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Control of Electric Vehicle Hybrid Energy Storage Systems Considering Aging and Temperature Effects

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Abstract: Batteries are considered as the most important component of an electric vehicle in terms of their costs and weight and the assurance of their longevity is a major concern. One way to protect batteries from high currents, supercapacitor is employed to form a hybrid energy storage system (HESS). In these systems, a control algorithm called power distribution system (PDS) is employed to distribute the power demand between battery and supercapacitor efficiently. There are different energy management strategies reported in the literature in order to optimize these systems to achieve the best battery life and state of heath. There are off-line strategies which implement different driving cycles classified as high and low energy and are offered for different driving scenarios, which rely on predefined rules. Dynamic programing, predictive, fuzzy, stochastic, wavelet decomposition and online ones which use real driving conditions for power management. In this work, an electric bike and HESS are modelled and four different energy management systems are evaluated and compared for their effectiveness in improving battery life and traveled distance at two conditions; 20 degrees Celsius excluding battery and supercapacitor aging effects and 45 degrees Celsius including battery and SC aging effects. The results suggest that the proposed method is effective for improving battery life and vehicle driving range.

Keywords: battery, energy management system, hybrid energy storage system, supercapacitor, power distribution system.

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1. INTRODUCTION

Number of electric vehicles is on the rise and vehicles running in cities are converting from conventional powertrains to electrical ones to mitigate some of environmental issues such air pollution and global warming and to find a sustainable and less fossil fuel dependent replacement powertrain in the face of declining global fossil fuel resources. As the number of electric vehicles increases new challenges show up, batteries specific power and specific energy density limitations, aging, capacity loss and output power sensitivity to temperature change. Among all available energy storage systems lithium-ion battery is more common due to its relatively higher specific energy and power densities, lower cost and better safety [1]. The aforementioned challenges for batteries are the main hindrance on the way of mass production and usage of electric vehicles. These challenges have reduced the range of electric cars that should be considered to increase the use of electric cars. The advantages of a hybrid storage system include lower battery and super-capacitors and increased power, energy and battery life over ESS[1]. In examining the performance of the HESS system, it is important to select the proper driving cycle [2], [3] where the FTP cycle is used here due to high-speed variations. Variety effect driving cycles at temperatures of -20 to 20 ° C have been investigated by [4], but temperatures above 20 °C have not been investigated. HESS has been investigated and optimized at temperatures below zero by [5]. For electric vehicles, the capacity reductions in charge and discharge currents are high and in the upper and lower range of lithium battery operating temperatures. This performance loss also includes battery power loss and should be controlled in the range of 20 degrees Celsius [2]. To solve this problem, instead of looking at automotive energy management, we can increase the battery power by increasing the number of battery cells, making it more difficult to balance the battery. As we will see in this thesis. Driving according to driving cycles requires charging and discharging at high frequencies and flow rates at high temperatures, which greatly reduces battery life. To reduce this the effects of a

