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A mathematical representation of an energy management strategy for hybrid energy storage system in electric vehicle and real time optimization using a genetic algorithm

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HIGHLIGHTS

- Simple and easily optimizable mathematical representation of EMS is proposed.
- Real time EMS optimization system using the GA is developed.
- Analysis of energy consumption, battery current rates, and cycle cost is performed.
- Two developed strategies are compared to the rule-base strategy and battery ESS.
- Proposed strategies decrease battery RMS current rate by 40%.

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ABSTRACT

This paper proposes a simple and easily optimizable mathematical representation of an energy management strategy (EMS) for the hybrid energy storage system (HESS) in EV. The power of each device in the HESS is provided as a continuous function of load power called γ. Two strategies based on the proposed method, one incorporating fixed coefficients of the γ function (GBS) and one with coefficients optimized by a genetic algorithm (GAS) in real-time using a backward time window, are tested and compared to the rule-based strategy (RBS) and battery storage system. The calculations are made for an electric car with a $LiFePO_4$ battery-supercapacitor HESS. The analyzed parameters are: energy consumption, RMS and maximum current rates of the battery, and the cycle cost of an EV with HESS and a battery-powered EV. The analysis is made in dependence on drive cycle speed and an internal resistance of the battery module. The obtained results show that the GBS and the GAS are able to reduce the RMS current rate by 40% in the NEDC in comparison to battery-powered EV, as well as that maximum current rates do not exceed nominal values. The GAS aims at the minimization of energy consumption. It obtains best results in low speed cycles.

1. Introduction

The intensive use of fossil fuels in transportation has led to public concerns over climate changes and energy sustainability [1]. Cars are responsible for a significant part of energy consumption in transportation. They also have a great impact on air pollution in cities. Due to the said fact, scientists and automobile companies have made some efforts to improve electric vehicles (EV) and hybrid electric vehicles (HEV) [2–7]. The major obstacle in the case of the development and the spread of autonomous EVs is a low specific energy and high price of energy storage systems (ESS). Energy storage has become one of the key elements of power systems in a variety of applications, ranging from mobile electronics, electric and hybrid electric vehicles, up to traction and electricity networks. The rapid development and multiplicity of energy storage technologies has allowed for their wide use. However, a uniform ESS using one type of device poses significant limitations [8]. Lithium-ion batteries, which are currently most widely used energy storages in EVs, do not always provide a sufficient capacity and maximum power. Yet another problem is the durability of the battery. The number of cycles performed until the loss of 20% of the capacity of the lithium battery ranges from approx. 500 in the case of $LiCoO_2$ batteries to 2000 for $LiFePO_4$ batteries at nominal conditions. High charge and discharge current rates accelerate the aging process. Although EVs and HEVs have much less negative impact

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on the environment, including green house gases emission, than ICE cars during the drive cycle, their production consumes much more energy and causes higher emission [9–12]. This is mainly caused by the battery manufacturing process. Taking that into account, a conclusion can be drawn that the longer the EVs and HEVs are used the lower their total life emission. Therefore, the research focuses on extending the battery life in order to prolong the usage of EVs and HEVs and to reduce their negative impact on the environment.

The said problems can be solved by combining the ESSs with various other phenomena, as well as utilizing generators in hybrid ESS (HESS). This approach grants benefits stemming from the usage of individual devices. HESSs have been described in numerous publications [4,13]. The majority of the analyzed solutions, especially those that can be used in vehicles, constitute a combination of electrochemical batteries and supercapacitors. The reason for that is, in most cases, a high specific power of supercapacitors and the willingness to utilize them to limit the power of batteries. Such an approach gives the possibility of decreasing battery capacity fading over the cycle life, as the aging process is strongly dependent on the rates of RMS and maximum charge and discharge currents [14–17]. Hybrid systems give a great opportunity to design the energy source with nearly optimal parameters for a specific load.

