric motors combined with lack of reliable rechargeable batteries swung the balance in favor of a combustion engine. An electric motor outdoes a combustion engine in terms of torque-speed characteristics, environmental issues (among other things: exhaust fumes, acoustic noise), and maintenance costs. Nowadays, the biggest obstacle to BEV (Battery Electric Vehicle) popularization is its electrochemical battery. An energy density offered by currently produced cells reaches 200 Wh/kg. This gives an effective gravimetric energy density of battery pack at the level of 100 Wh/kg [1] assuming deep discharge which is not practiced due to life span issues, e.g. Chevrolet Volt uses only up to 8.8kWh from its 16kWh battery pack [2]. At the same time gasoline enables us to store about 12000 Wh/kg. An ICEV (Internal Combustion Engine Vehicle) operates at about 20% tank-to-wheel efficiency. This gives an effective gravimetric energy density of ca. 2400 Wh/kg. Taking into account higher efficiency of electric drive system and factory limited DoD (Depth of Discharge), a ratio between range of a car and weight of installed energy storage is typically 15-20 times smaller for BEV. Therefore most passenger all-electric cars are designed to have 100km-150km range. In a hybrid electric vehicle (HEV) an electric motor assists combustion engine and optimizes its working point. An electric energy storage (ultracapacitors or electrochemical battery) is relatively small and is used for regenerative braking and delivering additional power during acceleration. In a plug-in hybrid vehicle (PHEV) electric energy storage can be restored to full charge by connecting a plug to an external electric power source [3], [4]. The energy storage in PHEV has higher capacity in comparison to the one in HEV. PHEVs can be designed to operate as BEVs at the distances of tens of kilometers (e.g. PHEV-30 is designed to have all-electric range of 30 miles). To extend distance range a combustion engine is started and delivers mechanical power directly to wheels (a parallel PHEV) or its power is converted by a generator to electric one and stored in a battery or directly supplied to an inverter (a series PHEV). The series PHEV benefits from lack of mechanical link between the combustion engine and the road wheels (similarly to BEV) and at the same time solves problem of limited range of BEV (Fig. 1). Thus, there is no need for clutch and gearbox. All energy flows are controlled by electronic power converter. More possible drivetrain topologies can be found in e.g. [5]. Our current research focuses on control strategies in the series PHEV. In this paper an experimental setup employed to investigate control strategies for electronic power converters in the series PHEV is described.

It is forecasted that in 2025 electric cars or plug-in hybrid cars will have approx. 50% market share at new cars in highly developed countries [6] with PHEV to BEV share ratio at the level of 4. There are governmental plans to put one million EVs on U.S. roads by 2015. More moderate forecasts say about 750 000 EVs only on U.S. roads and PHEVs are supposed to play key role in achieving this goal [7], [8], [9]. The developed laboratory system enables us to test control strategies for both powertrains: a BEV's one and a series PHEV's one (also known as an Extended Range EV). One of our goals is to encourage domestic investors to follow global trends in powertrains for automobiles.

