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J. Lasocki, P. Krawczyk, A. Kopczyński, P. Roszczyk, A. Hajduga

Analysis of the strategies for managing extended-range electric vehicle powertrain in the urban driving cycle

Introduction. *An Extended-Range Electric Vehicle (EREV) is a type of electric vehicle that uses an additional internal combustion engine (ICE) to charge the battery in order to provide the vehicle with a greater range than in electric only mode.* ***Purpose.*** *Analysis and comparison of the performance of EREV powertrain managed according to three control strategies: pure electric mode, hybrid mode with ICE constantly working, and hybrid mode with ICE working only at high power demand.* ***Methods.*** *The tests were carried out using a laboratory test stand that represented the structure of EREV powertrain. Liquefied petroleum gas was used as a fuel to supply the ICE. The test conditions were defined by a special driving cycle simulating urban driving.* ***Results.*** *Time series plots of selected parameters of electric motor, electrochemical battery pack, range extender generator and active load system.* ***Practical value.*** *Among the considered control strategies of EREV powertrain, the energy balance of the electrochemical battery is negative for a purely electric mode, significantly positive for continuous range extenders (REXs) operation mode and moderately positive for the mode with REX activation only in dynamic states.* References 16, figures 22.

Key words: **extended-range electric vehicle, alternative fuel, liquefied petroleum gas, driving cycle.**

Вступ. *Електромобіль зі збільшеним запасом ходу (ЕЗЗХ) – це тип електромобіля, який використовує додатковий двигун внутрішнього згоряння (ДВЗ) для заряджання акумулятора, щоб забезпечити транспортний засіб більшим запасом ходу, ніж у режимі лише на електричному ходу.* ***Мета***. *Аналіз та порівняння ефективності силової передачі ЕЗЗХ, керованої відповідно до трьох стратегій управління: чисто електричний режим, гібридний режим з постійно працюючим ДВЗ та гібридний режим з ДВЗ, що працює тільки при високому споживанні потужності.* ***Методи***. *Випробування проводилися на лабораторному стенді, що представляє собою конструкцію силової передачі ЕЗЗХ. Скраплений газ використовувався як паливо для живлення ДВЗ. Умови випробувань визначалися спеціальним циклом водіння, що імітує водіння в умовах міста.* ***Результати***. *Графіки часових рядів вибраних параметрів електродвигуна, електрохімічної акумуляторної батареї, генератора-розширювача діапазону та системи активного навантаження.* ***Практична цінність***. *Серед розглянутих стратегій керування силовою установкою ЕЗЗХ, баланс енергії електрохімічної батареї негативний для чисто електричного режиму, суттєво позитивний для режиму роботи розширювачів діапазону (РД) та помірно позитивний для режиму з активацією РД лише у динамічних станах.* Бібл. 13, рис. 22.

Ключові слова: **електромобіль зі збільшеним запасом ходу, альтернативне паливо, скраплений газ, цикл водіння.**

Introduction. After over a century of domination of internal combustion engine (ICE) as the basic energy converter in vehicles, there is currently a dynamic development of electric propulsion systems in the automotive field [1, 2]. The latest powertrain solutions improve the performance, efficiency, safety and sustainability of electric passenger cars, commercial vehicles, buses, off-road utility vehicles, motorcycles etc.

Vehicle electrification takes different forms, depending on the purpose and conditions of use of vehicles, users' needs as well as availability of charging infrastructure. Common solutions include: Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Battery Electric Vehicles (BEVs), and recently also Extended-Range Electric Vehicles (EREVs) [1, 3, 4]. This paper focuses on the last of the above approaches. In essence, EREV is an all-electric vehicle with wheels driven solely by an electric motor, but equipped with a small ICE that provides energy for charging a battery and/or supplying the electric motor [1, 5]. In the literature, this arrangement is often classified as a PHEV [1, 5, 6]. Regardless of the definition, the main purpose of introducing EREV to the market was to beat the range limitation that is inherent in EVs.

A reliable control of power flow and energy management is of great significance towards the performance enhancement of EREVs. The main goal is to find the optimal control strategy for different powertrain operating conditions which would yield the minimum fuel consumption. There are many methods used for designing optimal EREV control strategies, among which several are based on estimating the battery State Of Charge (SOC) and vehicle speed.

