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Ultra-capacitor based Hybrid Electric Vehicle (Medium) for Developing Countries

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Abstract

This research is directed to the hybridization of battery and ultra-capacitor for a better effectiveness. This portrays the benefits of introducing an ultra-capacitor into a battery pack of an urban electric vehicle drivetrain. Matlab Simulations are done taking two basic scenarios into consideration: fresh cells and half-used battery cells. The simulations show that the lower the temperature (25-28^{o}C) higher the hybrid system efficiency (25-30%). Data from the real world and previous studies are considered to conduct this study. Previous studies showed efficiency raise up to 7%, whereas this system showed around 14% efficiency raise. 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% regarding the conventional system. Finally, hybridization not only increases the efficiency of the energy storage system also increases the powertrain efficiency and battery lifespan. This paper would help researchers for further development of this topic.

Keywords: *electric vehicle; energy storage; hybrid energy source; hybridization; ultra-capacitor*

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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 (Stienecker, 2005; Gao *et al.*, 2003). 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. (Juan *et al.*, 2010).
2. The main source provides only average power while hybridization of battery and capacitor provides large power pulse compared to only main source (Shidore and Theodore, 2008).

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.

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.

METHODOLOGY

From the literatures studied, a feasible system component modeling was done. Firstly the basic circuit analysis were considered to make the problem specific and after that firstly analytical modeling of the new system was done along with regarding system simulation by utilizing Matlab and Simulink platform. Acute differences were discussed in details in the subsections below.

Component Modeling

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

Battery bank

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,

$$I = \sqrt[\alpha]{\left(\frac{\beta}{t}\right)} \quad (1)$$

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

$$C_T = C_{T_o}\{1 + \sigma\,(T - T_o)\} \quad (2)$$

'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-hrs) relative to the total capacity. It is often expressed in percentage. If VOC is the open circuit voltage then with respect to SOC it can be functioned as: VOC = a1 + a2 SOC, at some specific tem-

Table 1. Different previous work done on battery-ultracapacitor hybridization

Year	Purpose of work	Major findings	References
2005	Did a performance comparison on battery-fuel cell and fuel cell- ultracapacitor power train	Did a broad comparison between this two types power train and showed advantages and disadvantages of the powertrains.	(Gao, 2005)
2009	did a fuel cell vehicle hybrid comparison with battery or ultracapacitor.	Showed how efficient the replacement of battery with ultracapacitor ca be.	(Thounthong *et al.*, 2009)
2009	Worked and reviewed on future necessities of energy storage hybridization technologies.	Showed previous and future importance of hybridization.	(Miller *et al.*, 2009)
2010	Did a review study on battery, ultracapacitor, fuel cell and plug in vehicle and possibility about their hybridization.	Did topology study of the vehicle and battery and ultracapacitor hybridization.	(Khaligh and Li, 2010)
2012	Optimized for efficiency or battery life in a supercapacitor/battery electric vehicle	Showed increment of battery life by implementing an ultercapacitor with battery.	(Carter *et al.*, 2012)
2013	Designed a semi active hybrid energy storage system using battery and ultracapacitor	Showed voltage drop controlling method by using battery/ultracapacitor hybridization.	(Kuperman *et al.*, 2013)
2014	Worked on battery-ultracapacitor materials for fast storage of electrochemical charge.	worked on materials and showed that PTMA constituents dominate the hybrid battery charge process	(Vlad *et al.*, 2014)
2015	Worked on the merging of battery and supercapacitor chemistries.	This review paper showed different merging procedures of battery and ultracapacitor.	(Dubal *et al.*, 2015)
2016	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.	(Farhadi and Osama, 2016)

perature. In the battery there exists both static and dynamic resistance, so the resistance measurement should be done with care.

Super-capacitor bank

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.

Electric loading

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 its terminal voltage frequency resulting in a power flow in reverse direction and causing Brake Torque. Figure 2 shows the Power train with ultracapacitor semi-active hybrid.

