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RESEARCH ARTICLE

Fuzzy control of dual storage system of an electric drive vehicle considering battery degradation

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ABSTRACT

In this manuscript, fuzzy logic energy management strategy for dual storage system including supercapacitors and battery is proposed in order to prolong battery lifespan and enhance the range of electric drive vehicle (EDV). First an EDV model and three drive cycles (NEDC, UDDS, and NREL) are established in Matlab/Simulink. Then a fuzzy inference system is designed considering three inputs: power demand, state of charge (SOC) of battery and SOC of supercapacitors. An output, which refers to split ratio between supercapacitors and battery power, is determined. Fuzzy rules are constituted in order to decrease not only high level battery current but also number of charge/discharge cycle of battery which are the main factors of battery deterioration. For a performance verification of the proposed method, three drive cycles with different characteristics are considered. Obtained results are compared to two other strategies; one of them is battery only system and the other one is dual storage system managed by logic threshold method. It is shown that the proposed method delivers better and robust performance to prolong battery lifespan.

1. Introduction

Environmental concerns, which ensued from greenhouse gas emissions and global warming, and energy conservation are two important topics which have attracted increasing attention from researchers over the past few decades. According to Environmental Protection Agency's report, 28.9% of greenhouse gas emissions were generated only by transportation sector [1]. By means of growing technology, electric drive vehicles come to forefront which have zero-emission engines. Besides that in the sense of energy, EDVs provide exhaustive, and fair energy opportunity that increases efficiency and usage of clean energy sources [2]. EDVs are appropriate energy efficient choices for transportation systems, however, as a main energy storage system, battery, has some weaknesses such as: short life cycle, low acceleration performance, and poor power density [3].

There are different aspects of the deterioration of a battery. The charge and discharge cycles of the battery are the main factors of degeneration. If the number of charge/discharge cycles raises, then deterioration accelerates. Another factor is electrical charge/discharge current. Not only high power demands which causes fast discharge but also high charge current affect battery life cycle adversely [4, 5]. Supercapacitors do not have much energy capacity as batteries, however, they are capable of delivering and acquiring this energy in very short time due to their high power densities. Therefore supercapacitors are convenient for applications which ensure high-power in order to expedite the vehicle or recover possible energy along braking mode [3, 6]. Considering an electric vehicle energy demand, it is more convenient to constitute a dual storage system which consists of both battery and a supercapacitor [7, 8]. This

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storage system conducts battery and supercapacitor in a parallel manner. Thus it has advantage of combining functionality of both energy sources at the same time. Furthermore, performance of electric drive vehicle is improved and the lifespan of battery is extended.

It is required to arrange power management of dual storage system in order to satisfy driving performance and energy efficiency of storage system. In recent years, a variety of power management control strategies have been proposed. These strategies are classified into two main parts: online (real-time) strategies and offline optimization strategies. As an offline optimization method dynamic programming was utilized to control actions and provide power distribution between two energy sources. During the simulations, three different drive cycle were taken into account. With the help of rule based power management, authors indicated that proposed control strategy could improve the performance of system for several state of health (SOH) and state of charge conditions. [9]. In another study, a nonlinear controller model developed and this model was evaluated using Lyapunov stability design techniques [10]. The DC bus voltage is also regulated using two DC/DC converters besides battery and supercapacitor currents. A Lyapunov function based controller and a sliding mode controller were proposed to regulate DC bus voltage and currents of battery and supercapacitor respectively [11]. Nonlinear control techniques provides reasonable solutions, however, computational complexity is still a drawback.

In recent years, many real-time energy management strategies have been recommended. A two-level model predictive control algorithm was proposed to control energy management system of a race car under lap time and energy consumption constraints [12]. An integrated optimization method was utilized to optimize hybrid energy storage system considering battery degradation and electricity cost. Authors realized the optimization process in terms of battery prices. Finally it is declared that the total cost of hybrid energy system is depicted to be 12 % less than a solo energy storage system [13]. In another study authors proposed a Haar wavelet transform in order to manage energy storage system of a tram [14]. A reinforcement learning based approach was applied to hybrid energy storage system. First, power transition matrices based on Markov chain were calculated. Then, reinforcement algorithm was utilized to optimize energy loss of system. The rule based power management and proposed method were compared [15]. Furthermore, Choi et al. proposed a model which consist of two parts: first, supercapacitor's reference voltage was calculated and then power management was optimized. They formulated a convex optimization problem model, subsequently solved this problem using general solvers [5]. Moreno et al. proposed an optimal control strategy based on neural networks which was appropriate for different power sources. They made several experimental tests in several conditions [16]. In order to optimize SOC values and battery life of hybrid energy storage system, Shen and Khaligh formulated a multi-objective optimization problem. They used not only dynamic programming method to solve optimization problem but also fuzzy logic approach for comparison of test results [17]. Stability and quality of distribution network are critical for power grids. In this sense, fuzzy logic controller was applied to energy management system in order to keep battery SOC values in secure limits [18] and to minimize grid power variation [19, 20]. Besides these control strategies also heuristic [21] and decentralized [22] controllers were used for energy management of storage systems.

