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Optimum sizing and optimum energy management of a hybrid energy storage system for lithium battery life improvement

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HIGHLIGHTS

- A formulation is defined for battery and ultracapacitor combination optimum sizing.
- ESS hybridization causes to reduce ESS cost and fuel consumption, simultaneously.
- The HESS optimum sizing shows strong dependency to the vehicle driving cycle.
- The optimum (dynamic programming) power distribution of HESS increases battery life.
- The method is useful for high energy and power application (HEVs, renewable energy).

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ABSTRACT

In this paper, a formulation is developed for sizing of a Hybrid Energy Storage System (HESS) in different applications. Here, the HESS is a combination of Lithium battery and Ultra-Capacitor (UC), which is useful for many high energy and high power applications such as Hybrid Electric Vehicles (HEVs) and renewable energy. The sizing formulas are based on initial cost and 10-years battery replacement cost which is arranged as an optimization problem. For battery replacement cost, the Lithium battery capacity depletion formulas are studied for a $LiFePO_4$ battery. As a case study, application of HESS in a Series Hybrid Electric Bus (SHEB) is considered. The results show by the addition of UC, the Lithium battery life is improved significantly. Furthermore, the optimum sizing of the HESS is dependent to the SHEB driving cycle. Therefore, considering the power profile of the HESS in its sizing process may reduce HESS cost. This effect is studied in three different cycles of the SHEB. In addition, the formulation is applied to cycle-based optimization of the Power Distribution Control Strategy (PDCS) of the HESS by dynamic programming. The results show the optimum PDCS has better $LiFePO_4$ battery life in comparison with the conventional PDCS.

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1. Introduction

The energy storage system (ESS) has a key role in many energy generation systems, such as renewable energies. Specially, the ESS is the main drawback in commercialization of different kinds of electric vehicles (EV) and Hybrid Electric Vehicles (HEV). The ESS is an expensive, heavy, and voluminous component of the EV. The characteristics of the ESS lead to limiting the mileage of the electric vehicle [1]. Moreover, life of the ESS as well as the cost of replacing them, prevent manufacturers from bringing EVs into play, even though their fuel economy reduces their everyday cost considerably [2]. Recently, a rapid evolution of EV has begun, which is driven largely by the development of batteries of large storage capacity and reduced cost [3]. In addition, considerable R&D activities are being performed to improve the ESS performance for different applications in the recent years.

The ESS provides the power and energy demands of the energy generation system. Analyzing the demands of many ESS applications shows that the average power demands are very much lower than the peak power demands which occur in short time periods. For example, the electric vehicles are loaded with large peak-to-average power ratios (between 4 and 7) [4]. The most common

Abbreviations: DoD, Depth of Discharge; EV, electric vehicle; ESS, energy storage system; GA, genetic algorithm; HEV, Hybrid Electric Vehicle; HESS, hybrid energy storage system; ICE, Internal Combustion Engine; PDCS, Power Distribution Control Strategy; SHEB, series hybrid electric bus; SoC, state of charge; UC, ultra-capacitor; USD, United States dollar; VFERI, Vehicle, Fuel, and Environment Research Institute.

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Nomenclature

Ah	Ah-throughput
B	pre-exponential factor
C-rate	ratio of battery current to battery capacity
$\mathrm{Cost}_{\mathrm{HESS}}$	equivalent HESS cost
$\mathrm{d}t$	time step of calculation
FUC	UC capacity
I_{bat}	battery current in each time step (k)
I_{UC}	UC current
LC	life capacity
n_{p}	number of the UC modules in parallel configuration
n_{s}	number of the UC modules in series configuration
P_{bat}	battery power
P_{dem}	vehicle demand power
P_{UC}	UC power
Q_{loss}	percentage of capacity loss
$Q_{\mathrm{loss-10y}}$	10-years capacity loss
R	gas constant
R_{UC}	UC internal resistance
SoC_{UC}	UC SoC
T	absolute temperature
t_{DC}	driving cycle duration
V_{UC}	UC voltage
VOC_{UC}	UC open circuit voltage