TOPOLOGIES OF HYBID 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 300 V battery to be boosted up to 600 V. An additional high power ultra-capacitor can be incorporated in this scheme. Directly connected parallel configuration is the most common and simplest configuration of the booth energy storage devices (Khaligh and Li, 2010; Lukic *et al.*, 2016; Puşcaş *et al.*, 2010) 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 (Kuperman and Ilan, 2011; Camara *et al.*, 2008; Kohler *et al.*, 2009; and Aharon and Kuperman, 2010). In the semi-active system no need of using any converter, hence improve the efficiency of energy recovery. 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 hy-

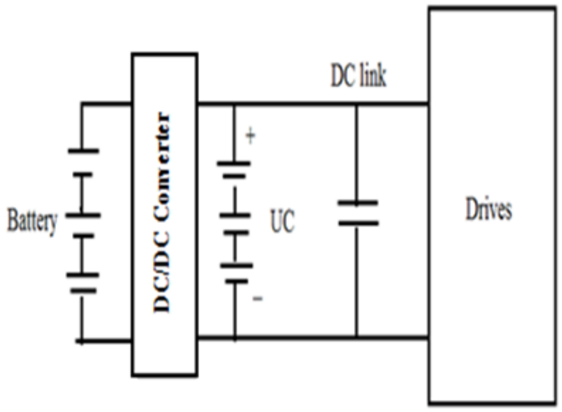

Figure 1. Power train with battery semi-active hybrid

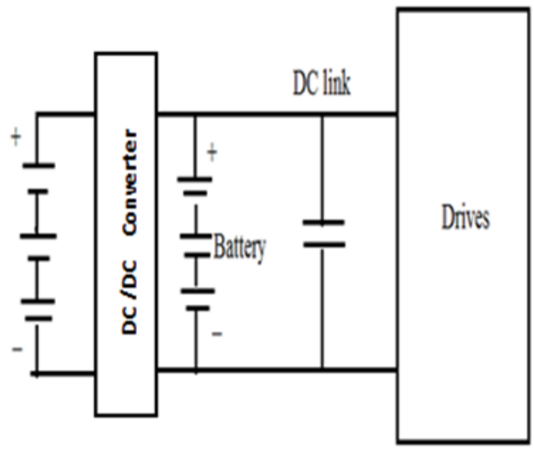

Figure 2. Power train with ultracapacitor semi-active hybrid

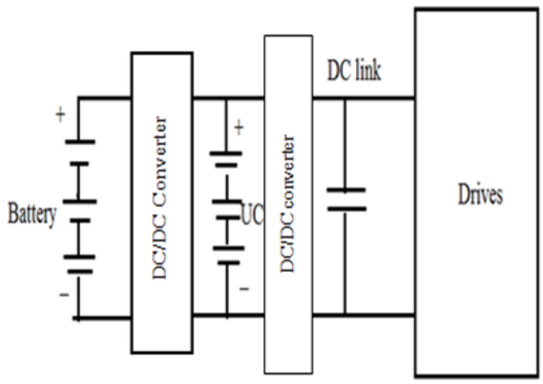

Figure 3. Power train with battery fully active cascaded hybrid

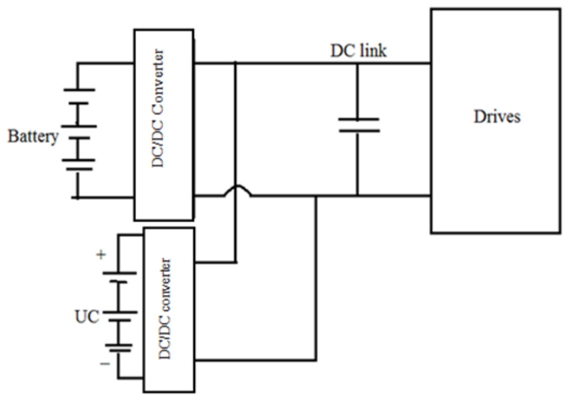

Figure 4. Power train of fully active parallel hybrid

brid has fewer drawbacks than the other systems. Figure 3 shows a fully active cascaded hybrid whereas Figure 4 shows a parallel active hybrid topology.

POWER MANAGEMENT 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 Figure 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.

Power management is the most important section to design an effective and feasible vehicle and this paper is based on introducing a new kind of HEV for developing countries. The circuit analysis has been done in the below sections.