Electric vehicle's performance and energy efficiency of storage system were the focus of algorithms mentioned above. However, complexity of driving cycle changes power demand for various conditions. This situation affects battery's SOH and SOC substantially. In this manuscript, the main concentration is the energy management of an electric drive vehicle with a dual storage system prioritizing battery's SOH and SOC states. First, a dual storage system is modeled including battery and supercapacitor. Then, a fuzzy inference system is proposed according to battery and supercapacitor characteristics. Afterward, a fuzzy controller is designed which is appropriate to assemble with electric drive vehicle model in Matlab.

2. System Description and Modeling

A simplified longitudinal vehicle model is used in this study in order to estimate the dynamic tractive requirements of the EDV powertrain.

2.1. Modeling of Electric Drive Vehicle

Four resistive forces affect the EDV along its motion; aerodynamic drag resistance force F_{aero}, rolling resistance force F_{roll}, road gradient force F_{grad} and bearing and mechanical friction force F_{frict}. Aerodynamic drag resistance is the drag force created by the friction between vehicle body and air flow around the vehicle. It can be expressed as follows:

$$F_{aero} = \frac{1}{2}\rho A v^2 c \quad (1)$$

where ρ is air density (kg/m^3), A is frontal area of the vehicle (m^2), c is drag coefficient of the vehicle and v is the velocity of the vehicle (m/s).

Rolling resistance is the required force to overcome the friction between the tires and the road surface and can be represented by

$$F_{roll} = mgf_r \cos\theta \quad (2)$$

where f_r is rolling friction coefficient, m is mass of the vehicle (kg), g is gravitational acceleration (m/s^2) and θ is the slope angle of the road ($degree$). Rolling friction coefficient can be also given as a function of vehicle speed, tire type and tire pressure, hence it can be formulated as follows [23]:

$$f_r = f_{R0} + f_{R1}(\frac{v}{27.78}) + f_{R4}(\frac{v}{27.78})^4 \quad (3)$$

In equation (3), values of f_{R0}, f_{R1} and f_{R4} are obtained from three standard graphs for different tire thread patterns and various vehicle speeds [23].

When EDV is moving on a inclined road, a road gradient force considerably affects the vehicle. This gradient force is originated from gravity and can be formulated as:

$$F_{grad} = mg\sin\theta \quad (4)$$

Additionally, rotating mechanical parts of the vehicle such as bearing, shaft, etc. cause some extra friction. This bearing and mechanical resistance can be modeled as [24]:

$$F_{frict} = mgk_{frict} \quad (5)$$

where k_{frict} is constant related to bearing and mechanical friction of the vehicle.

Throughout the motion of EDV, the electric motor should overcome all above resistive forces. The required motor power is transmitted to tires through the drive train which consists of gearbox and drive shaft. So, input-output relation of the drive train must be determined implicitly. Shaft parameters such as shaft force, F_{shaft} (N), shaft power, P_{shaft} (W) , shaft speed, n_{shaft} (rpm) and shaft torque T_{shaft} (Nm) can be obtained as follows:

$$F_{shaft} = F_{aero} + F_{roll} + F_{grad} + F_{frict} \quad (6)$$

$$P_{shaft} = F_{shaft}v \quad (7)$$

$$n_{shaft} = 60\frac{v}{\pi d_{wheel}} \quad (8)$$

$$T_{shaft} = F_{shaft}r_{wheel} \quad (9)$$

where d_{wheel} is diameter of the wheel (m) and r_{wheel} is radius of the wheel (m).

Similarly, motor parameters such as motor torque, T_{motor}, motor speed, n_{motor} and motor power, P_{motor} can be calculated by using following equations:

$$T_{motor} = \frac{T_{shaft}}{\eta_g i} \quad (10)$$

$$n_{motor} = n_{shaft}i \quad (11)$$

$$P_{motor} = \pi n_{motor}\frac{T_{motor}}{30} \quad (12)$$

where η_g is gearbox efficiency and and i is gear ratio. Note that positive P_{motor} values refer to the motor mode where the vehicle is propelled by electric motor while negative P_{motor} values refer to the regenerative mode where electric motor acts as a generator and charges the energy storage system that consists of supercapacitor and battery. Since proposed controller takes into account not only the required power but also state of charge values of battery and supercapacitor. In the next subsection, calculation of SOC values of battery and supercapacitor will be explained in detail.

2.2. Dual Storage System

By considering the constant auxiliary consumption P_{aux}, battery power P_{bat} and battery current I_{bat} are calculated as;

$$P_{bat} = P_{aux} + \frac{P_{motor}}{\eta_m} \quad (13)$$

$$I_{bat} = \frac{U_{bat}}{2R_{bat}} - \sqrt{(\frac{U_{bat}}{2R_{bat}})^2 - \frac{P_{bat}}{R_{bat}}} \quad (14)$$

For any required speed and torque values, motor efficiency η_m can be obtained from the motor efficiency maps provided by the manufacturer or can be derived experimentally. Likewise battery no-load voltage U_{bat} and internal resistance R_{bat} can also be calculated from the battery charge/discharge curves. Assuming 1 hour of run time, total charge of battery Q_{bat} and battery SOC (SOC_{bat}) can be calculated as:

$$Q_{bat} = \int_0^{3600} I_{bat}dt \quad (15)$$

$$SOC_{bat} = \frac{Q_N - Q_{bat}}{Q_N} \quad (16)$$

where Q_N is the nominal charge of battery.