[1] -Energy Storage System

super-capacitor are added to the battery [6] to create a hybrid energy storage system (HESS) [7]. Recently the effect of temperature on lithium-ion battery has been reported by [8] which shows that lithium-ion battery performance is lowered due to the decrease in ion conductivity and increased charge transfer resistance. The acceptable temperature for a lithium-ion battery is between 20 and 60 degrees Celsius [9] and the optimum temperature for this battery is between 15 and 35 degrees Celsius [10]. Each of these components has its own advantages, such as a supercapacitor, which has a longer life and power, and can withstand a higher temperature range, thus being very suitable for high transient power [3] and a very high battery capacity. It has large-scale energy storage and can supply the energy needed for travel. The advantages of a hybrid energy storage system for an electric car can be the protection of the battery in situations where high power consumption is required, and because of the high efficiency of the super-capacitor discharge it can be used to reduce energy losses due to the physical properties of the super-capacitor. It can be used to increase battery life. Finally, using a capacitor in the storage system, brake energy can be stored to alternately charge the lithium battery or the super-capacitor. Overall, the battery life is reduced by increasing the number of charging and discharging cycles and even the elapse of time, which will be addressed in this thesis. The power control system and its optimization have been studied extensively. The first and easiest way to manage HESS energy is by rule-based methods, including UC-based [11]. Dynamic Programming [12] [13] optimizes the power control system in which a driving cycle is based on the power demanded, the vehicle speed and the super-capacitor charge level. It is divided into several parts where the power is distributed by a control signal called the battery current. Based on the driving and simulating cycles of the vehicle power and energy storage system for each flow control, the probability of state transfer of variables at the end of each segment is calculated by homogeneous Marcov chains. This method is known as a reference algorithm and has been widely used to optimize the electric vehicle energy management system and is also used to compare other methods. Interpolation computation is very high in computational iterations. SOP-based power control system [15] [14] designed in this way to combine a battery and super-capacitor system with a view to the voltage and charging level of the super-capacitor in the future and considering the 1500-second FTP driving cycle for maximum reduction. Battery losses optimized [16]. Power control by changing the power filter frequency is proposed by changing the cutoff frequency based on the driving cycle to reduce the maximum amount of battery current by splitting the power with a super-capacitor and also applying the low frequency power demand can maximize the battery power [17]. Reducing the power demand from the battery and thus extend its lifespan is realized. Among the available wavelets, the Haar wavelet has the shortest filtering time range. Different types of wavelet decomposition surfaces are investigated [18] [19]. It is concluded that Level 3 wavelets for a combined management system including battery and super-capacitors in the NEDC cycle between the higher and lower levels. The wavelet is the best of all. The fuzzy control energy management method based on the Markov stochastic prediction has been studied by [20], the reason for using this prediction method is that even though according to present strategies the distribution of demand power between battery and super-capacitor seems reasonable Sometimes power is not supplied due to the limited capacitance of the super-capacitor and the power distribution system must be designed so that the super-capacitor will supply the required power when high power is needed. Fuzzy optimization with Particle Swarm [21] [22] where optimizing the rules established in the energy system using the PSO optimization method, for example due to the dependency of most optimized energy management strategies on driving cycles, [23] have proposed a method in which a set of rules is proposed based on actual driving conditions in which the power is divided into three parts with a predetermined range To optimize this range with the PSO method, the objective is to optimize the vehicle energy cost reduction. To optimize this range, 5 conditions include scale, set range for each of the 3 power, neighborhood range, initial starting location and initial speed, number of iterations. Determined and then the optimal power values are obtained. The fuzzy rules are based on fuzzy logic and the input values are the standard deviation and the average power value and the fuzzy logic output value is the power demand coefficient. [24] Has proposed a simple method based on genetic algorithm in which the battery and super-capacitor power is expressed by a continuous demand function called γ. Two management methods including constant coefficients γ and the other coefficients with function coefficients optimized by genetic algorithm have been tested realistically and compared with ESS based rules. Parametric study of power consumption, RMS and maximum battery flow rate is carried out [25]. Comparison of an electric vehicle equipped with HESS to a vehicle using only ESS is demonstrated. RMS value of the battery is improved by 40% using genetic algorithm optimization method. They proposed a method to determine the equilibrium factor for a minimum equilibrium strategy using actual velocity profiles obtained from a plug-in vehicle traveling in a fixed driving direction. Using the Battery Charging Level-Based Feedback Compatibility Law, the equilibrium factor is expressed as a combination of principal and adjustable components, and the Pontryagain minimization method is solved using the Shooting Method to obtain Co-State dynamics where the method Secant is used to adjust the Co-State initial values. SMC control [26] wavelet-based power distribution and CPE control method [27] in which the effect of temperature and battery life and super-capacitor are not considered in the power management system. Hybrid energy storage system only at low temperatures by [28], high voltage switchgear on both sides high voltage and low voltage DC-DC converter by [29], power distribution system based on random power prediction by [30] The effect of battery life in both the chronological and life-long forms of shortening is due to the number of battery charge and discharge and the depth of discharge by [31] but not the effect of temperature. In [32], the effect of temperature on power losses in a storage system including super-capacitors and batteries is discussed where control and optimization strategies are not discussed. Various methods have also been used to optimize HESS, including the use of PSO method [23] SA method [33] CP method [34], all of which neglect the effect of temperature and lifetime. The main purpose of this paper is first to compare and compare different power distribution systems including single battery (ESS) and hybrid system including battery and super-capacitor (HESS) first in standard temperature conditions without considering lifetime and then considering the effect. Temperature and life span, and finally a power distribution control system designed with genetic algorithm in mind considering the effect of battery life and temperature and super-capacitor.