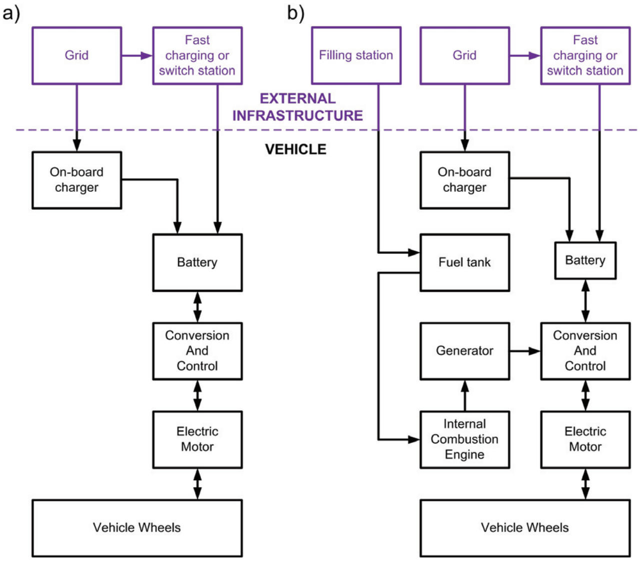

Fig. 1. The BEV (a) and the series Plug-in HEV (b) powertrain topologies

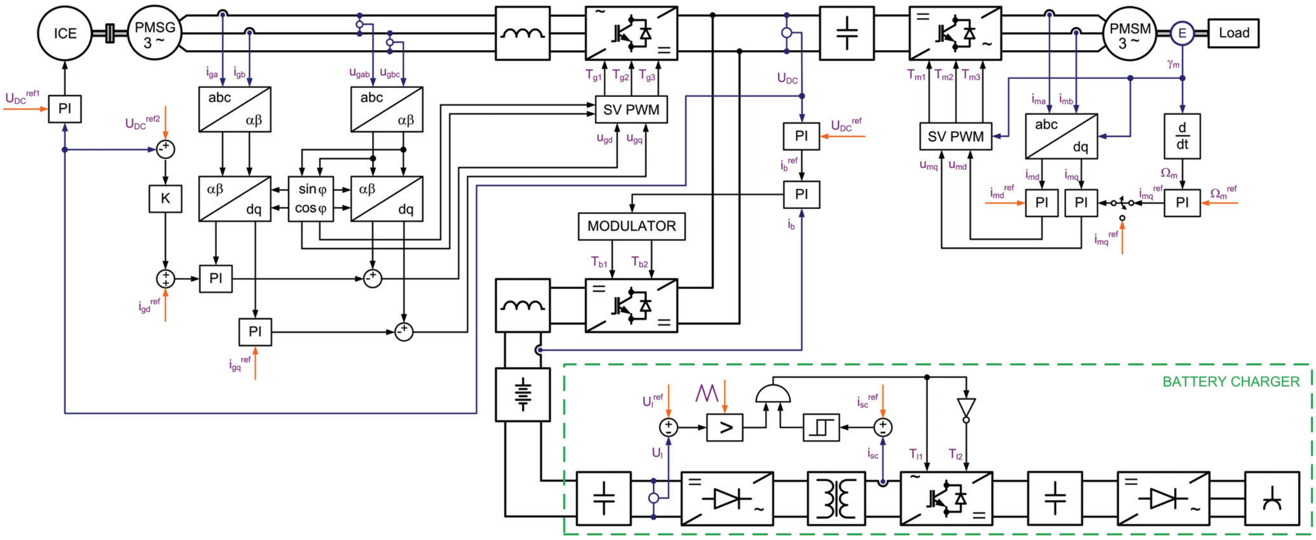

Fig. 2. Block diagram of a series PHEV powertrain control systems

Electronic power converter for series PHEV

An experimental setup consists of an internal combustion engine, a permanent magnet generator, an electrochemical battery, a permanent magnet synchronous motor, an electronic power converter and a load torque generation system. A block diagram of the system is depicted in Fig. 2. All control subsystems (for an active rectifier, a battery bidirectional step-up chopper, and a drive inverter), including a master controller, are developed on DSP platforms from the TI TMS320 C2000 family. All three control subsystems communicate via CAN bus (master control is programmed on the battery chopper controller). Additionally, a user interface was prepared. It includes: acceleration and braking pedals (potentiometers), LCD display, keypad, LEDs, switches and BNC interface for measurements. A topology of the converter is presented in Fig. 3.

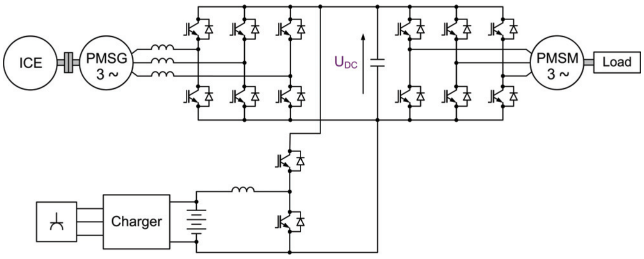

Fig. 3. Topology of a series PHEV main AC/DC/AC+DC/DC power electronic converter

Active rectifier

The combustion engine has built-in speed controller . A generation subsystem can operate in 4 different modes:

a) constant torque and variable speed,
b) constant speed and variable torque,
c) constant speed and constant torque,
d) variable speed and variable torque.