State of charge value of supercapacitor SOC_{sc} can be calculated in a similar manner by using simplified RC equivalent model including the ideal capacitor C and the series internal resistance of the supercapacitor R_{sc}. Here R_{sc} represents the energy loss converted to heat during charge and discharge process of the supercapacitor [25]. The block diagram of the dual storage system is given in Figure 1.

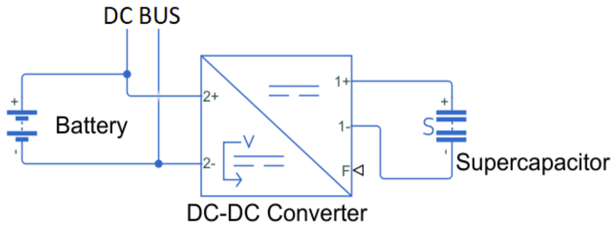

Figure 1. Block diagram of dual storage system

3. Energy Management Control

The purpose of energy management controller in the EDV is to allocate the instantaneous power between the battery and supercapacitor considering to prolong battery lifespan and the range of EDV. Controller should respond to the power request on time, however, real-time drive cycles are complex and differ from each other with respect to power demands. Fuzzy control system, which has the advantages of easy construct, robustness and no need to mathematical model in comparison to analytical model-based strategies, can be a good choice for controlling of an energy management system [26].

3.1. Structure of Fuzzy Controller

The fuzzy energy management system should specify the allocation between the battery and supercapacitor in order to meet power requirements. Fuzzy inference system generates an output to control power split using three inputs such as: power demand, SOC of battery and SOC of supercapacitor. Both SOC's are defined in the interval of $[0, 1]$. So their form is convenient to use with fuzzy inference system. But power demand should be fuzzified before it enters fuzzy inference system. Following equation can be used to fuzzify power demand:

$$F_{Pdemand} = \frac{P_{demand}}{P_{max}} \tag{17}$$

where P_{demand} is the required power, $F_{Pdemand}$ is fuzzified value of power demand and P_{max} is the maximum power demand. The fuzzy controller provides power distribution for battery and supercapacitor using output of fuzzy inference system, m_{bat}. Battery power is calculated by following formula:

$$P_{bat} = P_{demand} m_{bat} \tag{18}$$

where P_{bat} is power provided by battery. It is assumed that there is no power loss caused by DC/DC converter. So, power allocated to supercapacitor, P_{sc}, can be calculated by using following formula:

$$P_{demand} = P_{bat} + P_{sc} \tag{19}$$

$$P_{sc} = P_{demand} - P_{bat} \quad \text{or} \tag{20}$$

$$P_{sc} = P_{demand}(1 - m_{bat}) \tag{21}$$

The structure of fuzzy controller is shown in Figure 2.

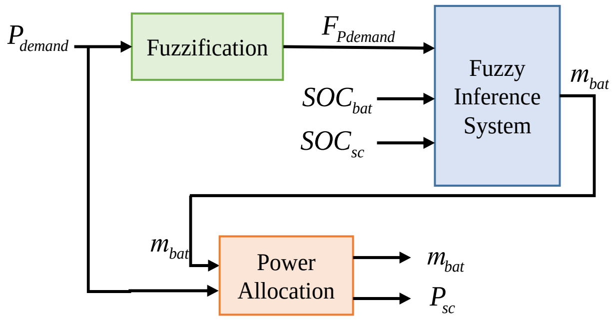

Figure 2. The structure of Fuzzy Controller

3.2. Modeling Membership Functions of Fuzzy Control

In order to prolong battery lifespan, it is required to avoid not only frequent charge and discharge of battery but also high battery current. Thus in terms of fuzzy energy management control, supercapacitor should deliver power as much as possible when the power demand is positive, high and the SOC of battery is low. On the contrary, when the power demand is negative and high - regenerative mode -, supercapacitor should be charged as much as possible.

Supercapacitors charge and discharge efficiency is sufficient, however, a SOC level of supercapacitors under % 5 is not desired. Fuzzy rules are constituted considering SOC level of supercapacitors. We can summarize the main idea behind the rules as following: If power demand is high (maximum acceleration mode), then battery and supercapacitor deliver power for the EDV together. If power demand is low (cruising mode), supercapacitor provides the entire power alone. If power demand is negative (braking or regenerative mode), then supercapacitor is charged first, remaining energy charges the battery if there is. The whole rules can be obtained by means of Table 1, Table 2, and Table 3.

Table 1. Fuzzy rule table for SOC_{bat} is BL.