2. MODELING

2.1 Electric bike model

The modeling implemented in this simulation is illustrated in fig.1. The model incorporates a battery and UC pack, an electric motor and a DC/DC converter.

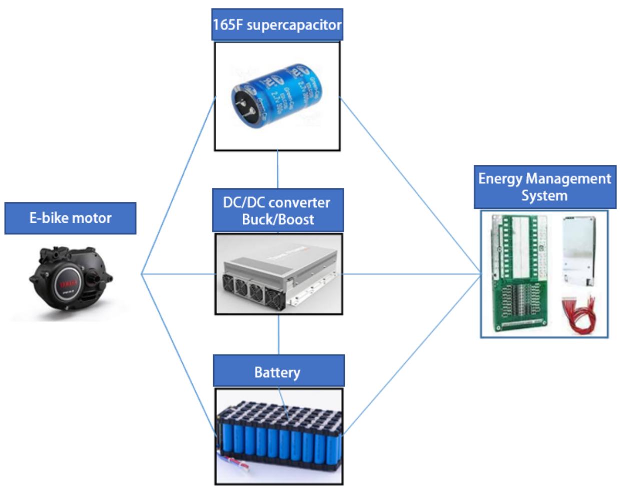

Figure 1. HESS, Electric Motor and EMS

Table 1. E-bike specifications.

E-bike Main Specifications		
Electric Motorcycle	Total Weight	250 kg
	Rolling Resistance	0.003
	Drag Coefficient	0.4
	Frontal Area	$0.6m^2$
	Wheel Radius	$0.24m^2$
High Voltage	70 VDC	
Electric Motor Spec.	Power: 6 kW Torque: 140 N.m	
Hybrid Energy Storage System	Configuration :DC-DC Converter Topology: Active, Battery-Super capacitor DC/DC Converter Power: 12KW DC/DC Converter Efficiency: 95%	
Battery Spec.	286 lithium Iron Phosphate Cells 22 series Cells, 13 parallel cells cell capacity and voltage:2.6 A.h / 3.5 V overall capacity:33.8 A.h cell continuous discharge current: 10 A cell max discharge current: 50 A cell charge current: 5 A cyclic life: 2000 cycles depth of discharge: 80%	
Super-Capacitor Spec.	Capacity: 165 F Max Voltage: 48.6 V (13*2.7 V) Max Pulse Current: 4000 A Max Continuous Current: 150 A ESR=0.0123Ω	

This simulation contains a hybrid energy storage system including a battery, a supercapacitor, an electric motor and a dc/dc converter. The modeled e-bike characterizations are demonstrated in Table 1.

2.2 Battery model

Rint equivalent electrical circuit model comprising of a capacitor representing polarization and a resistance representing battery internal resistance is employed as shown in Fig. 2.

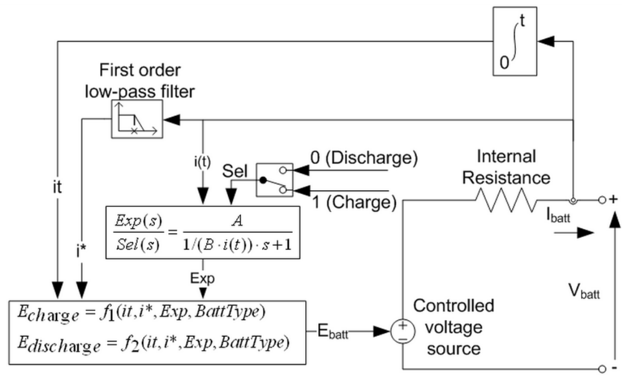

Figure 2. Battery Equivalent Model

2.3 Battery Thermal model

Aforementioned concludes relation that at higher temperatures the voltage and battery charge level increases [35]. Battery voltage variation versus temperature which represents the battery SOC increases as the temperature rises up-to 40 degrees Celsius and then falls down again. Each battery cell temperature (T) is expressed as a function of time (t) as below:

$$T(t) = L^{-1}\left(\frac{P_{loss}.R_{th} + T_a}{1 + s\,t_c}\right), \qquad P_{loss} = (E_0(T) - V_{bat}(T)).i + \frac{\partial E}{\partial T}.i\,T \qquad (1)$$

where, R_{th} is the thermal resistance between cell and the ambient, t_c is the thermal time constant between cell and the ambient, P_{loss} is the overall heat generated during charge and discharge process.

