Integration of battery of ultracapacitor for energy storage for low weight electric vehicle for Bangladesh

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***Abstract*— This paper portrays the benefits of introducing an ultracapacitor into a battery pack of an urban electric vehicle drive train. Simulations are done taking two basic scenarios into consideration: fresh cells and half-used battery cells. The simulations show that the lower the temperature higher the hybrid system efficiency. Data from real world are considered to conduct this study. Simulations are done considering modified Bangladeshi drive cycle for low weight vehicles. Several issues like volumetric, gravimetric and cost issues of hybridization are present in this paper. By this system the power loss of the system can be reduced by up to 5% to 10%.Finally hybridization not only increases the efficiency of the energy storage system also increases the power train efficiency and battery lifespan. This paper would help researchers for further development of this topic.**

Keywords— ultracapacitor; hybridization; electric vehicle; energy storage; hybrid energy source

I. INTRODUCTION

The efficiency of hybrid and electric vehicles largely depends on their capacity to store energy and quickly extract power from that energy as well. Nowadays electric vehicles depend on battery systems composed of NIMH or Li-ion batteries to store energy. However, the use of battery with ultracapacitor energy storage systems not only increases the efficiency of the vehicle also increases the life span and runtime of the batteries [1,2]. Hybridization enables us to solve some key problems in vehicles like-

1. Deterioration of energy storage performance in harsh exploitation conditions, for instant sub-zero winter temperature. [3].

2. The main source provides only average power while hybridization of battery and capacitor provides large power pulse compared to only main source [4].

There are not many variations in the electrodes of ultracapacitors, that's why they are characterized by small changes in resistance and capacitance with temperature, high power density above 6000 w/kg and long life. Table 1 shows different previous work done on battery and ultracapacitor hybridization.

A performance comparison on battery-fuel cell and fuel cell- ultracapacitor power train is found in [5]. The authors did a broad comparison between this two types power train and showed advantages and disadvantages of the powertrains. In

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[6] authors did a fuel cell vehicle hybrid comparison with battery or ultracapacitor. They showed how efficient the replacement of battery with ultracapacitor can be. In [7] the authors worked and reviewed on future necessities of energy storage hybridization technologies. They showed previous and future importance of hybridization. The authors in [8] did a review study on battery, ultracapacitor, fuel cell and plug in vehicle and possibility about their hybridization. In that paper topology study of the vehicle and battery and ultracapacitor hybridization is analyzed. In [9] the authors optimized for efficiency or battery life in a supercapacitor/battery electric vehicle. The authors showed increment of battery life by implementing an ultracapacitor with battery [9]. Hybridization using different type of energy bank is found in [10-12].The authors used different type of battery and drive cycle. The authors worked on different energy storage technologies for several high power applications. In this study author discussed about different high energy storage technologies including battery and ultracapacitor [13].

From the literature it is clear that several works have been done on battery and ultracapacitor hybridization. But there are lack of research about the efficiency increment using this kind of hybridization and how this system will work if implemented on a low weight vehicle (i.e. three-wheeler, small automobiles and etc.). In this paper first component modeling, topology and power management of battery and ultracapacitor modeling is shown then along with the total system simulation, the system is implemented on a low weight vehicle and the simulations were performed in MATLAB platform. In the simulation modified Bangladeshi drive cycle is taken to see how compatible the system can be for Bangladesh.

II. COMPUTATIONAL MODELLING

The modeling of the main power system is discussed briefly in this section. There are mainly three components namely the battery bank, the super-capacitor bank and electric loading which controls the power train. Those components are discussed below:

A. Energy Storage Device Modelling

Modeling of batteries is much difficult due to their electrochemical behavior which involves thermal energy transfer. Electrical behaviors of batteries are quite non-linear and contain a number of consecutive changes in some parameters of its function, namely state change, discharge rate, temperature difference and etc. Its capacity depends upon temperature of the system along with discharge rate.

This relationship is described by Peuket's equation relating the discharge current I (A) to the time 't' (hr) it takes it to discharge,

$$I = \sqrt{(\alpha\&(\beta/t))} \;\ldots\ldots\ldots\ldots\ldots.. (1)$$

Where 'α' and 'β' are constants. Given the battery capacity C_{To} at temperature To, the capacity at some other temperature is computed by,

$$C_T = C_{T0}\,\{1+ \sigma\,(T - T_0\,)\}\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where 'σ' is a constant.