Dynamic Programming (DP) has been particularly successful in this scope and can be considered as a benchmark method for control of hybrid powertrains [7]. Pontryagin's Minimum Principle (PMP) has also been widely applied and has been proven to provide near-optimal solutions [8]. A traditional PMP-based control strategy becomes a practicable and effective solution when combined with an adaptive concept for balancing SOC of a battery [9]. Other EREV control strategies are usually an extension of the DP- and PMP-based methods.

For example, the charge-deplete-charge-sustain strategy [10] has been developed via Power Split Ratio (PSR) from simulation of Extended-Range Electric Bus (EREB) using DP algorithm. Obtained results show that the overall energy efficiency can be improved and operating costs can be reduced to a great extent. Other research works [11] utilize even more factors affecting the system costs and performance, ranging from fuel consumption to noise emissions up to battery aging and engine start-up costs.

However, most EREV control strategies may not be as highly effective in practice as they are in theory, unless the future driving conditions are known. In order to solve this problem, paper [12] introduces an energy management strategy based on driving cycle identification. The results of simulation show that this strategy is effective in terms of reducing fuel consumption and pollutant emission from EREV. Finally, an energy management strategy that can adapt to the driving characteristics of the driver and adjust the control parameters on-line is proposed [13]. It has been verified in simulation, achieving good fuel-saving and emission-reduction results.

Extensive research on electric vehicles has been carried out at the Faculty of Automotive and Construction Machinery Engineering of the Warsaw University of Technology. Recently, much attention has been paid to EREVs, which results in publications [14–16]. Current paper presents the results of testing extended-range electric powertrain in laboratory conditions. An important aspect is the use of alternative fuel – Liquefied Petroleum Gas (LPG) to supply the ICE, which is very rare in commonly used range extenders (REXs).

The goal of the paper is to analyze and compare the performance of EREV powertrain managed according to three control strategies: pure electric mode, hybrid mode with ICE constantly working, and hybrid mode with ICE working only at high power demand.

Materials and methods. The tests were carried out on a laboratory test stand shown in Fig. 1 and Fig. 2. It consisted of a traction electric motor powered by an electrochemical battery pack. The battery pack was controlled by a master control unit that managed its energy flow – discharge to provide power to the electric motor and recharge using REX. The range extender was based on a spark-ignition ICE supplied with LPG. The traction electric motor was connected by the gear transmission to the shaft that drives the inertia disc, simulating the inertia of the vehicle. The electric motor was loaded by an active load system, allowing for better representation of rolling and aerodynamic resistance, depending on the vehicle speed. This system consisted of a DC generator, which excitation circuit was connected to a controllable power supply while the main circuit – to an electric load, i.e. resistors cooled with external forced air circulation. The DC generator was connected to the shaft with inertia disc through a belt transmission. An external measuring system connected to a computer recorded the operating parameters of the components of laboratory test stand.