As shown in the super-capacitor life model, the capacitance and consequently super-capacitor lifespan decreases exponentially with increasing temperature and increasing temperature decreases the super-capacitor lifetime.

2.4 Battery aging model

According to [36], there are two forms of longevity effect: 1) loss of battery life and 2) loss of number of charging and discharging cycles applied to the battery. Loss of life is a function of temperature and time, while cyclic losses depend on the flow rate, the cumulative current (integral of all current flowing through the battery life), and the temperature, and the life span through charge and discharge cycles, and increase battery resistance is expressed. The following relationships illustrate these casualties [31]. These relationships show that the rate of loss of battery capacity is greatly reduced due to the effect of chronological life and cyclic life because the rate of capacity loss is directly related to the increase in temperature. It can also be seen that the decrease in battery life has an exponential relation with the flow rate.

2.5 Supercapacitor model

Different thermal models of super capacitors are presented, including the model proposed by [37]. A thermal model for super capacitor has been developed by [38], which is used here. The equivalent circuit of this thermal model is shown in Fig. 3.

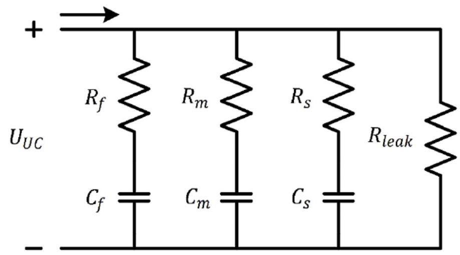

Figure 3. Equivalent super capacitor circuit for temperature effect

The super capacitor internal resistance decreases with increasing temperature and decreases with increasing temperature, which results in an increase in the super capacitor charge level at the same loading end at higher temperatures than at lower temperatures.

2.6 Supercapacitor aging model

Lifetime of the super capacitor is intended by Eyring's law to reduce its capacity by 20% or to double its equivalent serial resistance (ESR). The two main parameters affecting the lifetime of the capacitor and voltage super capacitor are the effects of temperature in the super capacitor thermal model and the effect of voltage on the lifetime [39].

3. SCENARIO 1

This scenario considers the battery operating at standard temperature (25 deg C). In this scenario, the aging effect is not considered. In the next scenario, presented in the Section 3, the aging effect will be introduced into the model. Therefore, a fair comparison could be made between the two scenarios.

3.1 Supercapacitor-based energy management strategy

The method of energy management (UC Based PDCS) is used to assist the battery using the method shown in Fig. 4 [27]. In this figure, P_{dem} represents the cycle power demand, and P_{uc} means the super capacitor power demand and P_{bat} battery power. This reduction in battery demand with the presence of a super capacitor will help increase electric motor scrolling, reduce battery weight, and increase battery life. In this method, the super capacitor is charged in A, B, C mode.

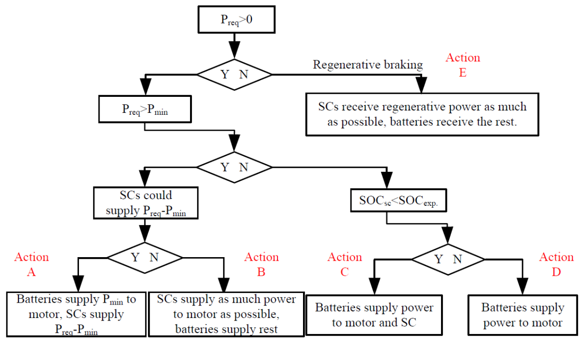

Figure 4. Supercapacitor-based energy management system diagram

Where SOC_{exp} is the expected level of charge and V_{exp} is the voltage predicted. P_{min} is the main factor in balancing the charge and discharge of the super capacitor. If P_{min} is too large, the super capacitor cannot prevent battery burn. However, if P_{min} is too small, action *B* increases due to the low capacity of the super capacitor, which is not suitable for reducing battery wear. The average cycle power demand is used here as P_{min}, which should be close to the average power demanded by the driving cycle. Otherwise, the energy flow between the battery and the super capacitor will increase the battery consumption and thus increase the losses [29]. To evaluate this control method with a battery-only energy storage system (ESS), the level of battery charge in a cycle decreases as shown in Fig. 5.