Thevenin's equivalent circuit has been applied here to design the circuit of the model. Voltage and resistance here are functions of SoC (System on a Chip). SOC or SoC is termed as the energy existing in a battery (after supplying a definite amount of energy in amp-hr) relative to the total capacity. It is often expressed in percentage. If Voc is the open circuit voltage then with respect to S_OC it can be functioned as: $V_{OC} = a_1 + a_2$ SoC, at some specific temperature. In the battery there exists both static and dynamic resistance, so the resistance measurement should be done with care.

B. Ultrqacapacitor modelling

In general operations, capacitors, resistance and inductance of an electric system are represented by R-L circuit (series). As perfect insulation is not possible in practical operations, thus the leakage currents in the device electrodes are replaced by a shunt resistance higher in value. The key difference between a normal and a super-capacitor is efficiency. Super-capacitors are far more efficient than a regular one; i.e. in general series resistance have much lower value than a shunt.

C. Electric Load

The electric loading results from mainly motive/mechanical power from an inverter-fed induction motor. In time of regenerative braking, induction motor works as a generator by lowering it's terminal voltage frequency resulting a power flow in reverse direction and causing Brake Torque.

III. TOPOLOGIES OF HYBRID ENERGY STORAGE

The HES (hybrid energy storage) being consideration as a vey potential choice for city vehicles considered as an extension of a energy storage consisted with a battery pack and a bi-directional set up converter. This enable a 250 to 300V battery to be boosted up to 600V.An additional high power ultracapacitor can be incorporated in this scheme. Directly connected parallel configuration is the most common and simplest configuration of the booth energy storage devices [8, 14-15]. Passive hybrid system is most common system used for several years, though the uncontrolled power distribution is the most common drawbacks of the passive hybrid system. Semi-active hybrids are the enhancement of the passive topology. Semi-hybrid system is shown in figure 1 [16-19]. In the semi-active system, no need of using any converter, hence improves the efficiency of energy recovery [10, 11]. This type of system is favorable in the portable electronic devices. In alternative semi-active topology, a bi-directional DC-DC converter is used to the battery through an additional storage system. Fully active hybrid has fewer drawbacks than the other systems. Fig.3 shows a fully active cascaded hybrid whereas Fig.4 shows a parallel active hybrid topology.

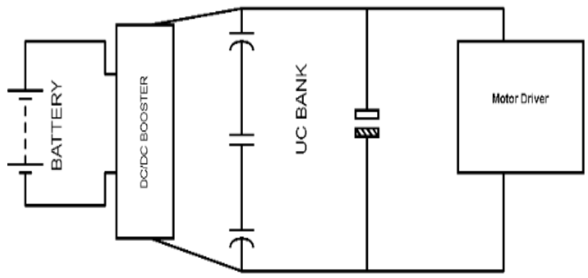

Fig.1. Power train with battery semi-active hybrid

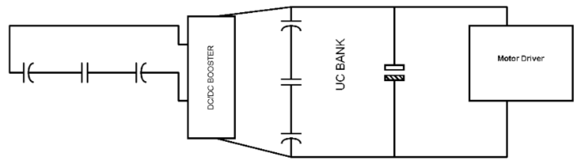

Fig.2. Power train with ultracapacitor semi-active hybrid

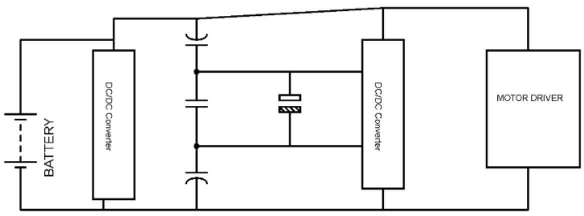

Fig.3. Power train with battery fully active cascaded hybrid

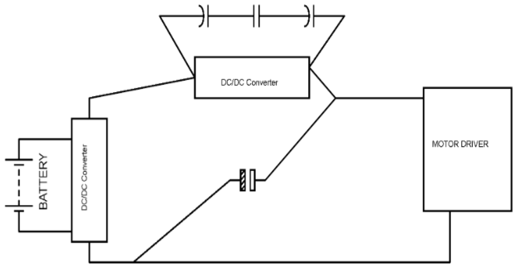

Fig.4.Power train of fully active parallel hybrid

IV. POWER MANAGEMENT STRATEGIES OF HES

For city vehicle in discussed power train ultracapacitors serve as a high-power low energy auxiliary storage device. The UCs is engaged during regenerative braking and high-power loads. Additional cost can be minimized by introducing an auxiliary storage device on the basis of instantaneous vehicle speed, power demand and UCs charges. The power distribution is shown in Fig.5. All energy from regenerative braking is captured by ultracapacitor for balancing UCs state of charge. Additional storage is recharge by the battery during the stop if necessary.