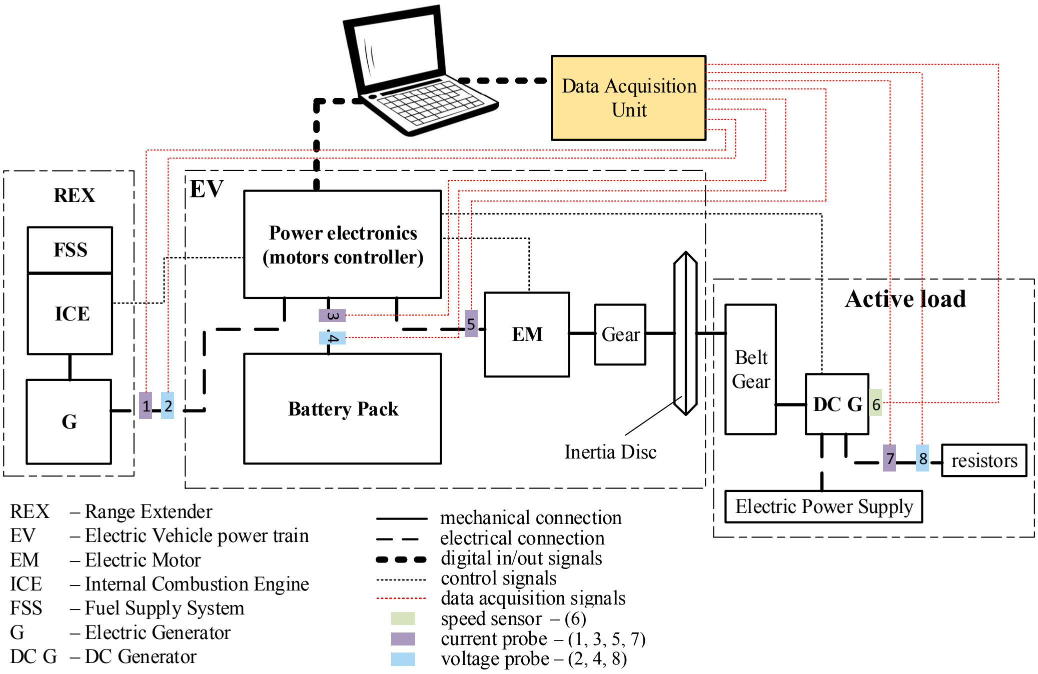
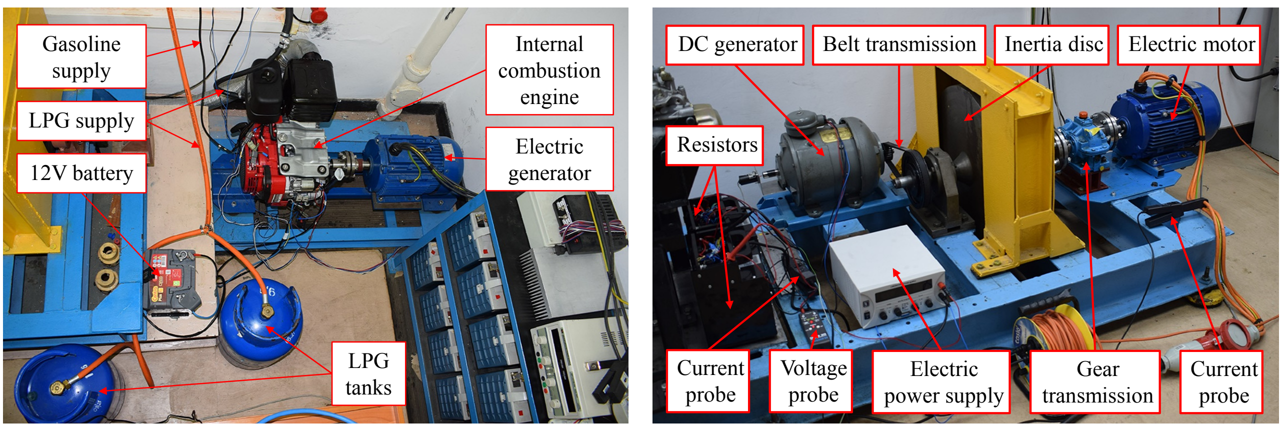


Fig. 1. Schematic diagram of laboratory test stand



a *b*

Fig. 2. General view of laboratory test stand: *a* – range extender; *b* – electric vehicle powertrain with active load system

The main parameters of the laboratory stand elements are given below:

- Traction motor: Permanent Magnet Synchronous Machine, 3-phase, rated power 15 kW, rated rotational speed 3600 rpm, air cooled, manufactured by KOMEL;
- Electrochemical battery: Li-ion battery pack consisting of 36 prismatic cells (MGL-SPIM23300260) 90 Ah in series connection, nominal voltage 144 V, air cooled;
- Range extender:

  – ICE: Honda IGX440 – four-stroke, single-cylinder, spark-ignition, OHC, displacement volume 438 cm^3, cylinder bore/stroke 88 mm/72.1 mm, max power 9.5 kW at 3600 rpm, max torque 29.8 Nm at speed 2500 rpm, carbureted, air cooled;

  – Generator: Permanent Magnet Synchronous Machine, 3-phase, rated power 15 kW, rated speed 3600 rpm, air cooled, manufactured by KOMEL;
- Active load: DC generator manufactured by KOMEL, rated power 3.5 kW, rated speed 2850 rpm, separately-excited (from electronic power supply);
- Data Acquisition Unit: ESAM PP/SP in/out signals compiler box with filtration;
- Inertia disc (fly wheel): moment of inertia 6 kg·m^2;
- Gear transmission: ratio 1:2.7;
- Belt transmission: ratio 1:3, belt type 8M-20.