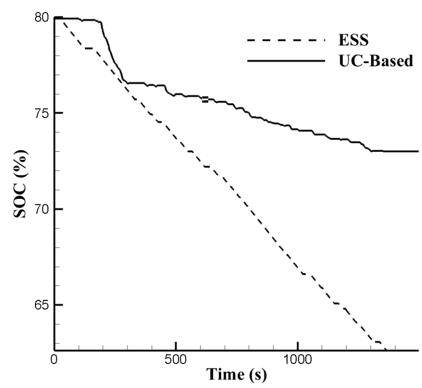

Figure 5. Comparison of Battery Charging Levels of ESS and UC-based Method for an FTP Driving Cycle.

As can be seen, the level of battery charge after 1,500 seconds in the ESS method is 62.5%. The SC-based method the battery charge rate is 73.38%, which represents an improvement of 17.4%.

3.2 SOP[2]-based energy management system

The SOP based PDS method examines the limitations of battery and super capacitor power so that components of energy storage do not exceed their limits (maximum and minimum level of charge and power). In a hybrid storage system, the capacity of the super capacitor is lower than the battery, so the super capacitor reaches its upper and lower charge sooner. In other words, the super capacitor's temperature dependence, which is discussed later in this thesis, is almost zero. Therefore, the super capacitor power level can be obtained by predicting the charging and voltage levels at a given time [15]. The algorithm for this method is shown in Fig. 6.

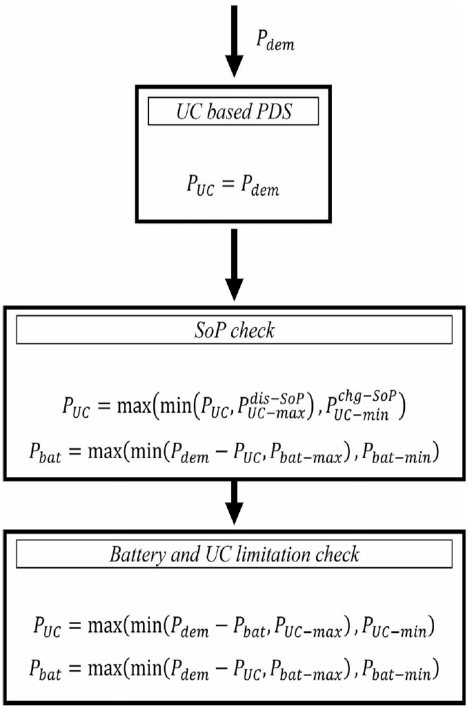

Figure 6. SOP-based Energy management system.

3.3 Haar wavelet-based energy management system

Compared to UC-Based and ESS methods, the charging surface has a lower drop rate as shown in Figure 3-5. After 1500 seconds battery level in ESS method was 62.5% and in UC-based method was 73.38% which shows 17.4% improvement and 73.52% in SOP-based method which shows 17.6% improvement. Compared to the ESS method, the distance traveled increases by 111.147 km. The overall structure of the decomposed power signal of the electric vehicle and its reassembly by high frequency and low frequency filters is shown in Fig. 7.

The wavelet transform function divides the demanded power into its components by different scales. The wavelet can be used to parse transient waves. In this method, high frequency transient power can be extracted from the requested power and given to the super capacitor because the charge and discharge time of the super capacitor can range from a few milliseconds to a few minutes.

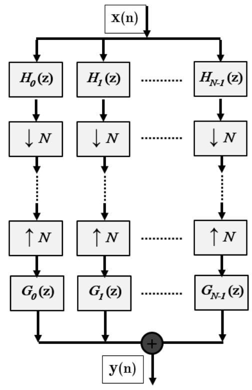

Figure 7. Overall structure of filtering by Haar wavelet.