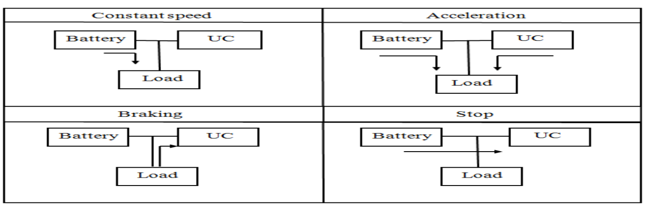

Fig.5. Energy flow diagram at nominal stages

At dynamic state when the acceleration occurs both the storages are discharged simultaneously. At that time for balancing UCs state of charge UCs automatically captures all the energy from regenerative braking. Additional storage is recharged during the stop if needed. A power time graph (Fig.8) shows all these states. If UCs is reached at its minimum or maximum state of charge, then the consecutive charging and discharging is impossible UCs voltage that ensures reserve of energy for the sake of accelerating to maximum is operated by control algorithm. According to below equation 3, the value depends on instantaneous speed.

$$U_{ref\text{-}down} = \sqrt{U_{min}^2 + \frac{m(V_{max}^2 - v^2)}{C\eta_1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

$$U_{ref\text{-}up} = \sqrt{U_{max}^2 - \frac{mv^2\eta_2}{C}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (4)$$

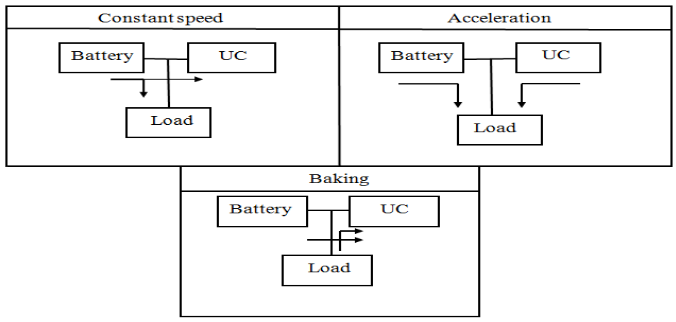

Fig.6. Energy flow diagram at low SOC and low speed of ultracapacitor.

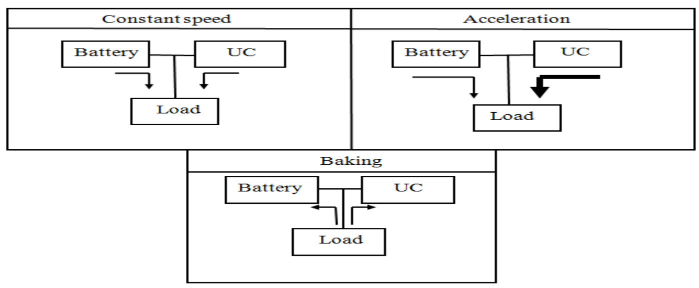

Fig.7.Energy flow diagram at high S_OC and high speed of ultracapacitor

Similarly, the equation 4 is used to determine the upper value of reference UCs voltage which provides the capability of recover energy from braking.