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 (Figure 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.

$$U_{ref-down} = \sqrt{U_{min}^2 + \frac{m\left(V_{max}^2 - U^2\right)}{c\eta_1}} \quad (3)$$

$$U_{ref-up} = \sqrt{U_{max}^2 - \frac{mV^2\eta_2}{c}} \quad (4)$$

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

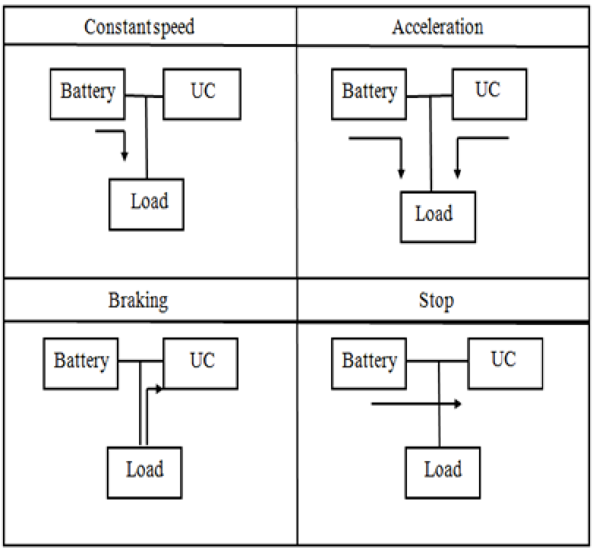

Figure 5. Energy flow diagram at nominal stages

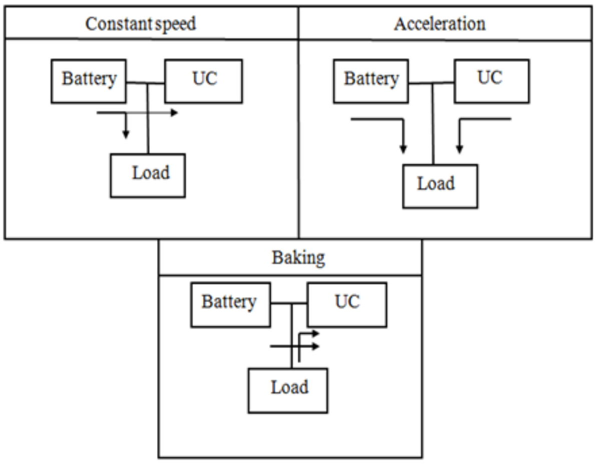

Figure 6. Energy flow diagram at low SOC and low speed of ultracapacitor

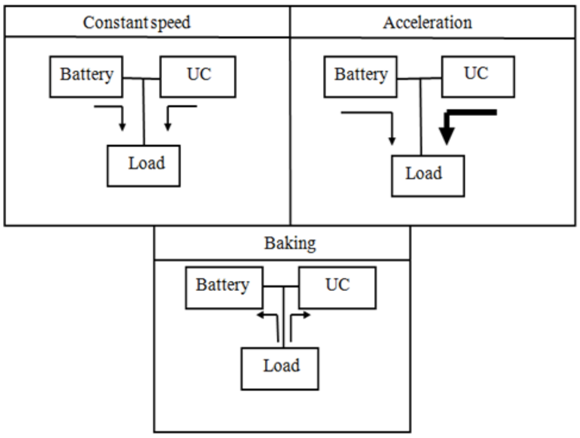

Figure 7. Energy flow diagram at high SOC and high speed of ultracapacitor

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

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

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.

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 (Gao *et al.*, 2002; Schonberger, 2009). Model parameters are given based on the manufactures data. In Figure 11 the simulation results are shown.

A simplified ultracapacitor model is shown in Figure 10. Resistor R is responsible for the losses oc-