3.4 FLC[3] based energy management system

In general, there are two types of fuzzy control system: 1-Fuzzy Mamdani 2-Fuzzy Sugeno. The latter suits better for HESS since it works better for non-linear shift loads such as on-demand electric vehicle. This control method is based on the rules set by the designer and outputs as one it is not a fuzzy set and is either a constant or a linear equation. In this method, various parameters such as the amount of power demanded and the level of charge of the battery or super capacitor or both can be considered as input parameters to the fuzzy control system and by defining a series of if-then rules they are output variables such as the amount Connected on demand battery and super capacitor. Here, the fuzzy controller input variables are considered as the electric vehicle demand power and the super capacitor charge level and the super capacitor demand power is extracted as the output of the capacitor.

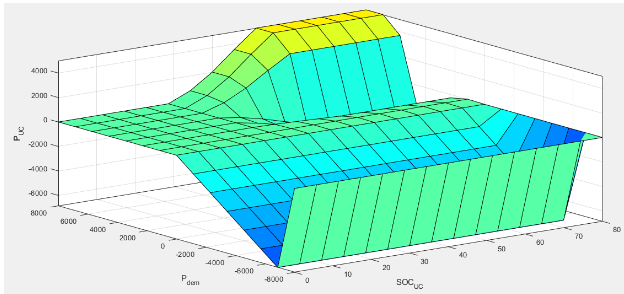

Figure 8. Relationship between input and output parameters according to defined rules.

3.5 Comparison of different methods employed in Scenario 1

A summary of the comparison of the different power distribution methods is presented in Table 2. As can be seen in the SOP-based method, the battery life is longer than other methods because it takes maximum advantage of the super capacitor energy and the voltage and charge

[2] -State Of Power

[3]- Fuzzy Logic Controller

level of the super capacitor is kept at a level always maintained for high power loads.

Table 2. Performance comparison at 20 °C.

EMS Method		Battery SOC in the end of driving cycle	Battery energy consumption (Wh)	Super capacitor energy consumption	Distance traveled (km) per charge	Battery life in years	Relative improvement to ESS
Battery only (ESS)		62.5%	192.22	-	41.108	3.73	-
UC-based		73.38%	178.42	13.80	108.629	4.75	27.34 %
SOP-based		73.52%	173,00	19.22	111.147	4.88	30.83 %
Wavelet	Level 1	67.86%	187.43	4.79	59.258	3.97	6.43%
	Level 2	67.99	187.07	5.15	59.900	4.07	9.12%
	Level 5	68.40	186.03	6.19	62.017	4.34	16.35
Fuzzy		73.16%	173.56	18.65	105.152	4.11	10.18 %

The UC-based method employs supercapacitor along with the battery. It helps capture the regenerative power and is responsible for most of the received currents. By doing so, the battery service life is improved by 27.34% compared with the battery-only case (ESS). On the other hand, for the SOP method, considering the super capacitor charging level and voltage, the appropriate time difference of 15 seconds allows the maximum utilization of super capacitor. This is why life improvement in this method is better than all methods which equals to 30.83% improvement compared with the ESS. The one for the wavelet method is lower than the SOP, and among them, Level 1 wavelet has the lowest life improvement, since it uses only one filter to divide the high and low frequencies between the capacitor and the battery. While, 5-level Filter using 5-stage Haar Filter assigns very slow frequencies to the battery, which reduces the stress going into the batter and improving life better It should be noted that the use of higher-level filters is not practical due to the significant increase in SC numbers. Moreover, by increasing the level, amount of power allocated to the battery decreases and SC power increases dramatically, which is not desirable considering the small capacity of the SC. For the reasons mentioned, it is concluded that level 5 wavelet is the best wavelet level for hybrid energy storage system with 16.35% battery life. Since SOP based method is a predictive method optimized for the FTP cycle, it distributes power between the battery and the super capacitor according to their voltage and charge level. In the fuzzy control method, this lifetime improvement is about 10.18% since the fuzzy laws used do not take into account the rate or rate of change for the charge and discharge currents. Similar to the SOP and UC methods, it is not possible to maximize the capacity of the super capacitor according to the chosen rules, which can be improved by better selection of membership functions.