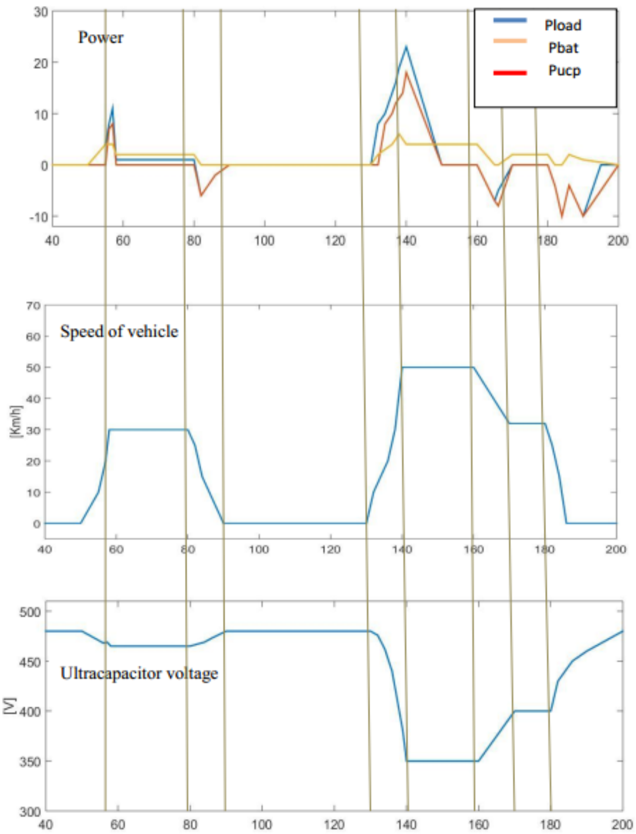

Fig.8. Power distribution of HES

V. Simulations and Results

In the following section description about components of energy storage system of a hybrid vehicle with its power train is given. All models are coded using MATLAB/Simulink platform.

A. Battery and ultracapacitor model

The battery model is shown in figure 9.A resistor is connected in series. Considering the charge in discharge current and temperature a discharge capacity is modeled using method [20, 21, 10, and 11]. Model parameters are given based on the manufactures data. In figure 11 the simulation results are shown.

Table 2. Battery pack for small electric vehicle

Battery Energy Storage	
Cell	LiFeP04-EVPST-55AH
Voltage	165 V
Current capacity	55 Ah
Mass	110 kg
Energy	9.1 kWh

A simplified ultracapacitor model is shown in figure 10. Resistor r is responsible for the losses occurred by the non-zero internal resistance of an ultracapacitor and capacitor C, which is the ultracapacitors capacitance [22, 10, 11]. This model is sufficient to evaluate power losses.

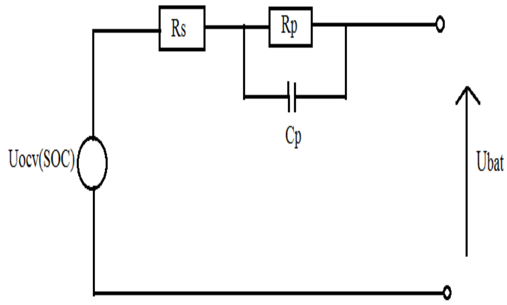

Fig.9. Electrochemical battery model

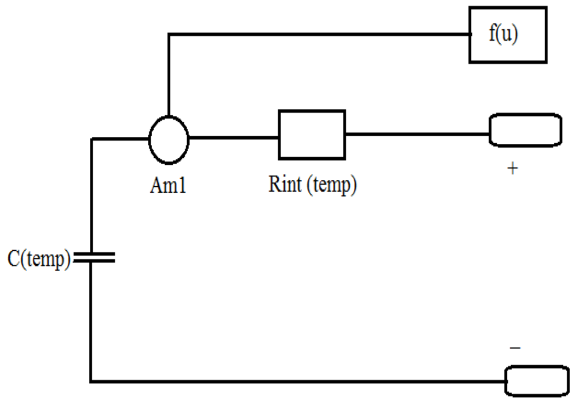

Fig.10. Ultracapacitor model

Table 3. Ultracapacitor pack for small electric vehicle

Ultracapacitor Energy Storage	
Cell	Maxwell K2 series
Voltage	105 V
Capacity	50F
Mass	14.5 kg
Energy	.081 kWh

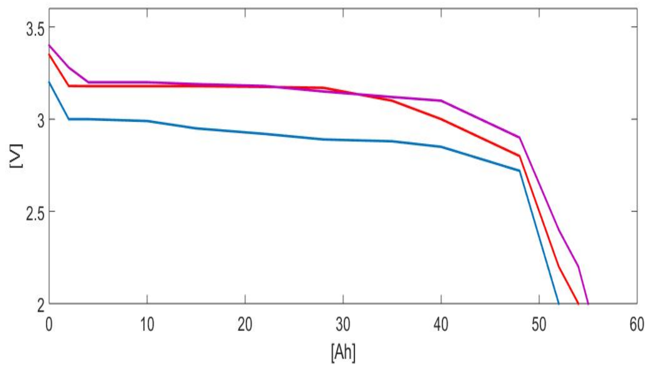

Fig.11. Discharge characteristics of battery (simulation results)

B. Dc/Dc converter losses

During the simulation a continuous model of the converter was implemented. Based on the equations below an I_{GBT+D} power losses were calculated.