SOC_{bat} BL		SOC_{cap} CL	CLM	CM	CHM	CH
P_{demand}	RH	OM	OM	OHM	OHM	OH
	RM	OM	OM	OHM	OHM	OH
	RL	OLM	OLM	OLM	OLM	OHM
	Z	OM	OM	OM	OM	OM
	L	OHM	OHM	OLM	OLM	OL
	M	OH	OHM	OM	OM	OLM
	H	OH	OH	OHM	OHM	OM

Table 2. Fuzzy rule table for SOC_{bat} is BM.

SOC_{bat} BM		SOC_{cap} CL	CLM	CM	CHM	CH
P_{demand}	RH	OL	OLM	OLM	OM	OH
	RM	OLM	OL	OLM	OLM	OHM
	RL	OLM	OL	OL	OL	OHM
	Z	OM	OM	OM	OM	OM
	L	OHM	OM	OLM	OLM	OLM
	M	OHM	OHM	OM	OLM	OLM
	H	OHM	OHM	OHM	OM	OM

The domain of fuzzy inference system variable power demand is defined as [-0.5,1] since there is negative power demand for regenerative mode. Furthermore, the domain for the battery SOC and supercapacitor SOC is defined as [0,1] and also the domain for output is defined as [0,1].

Table 3. Fuzzy rule table for SOC_{bat} is BH.

SOC_{bat} BH		SOC_{cap} CL	CLM	CM	CHM	CH
P_{demand}	RH	OL	OL	OL	OLM	OLM
	RM	OL	OL	OL	OL	OL
	RL	OL	OL	OL	OL	OL
	Z	OM	OM	OM	OM	OM
	L	OH	OHM	OHM	OLM	OL
	M	OH	OHM	OHM	OM	OLM
	H	OH	OH	OH	OHM	OLM

Fuzzy set for the first input variable is $P_{demand} = \{RH, RM, RL, Z, L, M, H\}$, where the power demand is split to seven fuzzy linguistics: "Regenerative High" (RH), "Regenerative Medium" (RM), "Regenerative Low" (RL), "Zero" (Z), "Low" (L), "Medium" (M), "High" (H). The second variable's fuzzy set consists of three membership functions: $SOC_{bat} = \{BL, BM, BH\}$, where "Battery Low" (BL), "Battery Medium" (BM), "Battery High" (BH). The last input variable's fuzzy set is $SOC_{cap} = \{CL, CLM, CM, CHM, CH\}$ where the linguistics are: "Capacitor Low" (CL), "Capacitor Low Mid" (CLM), "Capacitor Medium" (CLM), "Capacitor High Mid" (CHM), "Capacitor High" (CH). Each linguistic defined above is assigned by a triangular or trapezoidal membership function which is shown in Figure 3.

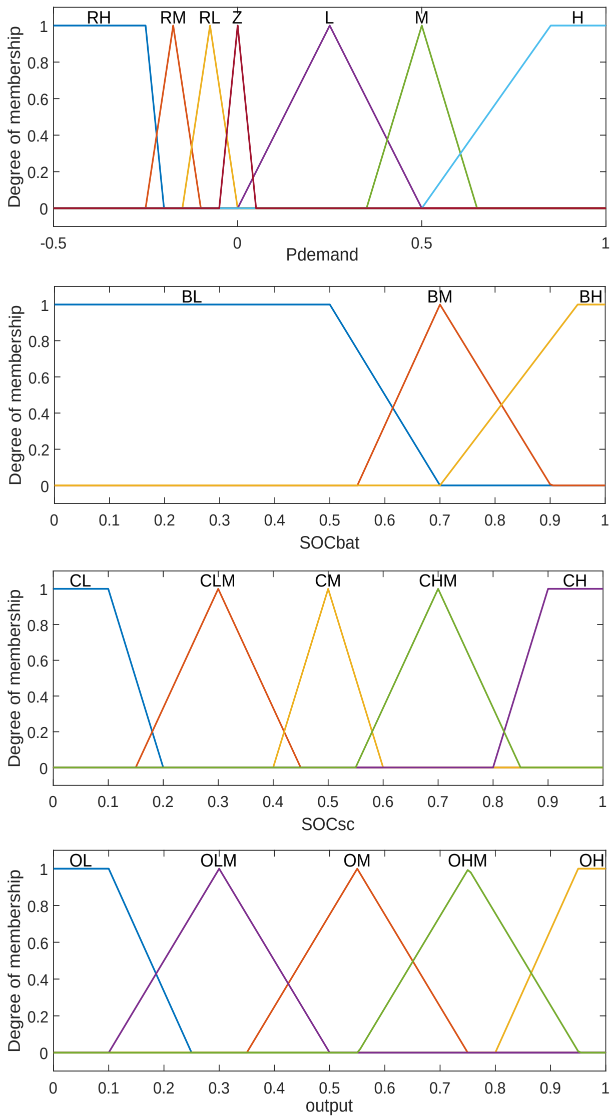

Figure 3. Fuzzy membership functions

A block diagram constituted in Simulink including proposed fuzzy controller, electric drive vehicle model, three different drive cycles and dual storage system which is shown in Figure 4. The fuzzy controller determines the m_{bat} parameter. Then it specifies the desired power from battery and supercapacitor by using (18)-(20).