ESS of EVs is a battery. Batteries are preferred in the market due to their low cost and portability [5]. Batteries have high energy and low power specifications for use in EVs (peak-to-average power ratios are between 0.5 and 2 [4]). As battery costs continue to decrease, EVs will become more attractive for a larger pool of customers. However, the life-time for battery advances is uncertain [6]. Another candidate for ESS is an ultra-capacitor (UC). The ultra-capacitors have good life cycle, low energy and high power specifications (peak-to-average power ratios are between 10 and 12 [4]). Also, the cost of ultra-capacitors has been falling significantly during the last decade [7]. As stated, the conventional ESSs have either high energy or high power specifications. Therefore, aimed at satisfying the energy and power requirements of the vehicle simultaneously, the design leads to the oversizing of either of them. This oversized design causes expensive, heavy, and voluminous ESS. The complementary specifications of batteries and ultra-capacitors can be beneficially combined to make a new ESS of EVs that shows high performance with low weight and suitable battery life at a reasonable cost [8]. In recent years, some designs have been proposed to implement this idea for developing a hybrid energy storage system (HESS) with high energy and high power specifications. The main objective of coupling batteries and UCs is to reduce the current stress in the batteries and to improve its life-time [9]. The main drawback of the HESS is its cost. Therefore, the sizing optimization is necessary. But, there is a knowledge gap in the literature for economic evaluation of a HESS during its lifespan.

$LiFePO_4$ (lithium iron phosphate) has been considered as one of most capable candidates for HEV applications because of its excellent chemical, thermal stability and low cost [10]. However, capacity depletion behavior and life modeling for this battery has not been well established. More importantly, there is little insight regarding the aging mechanisms associated with this type of battery [11,12]. Wang et al. [10] evaluated the aging mechanisms of $LiFePO_4$ lithium ion battery cells.

The HESS Power Distribution Control Strategy (PDCS) has a great effect on its behavior [13]. The main target of HESS is to moderate the battery currents by the UC. The common PDCS is the UC based PDCS. The PDCS commands the DC/DC converter to utilize the ultra-capacitor pack to provide the vehicle demanded power as a prior energy storage. The remaining demanded power is generated by the battery pack [14]. Furthermore, some additional features for PDCS are introduced in the literature of the HESS, such as the UC state of charge control [15,16].

The PDCS can be presented as a discrete sequential decision problem. Therefore, a forward Dynamic Programming (DP) algorithm is proposed in this paper as an optimum PDCS for optimizing the lithium battery life. This method is used in some recent research in the field of hybrid vehicles [17,18]. The dynamic programming algorithm is a recursive method for achieving the optimal solution in sequential decision problems [19]. By using the DP algorithm to get the optimal solution for a problem, we can avoid the large amount of time which is consumed in the exhaustive search method. The DP algorithm is presented for the first time by Bellman in 1957 [20]. He has introduced the algorithm through a theorem naming as Optimality Principle. Based on this principle [21]:*An optimal path has this characteristic that the taken decisions from each point in the path to the end are optimum regardless of the initial state of the problem. This property is conditioned on existing of connections between the point and the optimal decisions in the former steps.*

Some research works utilized the charge/discharge cycle counting methods to estimate the battery lifetime [2,22]. The complexity of these methods is that there are a few complete cycles during the real battery working situations in electric and Hybrid Electric Vehicles. Thus, the Depth of Discharge (DoD) of cycles are dissimilar and a correction method should be developed. Generally, batteries discharged at higher currents have lower discharge capacities [23]. The rate at which a battery charges and discharges has a clear effect on the capacity fade within batteries as observed by Ramadass et al. [24]. In this paper, a life model for a $LiFePO_4$ battery cell is formulated. This lithium battery life model is applied for the capacity loss calculation in a driving cycle.

As a case study for HESS application, a series hybrid electric bus (SHEB) is studied in this paper. The SHEB has been designed and fabricated in the University of Tehran, Iran [25]. The SHEB is a series HEV in which all of its propulsion energy is produced by the

Table 1
Specifications of LFP26650P power cell (http://store.peakbattery.com).

Characteristic	Value
Nominal capacity @ C/5 (Ah)	2.6
Average operating voltage @ C/5 (V)	3.2
Internal impedance @ 1 kHz, AC (mΩ)	<9
Weight (g)	80.5 ± 2
Recommended operating conditions	
Continuous discharge (A)	≤10
Pulse Discharge (A) 30 s	26
Charge current (A)	≤2.6
Charge voltage cutoff (V)	3.65
Discharge voltage cutoff (V)	2.50
High operating temp (°C)	60
Low operating temp (°C)	−20
Maximum operating conditions	
Continuous discharge (A)	42
Pulse discharge (A) 30 s	50
Short pulse discharge (A)	150
Charge current (A)	5
Charge voltage cutoff (V)	4.1
Discharge voltage cutoff (V)	2.0

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