The ICE of the REX worked at a single operating point, selected taking into account the two-dimensional efficiency characteristic (map) determined earlier [14].

The tests were carried out according to the special driving cycle developed by authors (Fig. 3). The cycle is based on ECE 15 and represents city driving conditions.

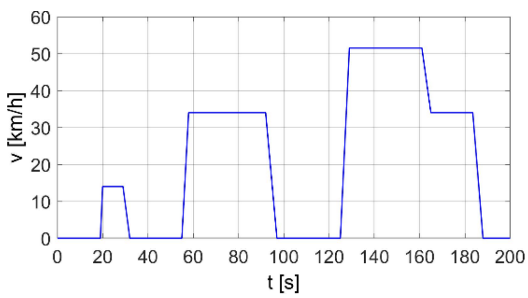


Fig. 3. Special driving cycle used for testing

REX control strategies. In this research three REX control strategies are evaluated:

- strategy 1: Pure electric mode;
- strategy 2: Hybrid mode I;
- strategy 3: Hybrid mode II.

The strategies govern the two states of the REX:

- OFF state, where REX is disabled and no power is delivered to the powertrain from the REX;
- ON state, where REX is enabled and constant power of 2.5 kW is delivered by REX to the powertrain.

These strategies are tested in isolation, meaning for each test only one strategy is used. No switching between the strategies is evaluated.

The first strategy results with pure electric driving. The REX is in OFF all the time during the drive with this strategy scheduled for operation. In real driving conditions, such strategy is suitable when traction motor demand is low and it is critical to not generate any emissions by REX engine. This includes city traffic driving and no pollution zones driving.

Scheduling the second strategy for operation results with hybrid driving, with REX always in ON state. This helps avoiding overcharging and excessive battery charging current. In real driving conditions, such strategy is suitable for high motor power demand and for areas where pollution restriction is not critical. This strategy is suitable for times when battery SOC is running low. Then, it is critical to provide additional energy to the battery, even by running REX when vehicle is stationary.

The third strategy, when scheduled for operation, results with REX changing the state between ON and OFF as requested. In this research, this request is triggered when power demand by the traction motor is greater than zero. In real driving conditions, such strategy is suitable when traction motor demand is moderate to high and SOC is not enough to provide demanded vehicle range in pure electric mode. The driving conditions suitable for this strategy include mixed city (without zero emissions zones) and motorway driving.

Results. Overview. This section presents time series plots of selected operating parameters of the tested powertrain. For AC current and voltage, the measured signals are marked in blue, while the effective values (RMS) – in red. Time series plots of rotational speed, power and current of the traction electric motor were almost the same for each analysed variant of the control strategy, therefore they were presented only in the first case. The power of active load generator (DC generator) results from the resistance to motion, which in turn depends on the speed of the vehicle (i.e. the rotational speed of the traction motor). Hence, for each analysed variant, its time series plot was very similar.

Strategy 1: Pure electric mode. Figures 4–10 show the results obtained for the first control strategy, where REX is turned off during the entire cycle (i.e. «zero emission» mode).

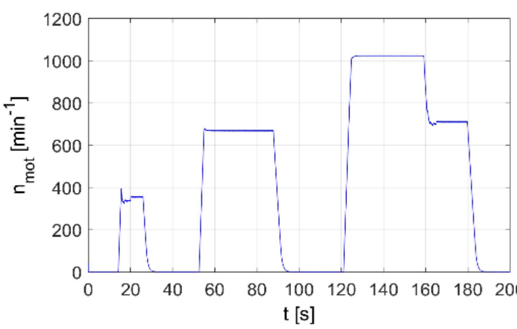


Fig. 4. Electric motor rotational speed for 1st control strategy

The battery current corresponds to the current of the traction motor. The battery power is higher than the power of the traction motor due to energy transmission losses and power electronic converter efficiency, which are variable and depend on the actual operating points. The battery voltage throughout the entire cycle is relatively constant, instantaneous voltage drops are caused by the higher instantaneous current load on the battery. As the battery discharges, the voltage at its terminals decreases slightly. The power, current and voltage of REX generator equal zero, due to the principle of the first control strategy in which extender generator is turned off. Current peaks occur in dynamic states, i.e. when the vehicle accelerates or when it brakes regeneratively. The battery current peak is positive for acceleration and negative for braking. This means that during acceleration, energy is drawn from the battery, while during recuperative braking the battery is charged.