4. SCENARIO 2

Using the mentioned models, it can be seen that as the temperature increases, the battery and super capacitor resistance decreases and as the temperature decreases their resistance increases, but the life span of the battery reduces proportional to battery temperature rise. As for the effect of temperature on the super capacitor, it can be said that, like the battery [40], it is higher at low temperatures and lower at high temperatures, but for the super capacitor, the internal capacitance decreases with longevity.

4.1 Comparison of different methods employed in Scenario 2

As shown in Table 3, the increase in losses due to the effect of temperature and lifetime of the energy required to run a cycle increased from 192.22 to 197.67, indicating an increase in energy loss of 5.45 Wh.

Table 3. Comparison of performance parameters for reviewed EMS.

Energy Management System		Battery SCO at the end of cycle (%)	Battery energy consumption (Wh)	UC energy consumption (Wh)	Travelled distance (km)	Battery life (year)	Life improvement, compared with ESS (%)
Battery only (ESS)		62.2	197.67	-	40.42	1.48	-
UC-based		72.95	183.87	13.80	102.42	2.01	35.81
SOP-based		73.34	178.45	19.22	108.02	2.75	85.81
Wavelet	Level 1	66.81	192.43	4.79	54.54	1.61	8.78
	Level 2	66.93	192.52	5.15	55.04	1.62	9.45
	Level 5	67.59	191.48	6.19	57.97	1.69	14.18
Fuzzy		70.47	187.01	10.66	100.65	1.57	2.02

As can be seen in Table 3, the SOP-based method provides the best lifetime since it maintains the charge and voltage levels of the supercapacitor in such a way that it can provides high currents when high power is required. The capacitor is capable of supplying it and requires less battery life and therefore, as the lithium-ion battery life formula has a higher flow rate, it reduces the capacity of the battery to 45 degrees. Longer lifespan than other methods. After this method, the SC-based method gives the longest life at high temperature because it uses the maximum capacity of the super capacitor and helps the battery as much as possible to supply the required power.

Haar wavelet-based methods are next in line because they give higher frequency power and higher power variations to the super capacitor, but the main drawback of this method is that it only considers the rate and frequency of change, not the current. The range of this issue makes this method less effective in increasing battery life than the previous two methods. It is also worth noting that the use of filters above level 5 is not due to the need to significantly increase the capacity of the cost-effective super capacitor. Finally, it can be said that the power distribution method is not optimized based on fuzzy method because its rules are adjusted according to the model without heat. For the new model, the rules also need to be optimized. Staying SOP better than the rest will deliver the power of even the UC, which is a basic approach. Also, the amount of energy required for a cycle of 1500 seconds FTP driving cycle with regard to super capacitor, battery, and other losses at temperatures of -20 to 45 ° C, without considering losses is presented in Table 4.

Table 4. Required energy and efficiency of SOP-based energy management system at different temperatures for FTP driving cycle.

Temperature (deg C)	Battery Power degradation (W)	UC Power degradation (W)	Required energy, considering power dissipation (Wh)	Required energy without considering power dissipation (Wh)
-20	7.19	1.02	195.34	192.22
-10	7.29	0.97	195.78	192.22
0	7.17	0.89	195.11	192.22
10	7.25	0.83	194.06	192.22
20	6.75	0.81	192.98	192.22
30	6.64	0.77	192.82	192.22
40	6.68	0.76	193.22	192.22
45	6.98	0.75	193.87	192.22

As can be seen, the energy efficiency increases at lower temperatures and decreases with increasing temperature. Super capacitor power loss also decreases with increasing temperature but this is not the case for battery power losses. In the fuzzy method the rules of power division between battery and super capacitor shall be done in such a way that in different load demand scenarios, the super-capacitor has enough energy to supply as much as demand power it can and to supply peak demand powers during each driving cycle.

5. CONCLUSION

Different power distribution system algorithms employed for hybrid energy storage system (HESS) consisting of battery and supercapacitor is investigated. In each method, the battery charge level, the traveled distance, and lifetime (meaning it loses 20% of its initial capacity) are calculated. The capacitor can run about 53600 driving cycles at 45 ° C before losing 20% of its initial capacity. Finally, the performance of each of these control strategies was compared.

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