4. Simulation Results

In order to validate the effectiveness of the proposed algorithm, an electrical drive vehicle is modeled as seen Figure 4. The vehicle parameters and the specifications of the dual storage system are given in Table 4, Table 5, and Table 6 respectively. The capacities of battery and supercapacitors are determined based on the power requirements obtained from drive cycle simulations.

Table 4. Vehicle Parameters.

Parameter	Value
ρ	$1.2\ kg/m^3$
A	$2.36\ m^2$
C	0.3
m	$1000\ kg$
f_{R0}	0.009
f_{R1}	0.0015
f_{R4}	0.0012
k_{frict}	0.005
r_{wheel}	$263.5\ mm$
η_g	0.98
i	8.59
P_{aux}	$250\ W$

Table 5. Battery Parameters

Valence UEV-18XP Battery Module	Number of Modules	15(15s1p)
	Peak Load Current	200 A
	Max. Cont. Current	120 A
	Rated Capacity	69Ah
	Nominal Voltage	288 V

Table 6. Supercapacitor Parameters

Maxwell	Number of Modules	54(18s3p)
BCAP 3400	Nominal Voltage	48.6 V
P270	Peak Load Current	2600 A
K04/K05	Max. Cont. Current	210 A

Table 7. Characteristics of drive cycles

	NEDC	UDDS	NREL
Distance (m)	10932	11989	10509
Duration (sec)	1180	1372	3697
Max. Speed (km/h)	120	91.25	78.42
Average Speed (km/h)	33.35	31.38	10.23
Number of Stops	13	17	32

Three different strategies are applied during simulations. In the first strategy, supercapacitors are ignored and battery is assumed to be the only energy storage system for EDV. In the second strategy, dual storage system with battery and supercapacitor is considered and controlled with traditional logic threshold control method [27,28]. In the third strategy, again, dual storage system is considered and fuzzy control method is applied to manage the storage system.

Each strategies are applied for three different drive cycles; New European Drive Cycle (NEDC), Urban Dynamometer Driving Schedule (UDDS) and National Renewable Energy Laboratory Class-3 (NREL Class-3). Characteristics of these drive cycles are given in Figure 5 and Table 7.

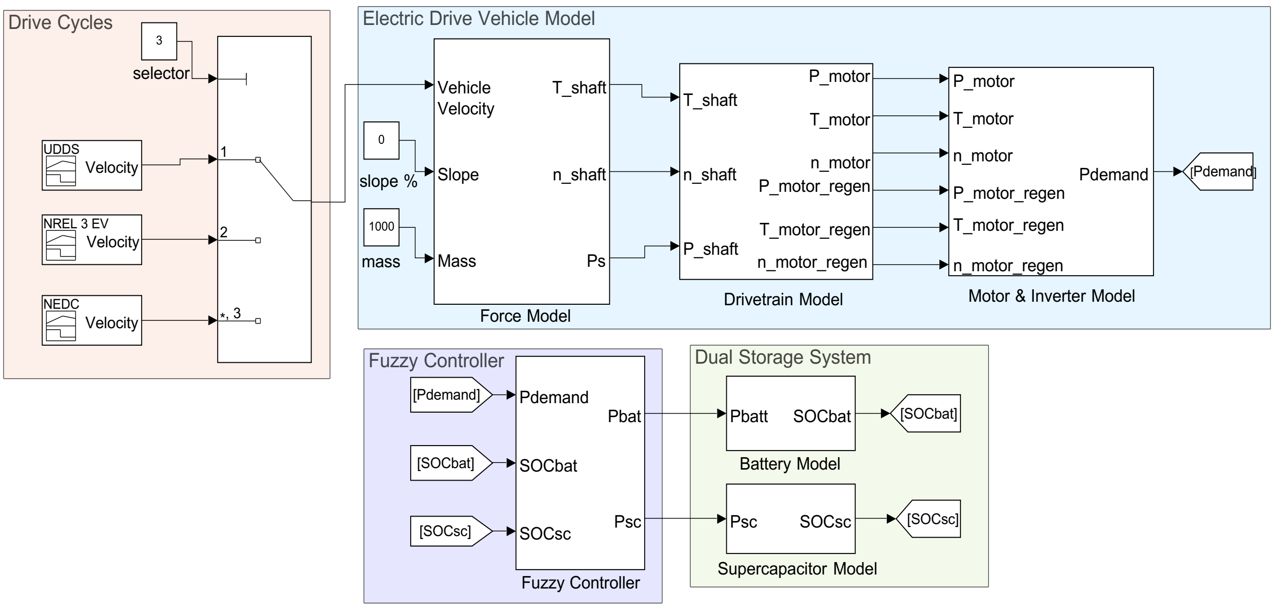

Figure 4. Block diagram of proposed control strategy for EDV with dual storage system