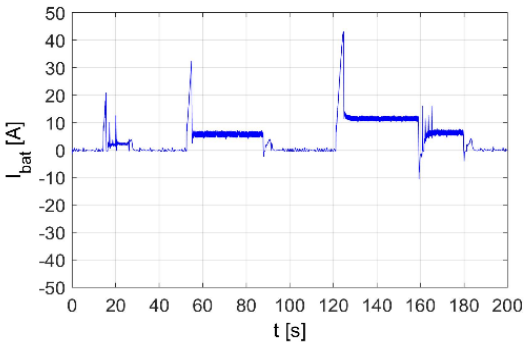


Fig. 5. Electrochemical battery current for 1st control strategy

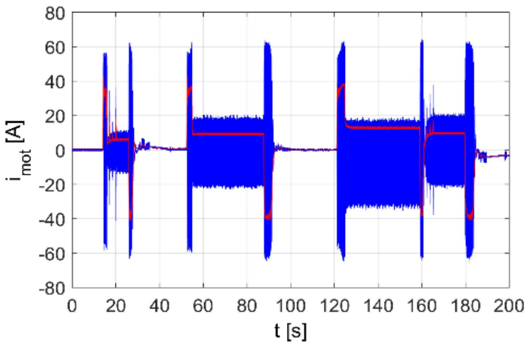


Fig. 6. Electric motor current for 1st control strategy

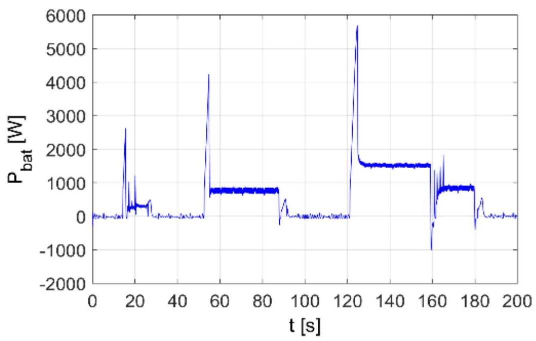


Fig. 7. Electrochemical battery power for 1st control strategy

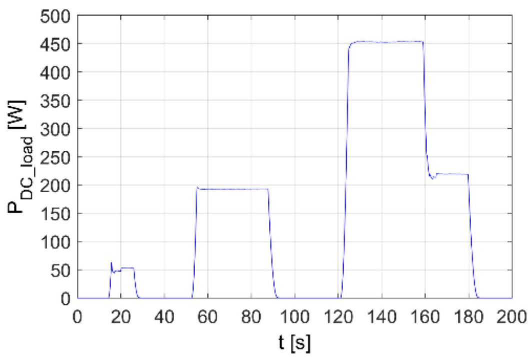


Fig. 8. Active load power for 1st control strategy

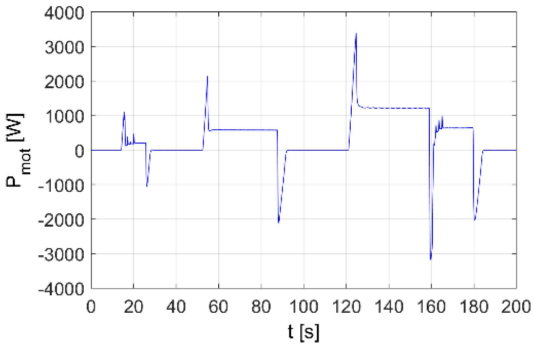


Fig. 9. Electric motor power for 1st control strategy

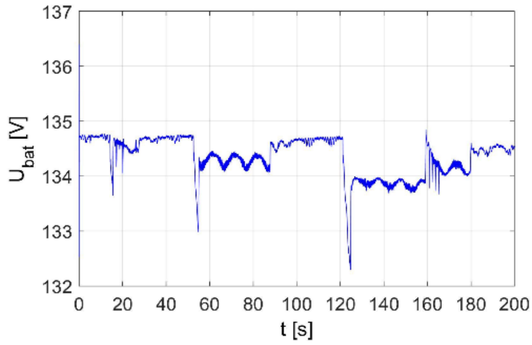


Fig. 10. Electrochemical battery voltage for 1st control strategy

Strategy 2: Hybrid mode I. Figures 11–16 show the results obtained for the second control strategy, where REX is turned on during the entire cycle.

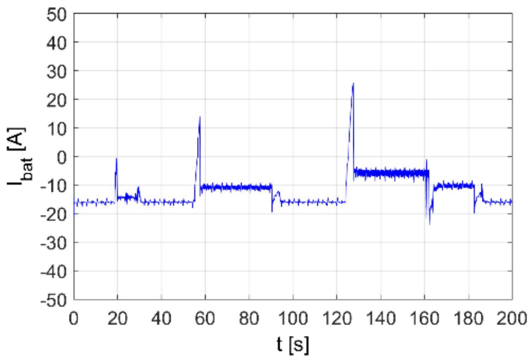


Fig. 11. Electrochemical battery current for 2nd control strategy

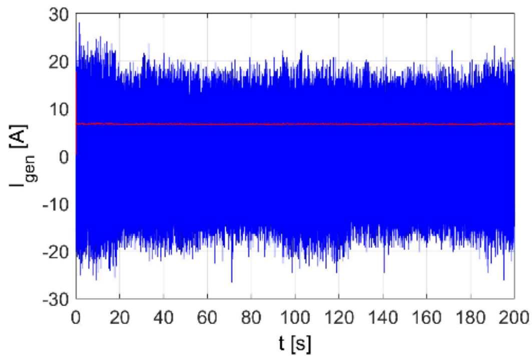


Fig. 12. REX generator current for 2nd control strategy

The surplus power, in relation to the demand resulting from the cycle, recharges the battery. The instantaneous battery current is the sum (excluding losses) of the REX generator instantaneous current and the traction motor current. In the case of regenerative braking, the battery is charged with current from both the traction motor and the REX generator. In this case, it must be ensured that the maximum battery charging current is not exceeded (depending on the capacity of the battery) or that it is not overcharged, as this may result in permanent damage. The REX generator current and voltage have positive and negative values, which means that AC is generated.