An active rectifier can be controlled using VOC (Voltage Oriented Control), VFOC (Virtual Flux Oriented Control) or DPC (Direct Power Control) strategy. Power ratings of all subsystems are approximately in scale of 1:1 for a small city car (A-segment car). The combustion engine is 12.7 HP (9.5 kW) @ 3,600 rpm Honda iGX440. It is an air-cooled 4-stroke OHC equipped with an integrated ECU (electronic control unit) with a self-tuning regulator (STR) governor system. A PMSG (Permanent Magnet Synchronous Generator) from KOMEL was used on generation side. It is the 3600 rpm, 15 kW, 224V, 120Hz, 4 pole generator.

Drive inverter

This part of the system was equipped with absolute encoder and phase current sensors. This enables researchers to work with all 3 most popular motors used in PHEVs and BEVs, namely permanent magnet synchronous motor (PMSM), brushless DC motor (BLDC) and induction motor. Currently FOC (Field Oriented Control) for PMSM is applied in the system. Rated parameters of this part of the system also correspond to a typical A segment car (15kW continuous and 30kW (40 HP) during acceleration).

Electrochemical energy source and storage

Most currently proposed BEVs and PHEVs are equipped with lithium batteries. These batteries have to be assisted with battery management system (BMS) to operate safely. Nowadays ready to use lithium battery packs with BMS and capacity of ca. 10kWh cost ca. 15000 EUR if retailed. We decided to use initially gel cells. Installed battery pack consists of 12 EnerSys PowerBloc Dry 12V 77Ah cells (ca. 10kWh) which is about 5 times more cost effective. Discussed system can work with any battery pack with BMS (preferably with CAN communication implemented). Nominal battery voltage is assumed to be at the level of 140V. The DC bus voltage is set to 300V. A DC/DC bidirectional chopper controls energy flow between battery and rectifier-inverter DC bus. Batteries can be charged from the generator or using an AC charger. This depends on experiment scenario. It is worth to highlight that developed system can operate in HEV, PHEV or BEV mode. In PHEV and BEV modes batteries are charged before the experiment using the charger connected to the grid. In HEV mode it is assumed that there is no external electric energy source available and the on-board battery storage is used only to assist combustion engine during acceleration and deceleration. The topology of designed battery charger is presented in Fig. 4. This device can work with various types of batteries. System allows user to set maximum charging current and voltage and automatically switches between constant-current and constant-voltage modes according to set values. The control system is based on Unitorode UC3526 chip from Texas Instruments. Selected oscillograms are presented in Fig. 5.

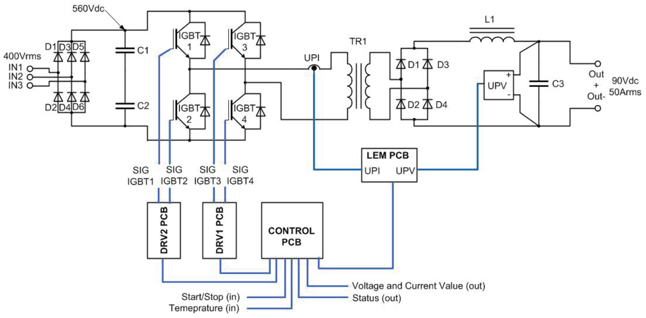

Fig. 4. Schematic diagram of a battery charger circuits

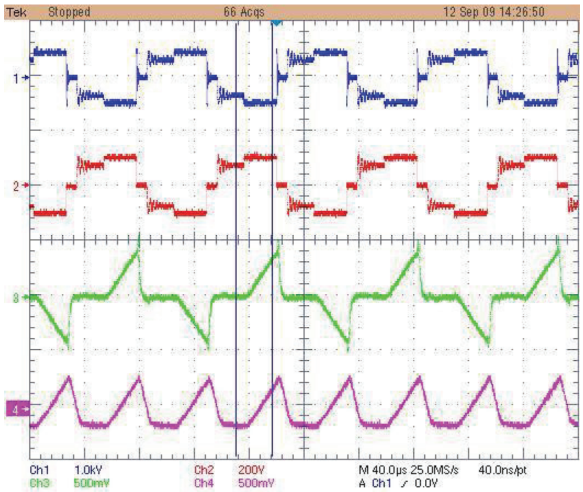

Fig. 5. Selected oscillograms recorded in the battery charger circuits: transformer primary and secondary voltages, transformer secondary current, output capacitor current