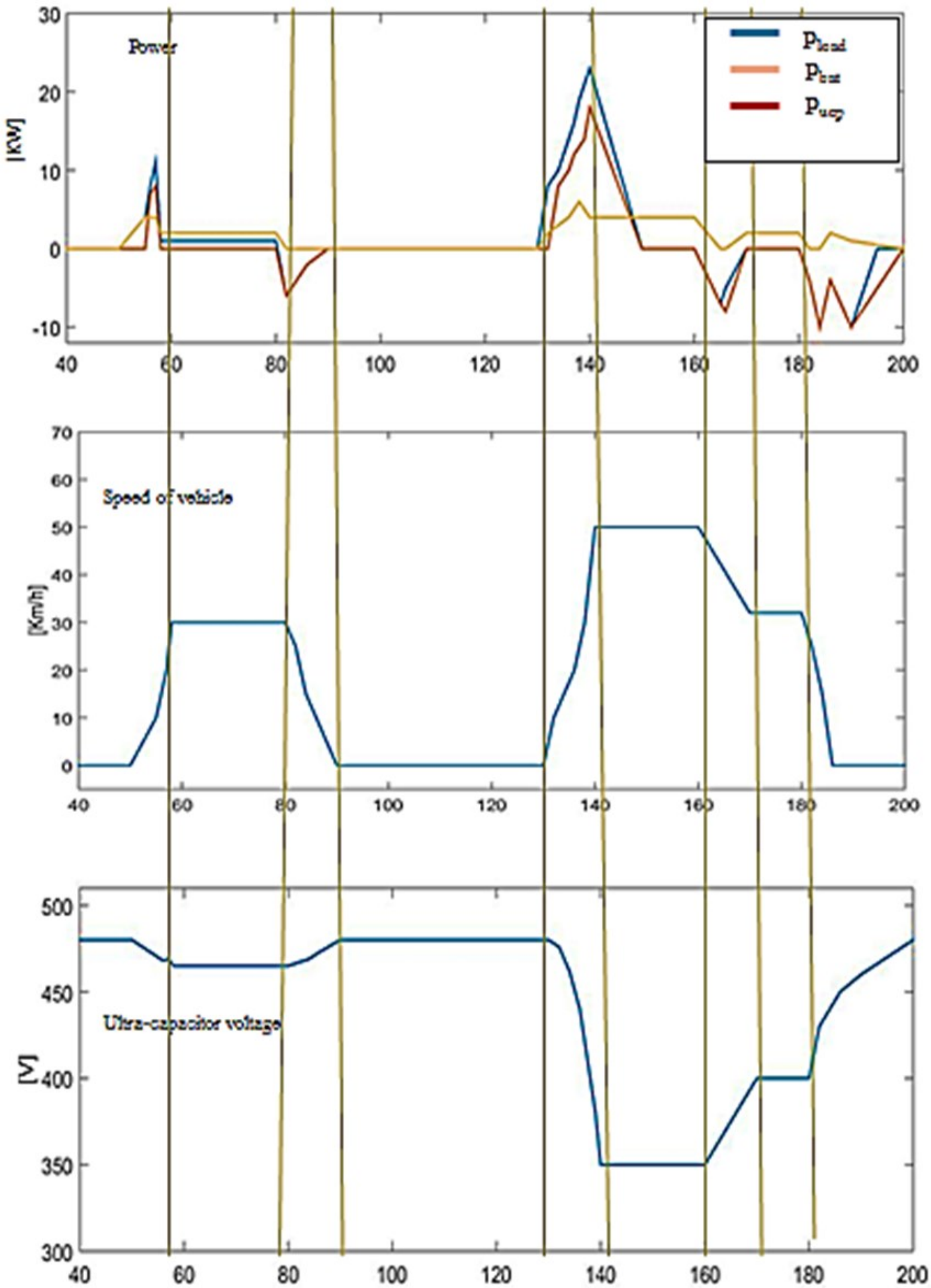

Figure 8. Power distribution in HES

curred by the non-zero internal resistance of an ultracapacitor and capacitor C, which is the ultracapacitors capacitance (Maxwell Technologies, 2012). This model is sufficient to evaluate power losses.

DC Converter Losses

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

Losses per transistor:

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

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

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

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

Losses per diode:

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

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

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

Total loss:

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

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 (Zhang *et al.*, 2009). Table 4 shows various vehicle model parameters.

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. Figure 12 illustrates it properly.

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. In Figure 13 the nature of current, voltage and SOC of ultra-capacitor has been shown. Figure 14 represents the ultracapacitor power and battery power.

Supporting of the ultracapacitor is more sig-

Table 4. Vehicle model parameters

Parameter	Value
Vehicle total mass	700 kg
aerodynamic coefficient	0.34
vehicle fontal area	2 m^2
olling friction coefficient	.013
converter switching frequency	14 kHz
efficiency of powertrain	82%