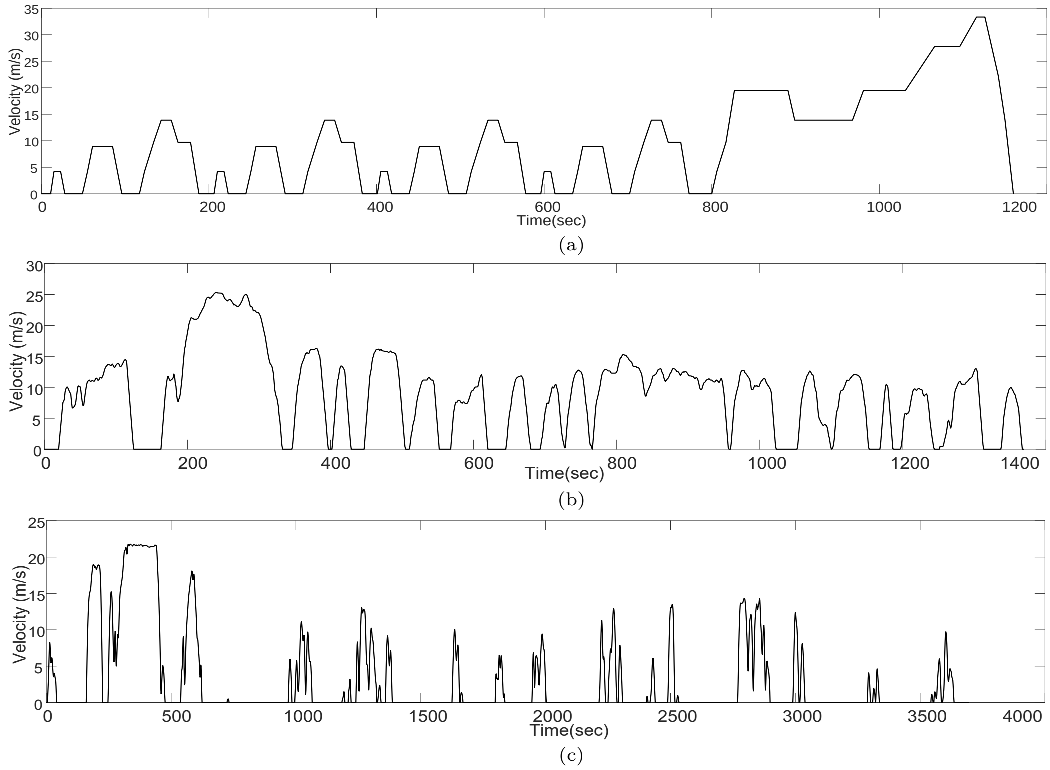

Figure 5. Drive cycles: (a) NEDC, (b) UDDS, (c) NREL

Simulations are carried out in Matlab/Simulink environment and EDV is assumed to be driven on a flat road and slope angle is taken zero. Results are analyzed in terms of SOC values and battery currents.

4.1. SOC Values

For each strategy, battery and supercapacitors are assumed to be fully charged at the beginning and initial SOC values are taken as 100 percent. Battery SOC vales obtained at the end of each drive cycle are given in Table 8. Beside the SOC levels for UDDS drive cycle obtained from all three strategies are given in Figure 6.

Initial SOC and cycle-end SOC values of batteries for different strategies and for different drive cycles are given in Table 8. Initial SOC is state of the charge of battery at the beginning of drive cycle and cycle-end SOC is state of the charge of battery when the EDV arrive to the end of drive cycle. Initial SOC values are taken %100 for all conditions as mentioned before. As it is seen from Table 8, cycle-end SOC values take higher values when proposed fuzzy control method is applied for all drive cycles compared to the other strategies. In table 9, initial SOC, minimum SOC, and cycle-end SOC values of supercapacitors for different strategies and for different drive cycles are given.

As one can see from Table 9 fuzzy logic controller method have the lowest cycle-end supercapacitor

Table 8. Initial and cycle-end battery SOC values.

	Only Battery System			Logic Threshold Method			Fuzzy Control Method		
	NEDC	UDDS	NREL	NEDC	UDDS	NREL	NEDC	UDDS	NREL
Initial SOC (%)	100	100	100	100	100	100	100	100	100
Cycle-end SOC (%)	92.90	92.50	91.30	94.00	93.00	91.90	94.29	94.00	93.00

Table 9. Initial, minimum and cycle-end supercapacitor SOC values

	Logic Threshold Method			Fuzzy Control Method		
	NEDC	UDDS	NREL	NEDC	UDDS	NREL
Initial SOC (%)	100	100	100	100	100	100
Minimum SOC (%)	8	55	71	8	21	13
Cycle-end SOC (%)	22	73	51	25	23	16