The properties of a HESS, though, are entirely dependent on an energy management strategy (EMS) taken advantage of. Designing the strategy is a laborious process, since it requires an exact alignment with the type of a load and the type of devices operating in the system. There are numerous strategies described in the literature of the subject. They are divided into rule-based strategies and optimization-based strategies [4]. The optimization of EMS has been the subject of several research papers [18]. Rui Esteves Araújo et al. presented sizing optimization method and filter-based EMS [19]. The research was done for light electric vehicle and energy consumption was decreased by 3–7.8%. A very useful comparison between strategies – filtration strategy and optimization-based strategy – was made by Castaings et al. in [20]. The research aimed at the decrease of the RMS current of the battery pack and provided experimental results. A three device-based system incorporating fuel cells, batteries, and supercapacitors, was considered by Chauvin et al. in [21]. A combinatorial approach was used to solve an optimization problem including component sizing and energy management control. The objective was to minimize global system cost. Song et al. handled the configuration problem of a semi-active HESS composed of $LiFePO_4$ batteries and supercapacitor in [22] and compared four different energy management strategies based on: fuzzy logic controller, model predictive controller, rule-based controller, and filtration based controller in [23]. The aim of the discussed piece of research was to minimize battery capacity fading over cycle life by decreasing its current. The case study was an electric city bus. The results showed 50% reduction of battery cycle life cost for fuzzy logic controller and rule-based controller, as well as 23% for the other ones in CBDC comparing to battery only ESS. In NEDC cycle, the fuzzy logic controller was also the best one, as thanks to its use 23% reduction of battery cycle life cost was obtained. A comparison of a battery storage, a supercapacitor storage and a hybrid system in HEV in terms of power density, energy density, and fuel economy was made by Hu et al. in [24]. Authors used convex programming to optimize both size of the storage system and EMS. A method that is often used for off-line optimization of EMS for HESS is dynamic programming. It was applied by Santucci et al. in [25] to increase battery cycle life by reducing battery RMS and maximum current using supercapacitors in HEV. The method in question was also used by Song et al. to simultaneously optimize the sizing and EMS of the battery-supercapacitor HESS [26]. In both cases, authors achieved a notable reduction of battery capacity fade over cycle life. It has to be mentioned, though that the dynamic programming method requires the knowledge of the drive cycle in advance, so the strategy obtained can be less resistant to drive cycle changes. It is also more complicated while comparing it to gamma based strategy (GBS) presented in this paper. A genetic algorithm was used in the global optimization of EMS for a hybrid electric bus with HESS composed of batteries and supercapacitors in [27] by Herrera at al. The algorithm was used to set optimal levels of values for rule-based strategy. Again, the strategy was optimized globally for a specific drive cycle and not in real time. The authors also presented fuzzy logic optimization of EMS for a light rail vehicle equipped with HESS [28]. The fuzzy logic strategy uses a forward sliding window to estimate the forward energy consumption and adapt the instantaneous power target for batteries and supercapacitors. Therefore, it needs information about the profile and future power demand.

The mentioned EMS optimization methods require a previously known drive cycle. It is more complicated in the case of an individual electric car. There is also the need of using the description of the problem specific to battery-supercapacitor system. It would require a lot of work to adapt them to a system with 3 or more devices. Moreover, the representation of the problem is usually complex enough for two devices and it would become even more complex for more. The question is how to describe the EMS for any number of devices in a way simplifying and improving the EMS designing process, as well as how to perform the optimization for dynamically changing drive cycle.

Therefore, in this paper the authors propose a new, simple, and easy-to-optimize mathematical representation of EMS. The proposed method can be applied to the system consisting of any number of devices. The study case in the paper is a $LiFePO_4$ (LFP) battery-supercapacitor HESS implemented in a typical electric car. Two strategies based on the proposed method, one with fixed coefficients and the other with coefficients optimized by a GA in real-time, are compared to a rule-based strategy and a battery-based electric vehicle. The optimization is focused on minimizing the energy consumption of the vehicle.

The description of EMS using gamma functions presented in this paper has never been provided in the literature of the subject before. This mathematical representation seems to be naturally fitted for the problem. It derives many possibilities just by tuning function coefficients without defining a long set of rules. Due to its simplicity, computational efficiency, and relatively easy calibration, it can be widely used in practical applications. Thus the paper shall have a big impact on future theoretical research on HESS and EMS optimization, but also on practical issues of designing and determining hybrid systems parameters.

The proposed method and details of simulation are described in Section 2. The parameters of EV used in the study and energy storage devices sizing are presented in Section 2.1. Section 2.3 is devoted to modeling of the HESS. The EMS real-time optimization system is described in Section 2.3. The results and discussion are presented in Section 3.

2. EMS design and simulation

According to Eq. (1), the power of i-th device P_i in a hybrid system is a part of load power P_0. The size of this part is determined by the coefficient called γ.

$$P_i = \gamma_i \cdot P_0, \quad \sum \gamma_i = 1 \tag{1}$$

The proposed energy management strategy is based on the assumption that γ is a continuous function of load power (2). This new mathematical representation allows for a significant simplifi-