Fig. 6. Real photos of system components: (from top to bottom) combustion engine and PMSM generator, batteries, battery charger, PMSM vehicle drive motor, power electronics and control, front panel

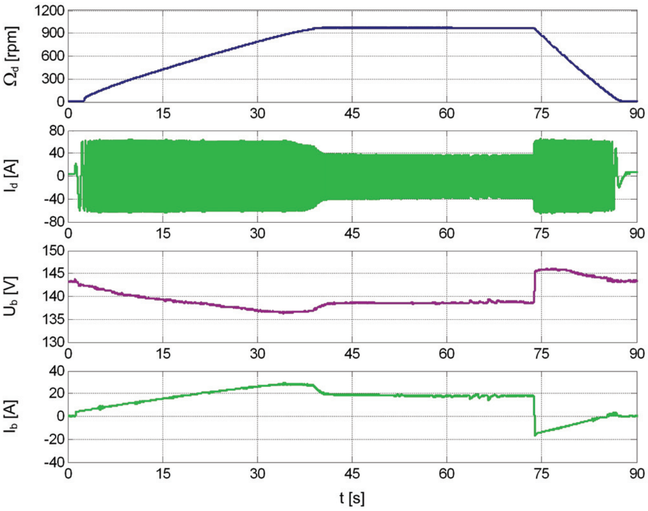

Fig. 7. System operation in all-electric mode: vehicle speed, motor current, voltage on battery terminals, and battery current oscillograms

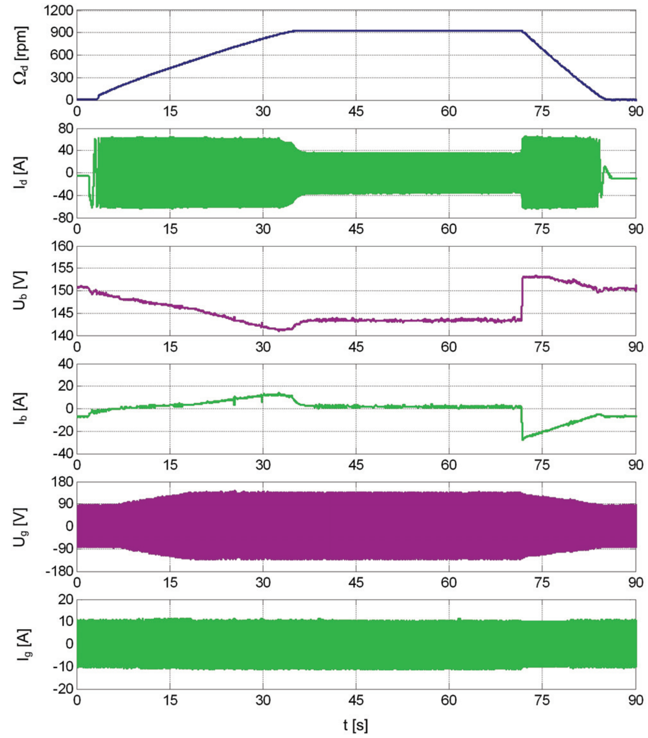

Fig. 8. System operation in combustion engine constant torque mode: vehicle speed, motor current, battery voltage, battery current, generator voltage, and generator current oscillograms