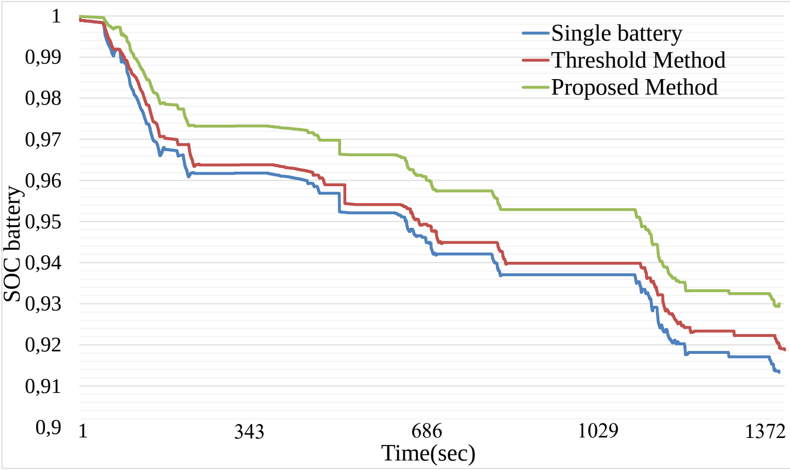

Figure 6. SOC values for three different strategies

SOC values which also means that supercapacitor power consumption is increased. This is quite reasonable because proposed method reduces the battery power consumption while EDV's total energy requirement is constant depending on the considered drive cycle. Also note that supercapacitor SOC values never drop to below %5 which is predefined as the lower limit value.

4.2. Battery Currents

For each strategy, battery charge and discharge currents obtained throughout simulations are given in Figure 7 and Table 10.

As it is seen from Table 10, in the case either logic treshold control or fuzzy logic control method is applied to manage dual storage system, both peak battery discharge and peak battery charge current values are considerably reduced for all drive cycles since supercapacitors support battery in both motoring and regenerating modes. Although logic threshold method gives the lowest battery peak discharge current values, proposed fuzzy control method improves the results in terms of avarage battery charge current values as seen in Figure 7. Also as seen from Figure 8 and Figure 7 not only the magnitude of battery charge currents but also the charging frequency of the battery are considerably decreased when the proposed fuzzy control method is applied. Battery power values for each strategy for UDDS drive cycle are given in Figure 8. As seen from Figure 8, batteries are consumed mainly in motoring mode and rarely charged. Therefore it can be concluded that battery lifespan is prolonged since the frequent charge and discharge of battery and high battery current values are avoided.

Furthermore peak charge and discharge currents of supercapacitor are given in Table 11. Note that charging / discharging currents of both supercapacitor and battery are under their predefined maximum limits.

5. Conclusion

In this manuscript, a fuzzy based energy management controller has been developed to allocate the instantaneous power between the battery and supercapacitor considering to prolong battery lifespan and the range of EDV. First, the model of EDV and dual storage system is studied, then fuzzy based energy management controller is designed, finally a simulations are carried

Table 10. Peak charge and discharge current values of battery for three different drive cycles.

	Only Battery System			Logic Threshold Method			Fuzzy Control Method		
	NEDC	UDDS	NREL	NEDC	UDDS	NREL	NEDC	UDDS	NREL
Peak Discharge Current (A)	111	117	108	110	60	60	102	97	97
Peak Charge Current (A)	50	50	66	20	20	20	5	15	20

Table 11. Peak charge and discharge current values of supercapacitor for three different drive cycles.

	Logic Threshold Method			Fuzzy Control Method		
	NEDC	UDDS	NREL	NEDC	UDDS	NREL
Peak Discharge Current (A)	650	650	640	195	257	331
Peak Charge Current (A)	290	305	400	263	263	282