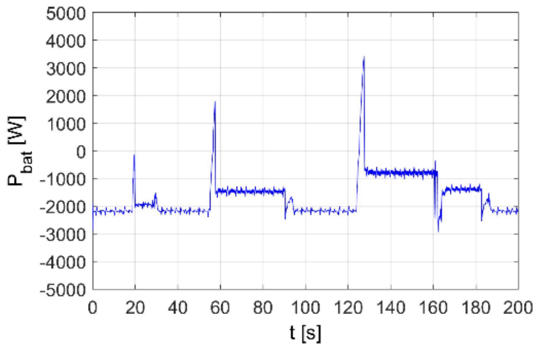


Fig. 13. Electrochemical battery power for 2nd control strategy

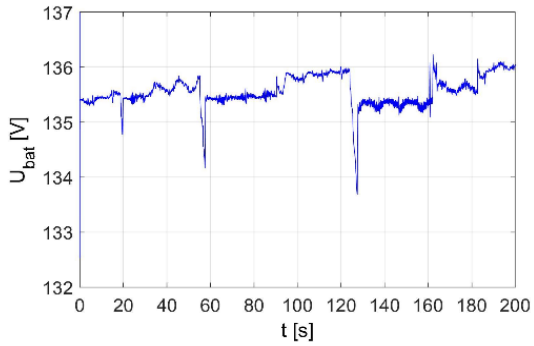


Fig. 14. Electrochemical battery voltage for 2nd control strategy

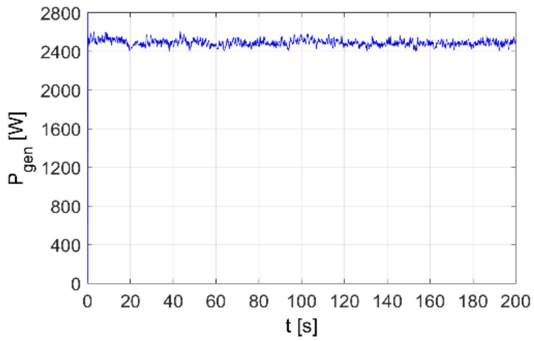


Fig. 15. REX generator power for 2nd control strategy

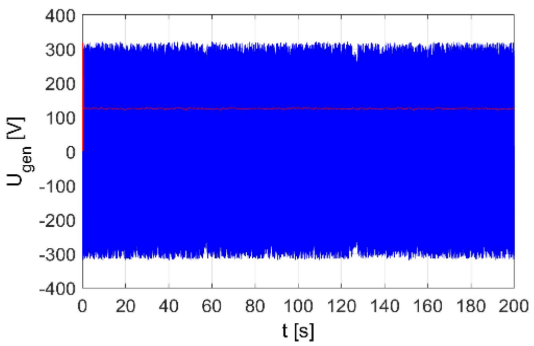


Fig. 16. REX generator voltage for 2nd control strategy

Strategy 3: Hybrid mode II. Figures 17–22 show the results obtained for the third control strategy, where REX is activated in situations of high power demand, determined by the driving cycle.

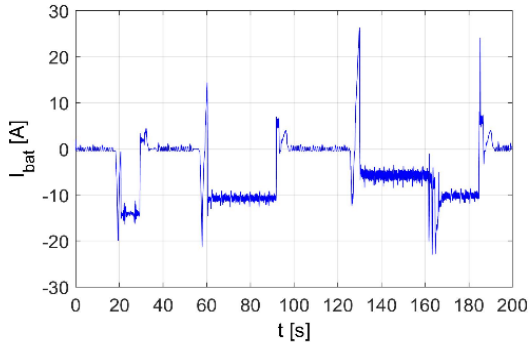


Fig. 17. Electrochemical battery current for 3rd control strategy

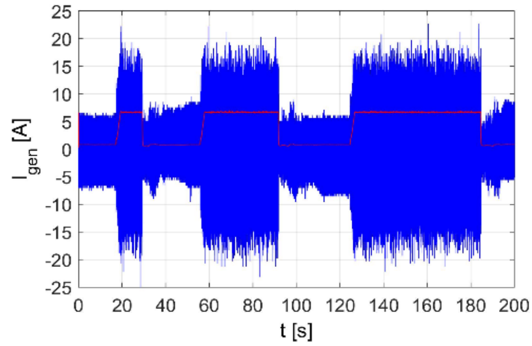


Fig. 18. REX generator current for 3rd control strategy