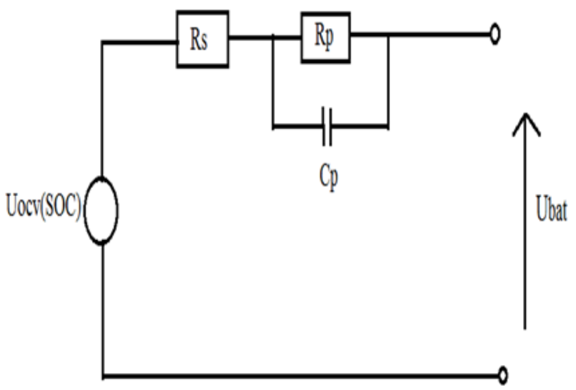

Figure 9. Electrochemical battery model

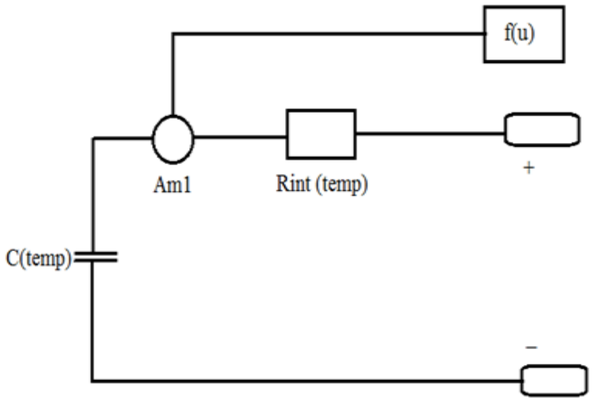

Figure 10. Ultracapacitor model

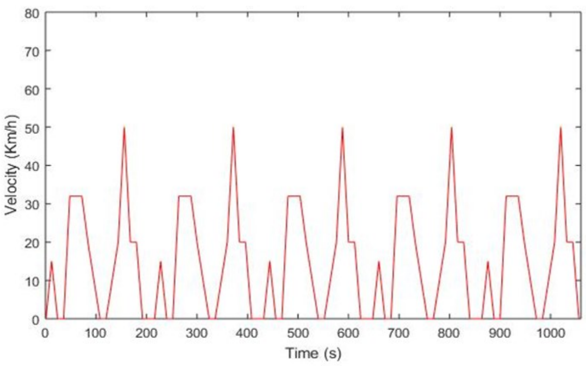

Figure 11. Modified Bangladeshi urban drive cycle

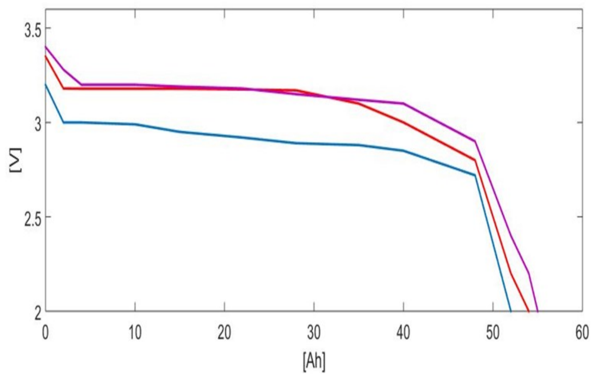

Figure 11. Discharge characteristics of battery, 5C (blue), 1C (red), 2C (purple)