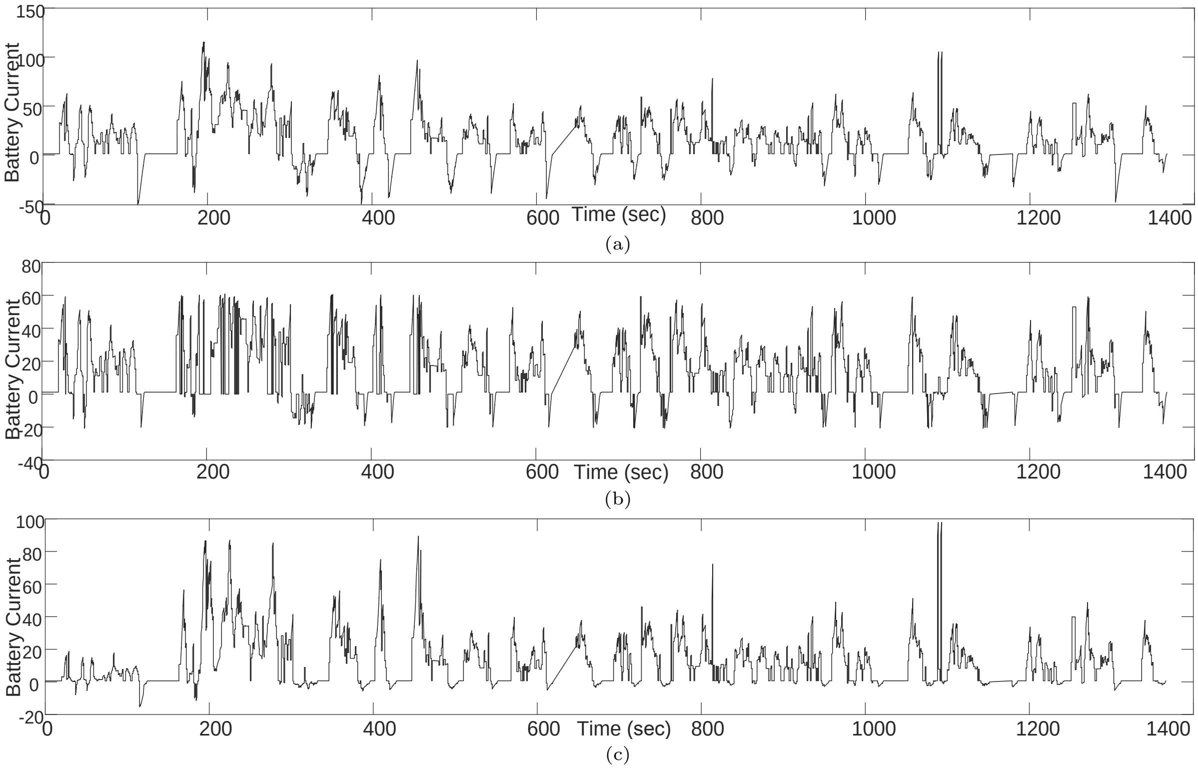

Figure 7. Battery currents of each strategy for UDDS drive cycle (a) Only battery system (b) Logic threshold (c) Fuzzy control

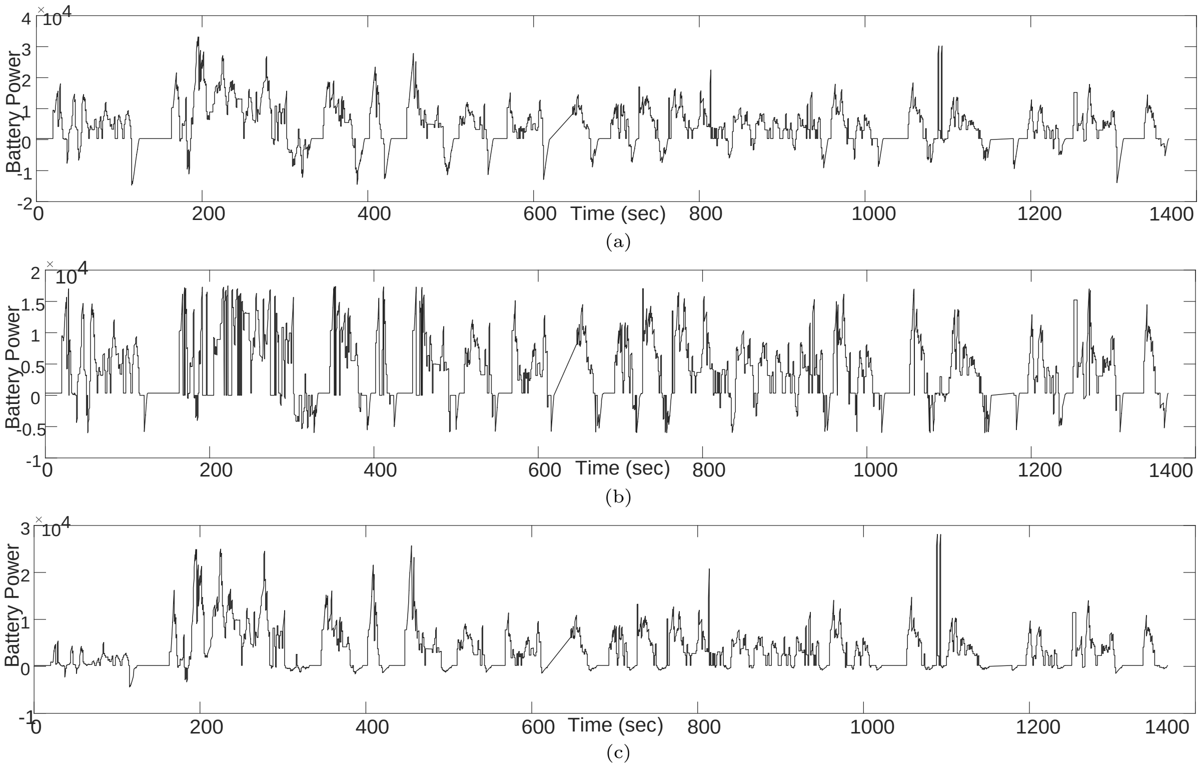

Figure 8. Battery powers of each strategy for UDDS drive cycle (a) Only battery system (b) Logic threshold (c) Fuzzy control

out in different drive cycles in Matlab/Simulink environment. The performance of the proposed method has been compared with two strategies: the battery only system and dual storage system managed with logic threshold method. The results show that, with the proposed method, the amount of power supplied by the battery is reduced by adding supercapacitors to the system. Besides both peak battery discharge and charge currents has been reduced for all drive cycles and the battery is much less exposed to high currents. Furthermore not only the magnitude of battery charge currents but also the charge frequency of the battery are considerably decreased. In consideration of these results, proposed method provides more effective battery energy usage and is helpful to prolong battery lifespan.

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