Experimental test results

This system was developed mainly as a platform for control algorithms testing, including an active rectifier, a battery DC/DC converter and a variable speed drive inverter control strategies. For this purpose no commercial power converters (without full access to program code) were used. All controllers (TMS320F2812 from TI) can be reprogrammed by user to suit given experiment. Fig. 6 shows real photographs of selected elements of the system. Due to many possible experiment scenarios only an illustrative subset of commonly performed tests will be depicted. Fig. 7 illustrates system operation in all-electric mode (PHEV in BEV mode). This means that all power demand is covered from electrochemical source. Fig. 8 shows selected oscillograms recorded in combustion engine constant torque operation mode. Speed of the engine-generator set is adjusted according to power demand. Due to limited dynamics of this part of the system additional energy demand needed to maintain assumed dynamics on the drive side is covered from the battery. Fig. 9 shows oscillograms for the system in constant speed mode on the generation side. In all modes regenerative braking is available. Such a system could be equipped with a braking resistor or all braking power could come from mechanical breaks but this would unnecessary limit vehicle range, especially if heavy traffic is taken into account. An overview of power flow control strategies for PHEVs can be found in e.g. [10].

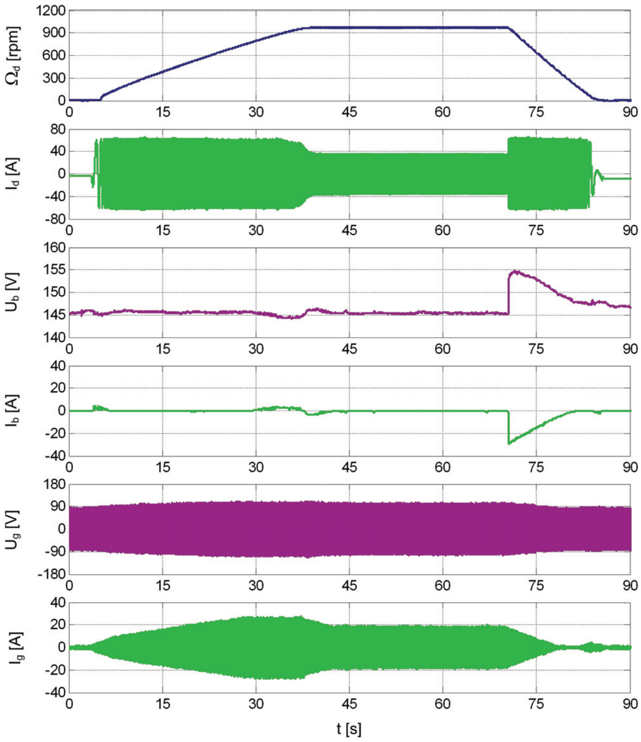

Fig. 9. System operation in constant speed mode on the generation side: vehicle speed, motor current, battery voltage, battery current, generator voltage, and generator current oscillograms

State-of-the-art and conclusions

A flexible platform for PHEV and BEV powertrain control systems testing was built. Its design assumed single electric motor on the drive side. This means that possible test scenarios will refer to BEV or series PHEV designed as 1WD (3-wheel vehicles like S.A.M. Re-Volt [11]) or 2WD with mechanical differential device. The main goal of this work was to build a series PHEV laboratory powertrain to support development of hybrid vehicles in Poland. There are several projects ongoing in Poland devoted to all-electric (BEV) urban vehicles, e.g. aforementioned S.A.M. Re-Volt, Romet 4E [12], ELV001 [13], just to name some of them. None of domestic companies known to the authors focuses on commercialization of any B- to D-segment hybrid vehicle (with an electric motor, an electric energy source/storage and a internal combustion engine in the powertrain). However, most global trends in compact and mid-size car powertrain "electrification" indicate a PHEV as possible winning competitor to a HEV and a BEV in these segments. It is worth pointing out that models designed originally as HEVs are being recently redesigned to be PHEVs, e.g. Toyota Prius Plug-in Hybrid [14], and that due to range expectancy from customers for mid-size cars many production electric cars are not pure-electric, e.g. Chevrolet Volt [15, 16], Opel Ampera (Opel-branded European version of Chevrolet Volt) [17], Ford C-MAX Energi [18]. The authors are convinced that the developed experimental powertrain equipped with microcontrollers with fully-accessible code will encourage domestic investors already producing BEVs to consider the series PHEV as their next product.

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