Losses per transistor:

$P_{cond\text{-}tr} = D.(I_{tr}.V_t+I_r^2.r_t)$............ (5)

$E_{sw} = E_{on} + E_{off}$ .... (6)

$P_{sw\text{-}tr} = f_{sw}.E_{sw}.\ (I_{tr}/I_{rated}).(V_{tr}/V_{rated})$.... (7)

$P_{tr} = P_{cond\text{-}tr} + P_{sw\text{-}tr}$ .... (8)

Losses per diode:

$P_{cond\text{-}d} = (1\text{-}D).\ (I_d.V_t + I_d^2.r_t)$ .... (9)

$P_{sw\text{-}d} = f_{sw}.E_{rr}.(I_d/I_{rated}).(V_d/V_{rated})$ .... (10)

$P_d = P_{cond\text{-}d} + P_{sw\text{-}d}$ .... (11)

Total loss:

$P_{tot} = P_{tr}+P_d$ .... (12)

A simulation of the whole hybrid vehicle is carried out. A driving cycle is obtained by considering low heavy vehicle properties. The power demand of the vehicle is also carried out based on the drive cycle. The drive cycle is mainly modified Bangladeshi drive cycle. The average speed of the vehicle is taken about 30 km/h and maximum speed is about 50 km/h. The rolling resistance corresponds to dry asphalt of concrete road [23, 10, 11].

Table 4. Vehicle model parameters

Parameter	Value
Vehicle total mass	700 kg
Aerodynamic Co-efficient	0.34
Vehicle Frontal Area	2 m^2
Oiling Friction Co-efficient	.013
Converter Switching Frequency	14 kHz
Efficiency of Powertrain	82%

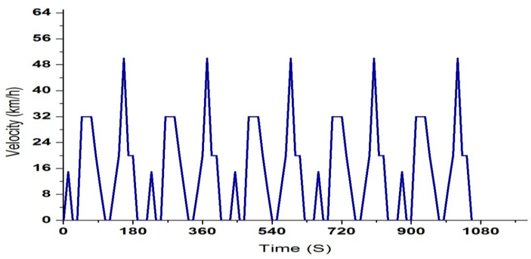

Fig.12. Modified Bangladeshi urban drive cycle

The drive power demand is computed at every moment for the whole length of the drive cycle. The drive power demand shows the approximate amount of power necessary to run the vehicle according to drive cycle.