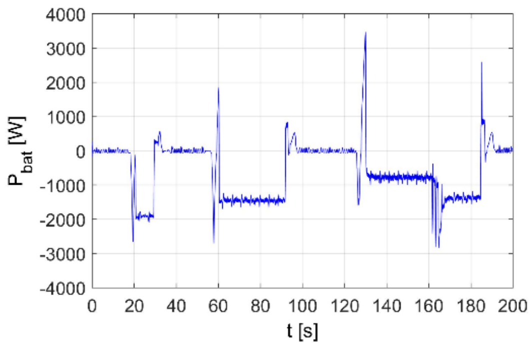


Fig. 19. Electrochemical battery power for 3rd control strategy

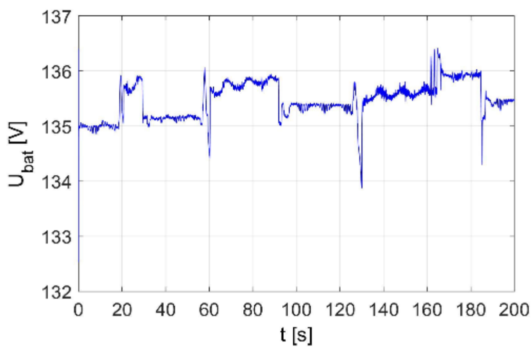


Fig. 20. Electrochemical battery voltage for 3rd control strategy

When REX is turned on, the graphs for battery pack show that the instantaneous current and power values are negative. This means that the power required by the traction motor, necessary for the vehicle to follow the driving cycle, is lower than the power supplied by REX, hence the battery voltage ends up being higher after the considered driving cycle. If similar test would be carried out, but using a different driving cycle with higher energy demand, expected results would show higher energy consumption, and therefore battery energy staying closer to the same level before and after driving cycle.