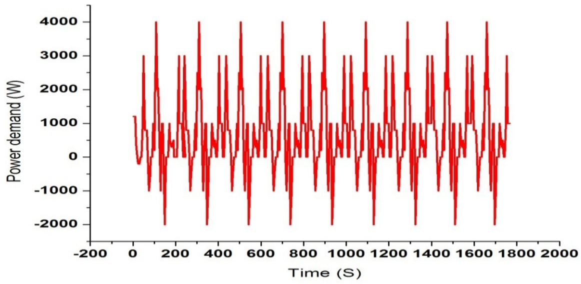

Fig.13. Drive power demand of the vehicle

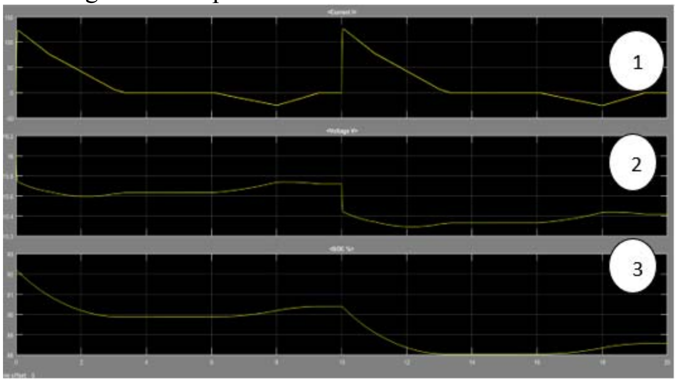

Fig.14. Current (1), Voltage (2) and SoC (3) of ultracapacitor

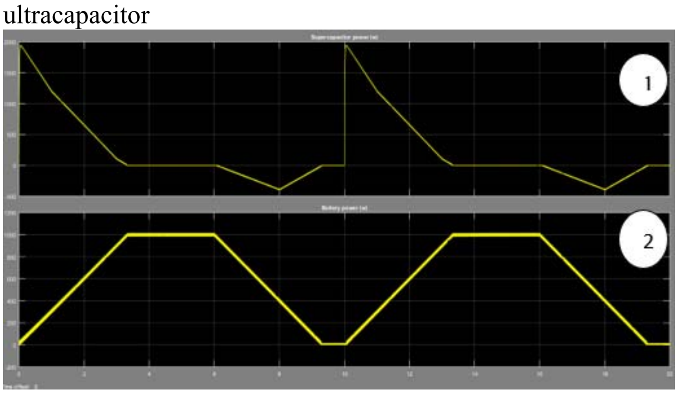

Fig.15. Ultracapacitor power (1) Battery power (2) in watt (W)

Table 5. Results for fresh cells

		Battery	Hybrid
40ºC	*Range*	124.03	129.8
	Power loss (%)	3.42	1.3
35ºC	*Range*	118.04	128.2
	Power loss (%)	4.52	1.9
25ºC	*Range*	113.8	121.7
	Power loss (%)	6.8	2.76

0ºC	*Range*	81.63	111.7
	Power loss (%)	9.81	2.9
-5ºC	*Range*	76.01	103.8
	Power loss (%)	16.98	4.65

Table 6. Results for half-life cycle cell

		Battery	Hybrid
40ºC	Range	109.3	112.4
	Power loss (%)	4.4	3.47
35ºC	Range	106.5	105.4
	Power loss (%)	3.56	3.77
25ºC	Range	100.2	102.32
	Power loss (%)	5.98	2.98
0ºC	Range	45.34	92.15
	Power loss (%)	9.12	3.57
-5ºC	Range	null	80
	Power loss (%)	null	3.09

At this stage (table 5) the temperature differences of individual cell have not been investigated. A uniform temperature is taken for the simulation. The results in table 5 clearly show the effect of hybridization on improving the performance of vehicle. In larger case hybrid source gives not only increased efficiency but also smaller decrease in capacity.

Supporting of the ultracapacitor is more significant when the battery is partially used up (Table 6). At -5ºC the vehicle is not able to run by only battery in accordance with the drive cycle. But hybrid system eliminated this problem, where ultracapacitor provides most of the power pulse. It clearly proves that in this type of case hybridization is not only technically justified but also it is essential to maintain the proper dynamics of the vehicle.

VI. ISSUES OF HYBRIDIZATION

Though hybridization has huge advantages but it imposes greater requirements. In this study mass of Lifepo4 cell is 110 kg and volume of the cell is about 60 dm^3 [24]. mass of additional storage is approximately 13.5% of the batteries mass. Besides substitution benefits, hybridization increases the total cost of energy source. Price of ultracapacitors are still higher though it is reducing day by day. In spite of all these drawbacks, hybridization not only increases the efficiency it also increases the battery lifespan. In a vehicle if hybridization system is implemented it reduces the frequent battery replacement issue.

VII. CONCLUSION

Benefits of hybridization as an energy storage device are presented in this paper. Different simulation results show that how combination of batteries and ultracapacitor improves the efficiency and reliability of the energy storage system. The energy which may be recovered from regenerative braking, first stored in the ultracapacitor which sufficiently reduces the battery ageing. In addition to it hybridization also reduces maximum battery current and number of executed cycles. Hybridization increase the power preserving capacity of the system at all conditions hence increases the battery maintenance interval significantly.

VIII. AUTHORS' CONTRIBUTIONS

The 1st two authors did the simulation and computational works. The 3rd author supervised the whole work and the rest of the authors did some analysis, writing and some part of the data assessment.

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Nomenclature

η_1- Efficiency of boost mode, η_2 - Efficiency of recovery mode, U_{max} - Maximum voltage od UCs, U_{min} - Minimum voltage of UCs, C – Capacity of UCs, v – Vehicle Instantaneous Speed, D – Duty Cycle, T_{tr} - Transistor current, I_d – Diode Current, I_{rated} – Rated Current, V_{tr} – Transistor Voltage, V_d – Diode Voltage, V_T – Threshold Voltage, E_{off} - Energy dissipation during turn-off time, E_{on} - Energy dissipation during turn-in time, E_{rr} - Energy dissipation during reverse recovery, r_T - Forward slope resistance, f_{sw} - switching frequency.