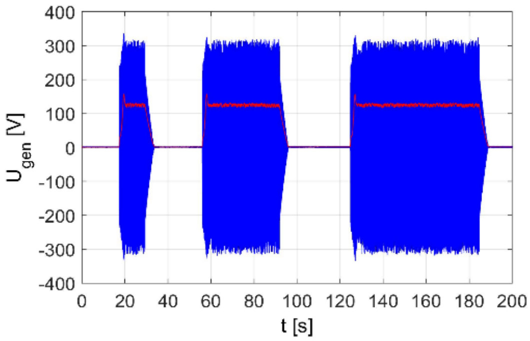


Fig. 21. REX generator voltage for 3rd control strategy

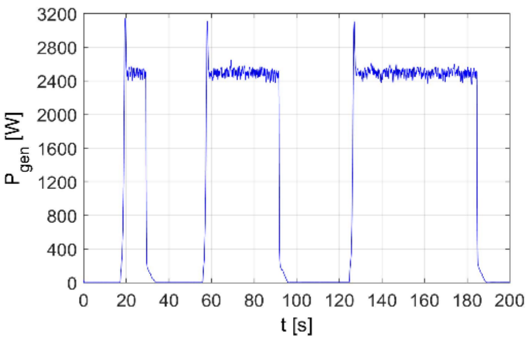


Fig. 22. REX generator power for 3rd control strategy

Conclusions.

The control strategy applied to EREV powertrain should ensure first of all:

- avoiding overcharging and excessive battery charging current;
- reduction of battery current in dynamic states with REX support.

Appropriate selection of powertrain components allows for proper choice of control strategy. The selection of components should take into account the power, voltage and current of the traction motor, battery and REX.

The energy balance of the electrochemical battery for the considered control strategies is:

- negative for a purely electric mode, i.e. the SOC level of the battery at the end of the cycle was lower than at the beginning;
- significantly positive for continuous REX operation mode, i.e. the SOC level of the battery at the end of the cycle increased significantly;
- moderately positive for the mode with REX activation only in dynamic states, i.e. the final battery SOC level increased (the battery SOC level at the end of the cycle), although to a lesser extent than for the case of continuous REX operation – the SOC levels of the battery at the beginning and the end of the cycle had close values.

It should be noted that when analyzing the energy balance of the whole powertrain, it is necessary to take into account the fuel consumption of the ICE and its correspondence to the SOC level of the battery. This may be one of the directions for further research.

Furthermore, the energy balance of the whole powertrain largely depends on the proper selection of operating parameters of the primary power source considering the driving cycle. The relationship between the parameters of individual components of the powertrain also plays an important role. For the considered laboratory test stand, the REX power was significantly higher than the average demand for the power of the driving cycle (traction electric motor) itself. The authors see this as limitations to the results obtained so far. It is assumed that further research will take into account the optimization of the parameters of the test stand.

Conflict of interest. The authors declare that they have no conflicts of interest.

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Jakub Lasocki[1]*, PhD,*
Pawel Krawczyk[1]*, PhD,*
Artur Kopczyński[1]*, MSc, MBA,*
Pawel Roszczyk[1]*, PhD,*
Arkadiusz Hajduga [1]*, PhD, Associate Professor,*
[1] Institute of Vehicles and Construction Machinery Engineering,
Warsaw University of Technology,
84, Narbutta Str., Warsaw, 02-524, Poland,
e-mail: jakub.lasocki@pw.edu.pl (Corresponding author),
pawel.krawczyk@pw.edu.pl,
artur.kopczynski@pw.edu.pl,
pawel.roszczyk@pw.edu.pl,
arkadiusz.hajduga@pw.edu.pl

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