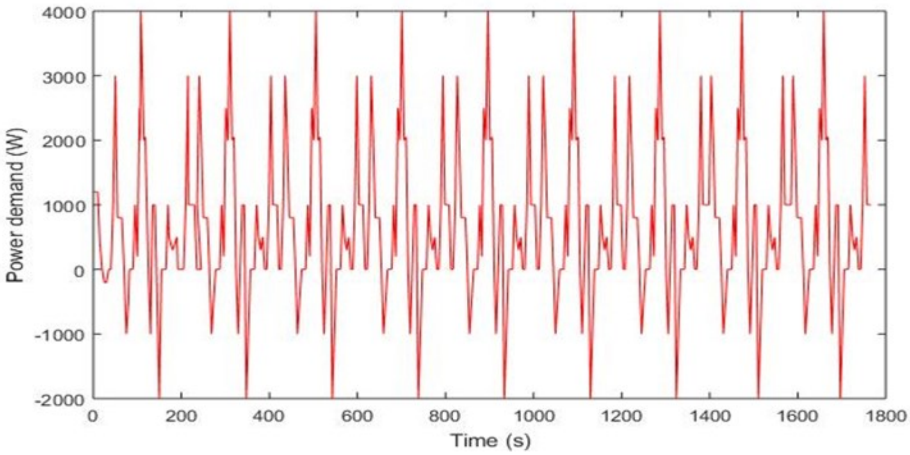

Figure 12. Drive power demand of the vehicle

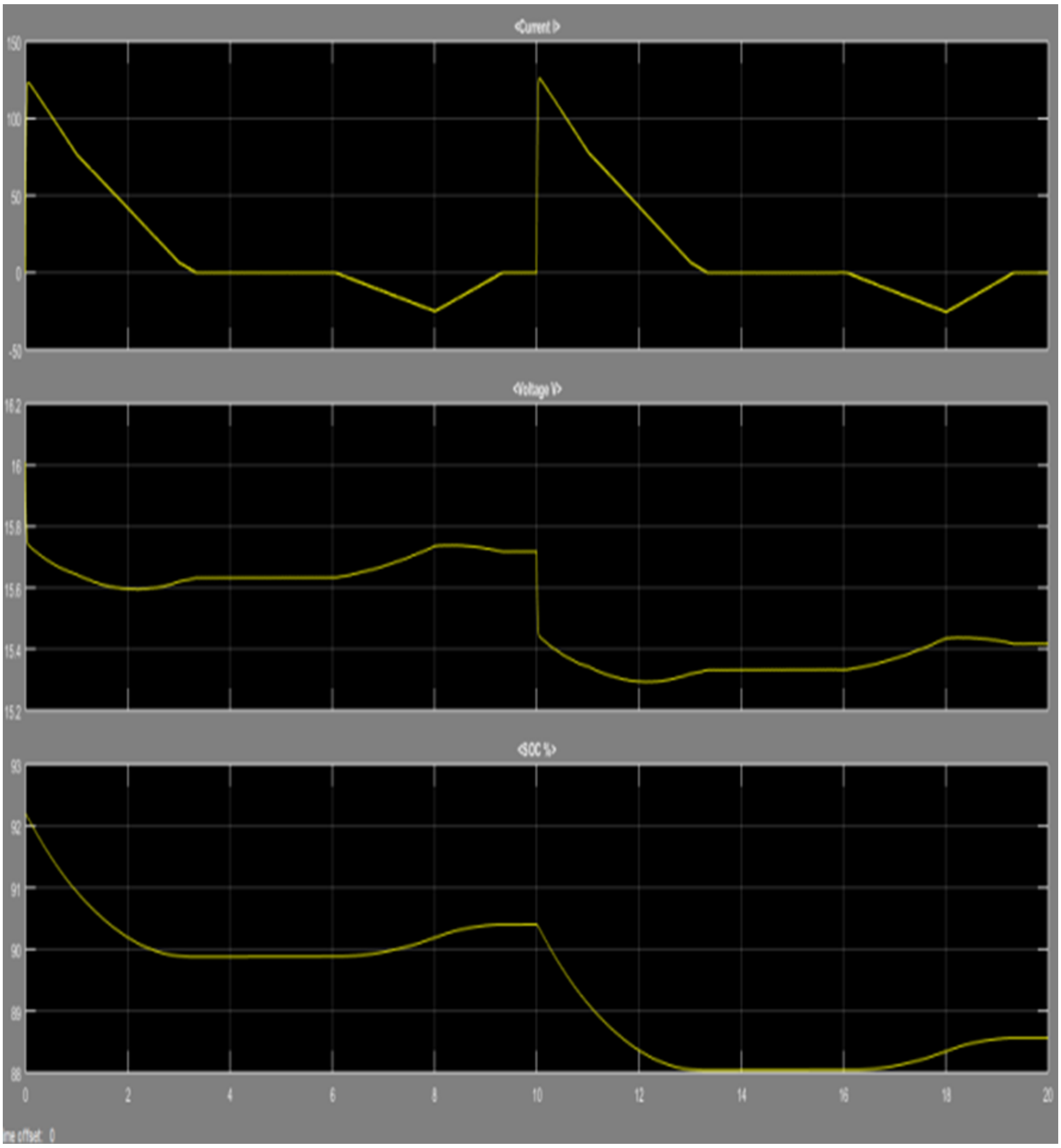

Figure 13. Current (1), voltage (2) and SOC (3) of ultracapacitor

Table 5. Results for fresh cells

		Battery	Hybrid
40°C	Range	120.03	122.8
	Power loss (%)	3.42	2.3
35°C	Range	116.04	121.2
	Power loss (%)	3.52	2.4
25°C	Range	114.8	120.7
	Power loss (%)	3.8	2.7
0°C	Range	86.63	111.7
	Power loss (%)	7.81	3.3
-5°C	Range	70.01	108.8
	Power loss (%)	8.98	3.65

Table 6. Results for half-life cycle cell

		Battery	Hybrid
40°C	Range	105.3	109.4
	Power loss (%)	4.4	2.47
35°C	Range	103.5	107.4
	Power loss (%)	4.56	2.77
25°C	Range	101.2	105.32
	Power loss (%)	4.98	2.91
0°C	Range	45.34	97.15
	Power loss (%)	10.12	4.57
-5°C	Range	null	80
	Power loss (%)	null	5.09

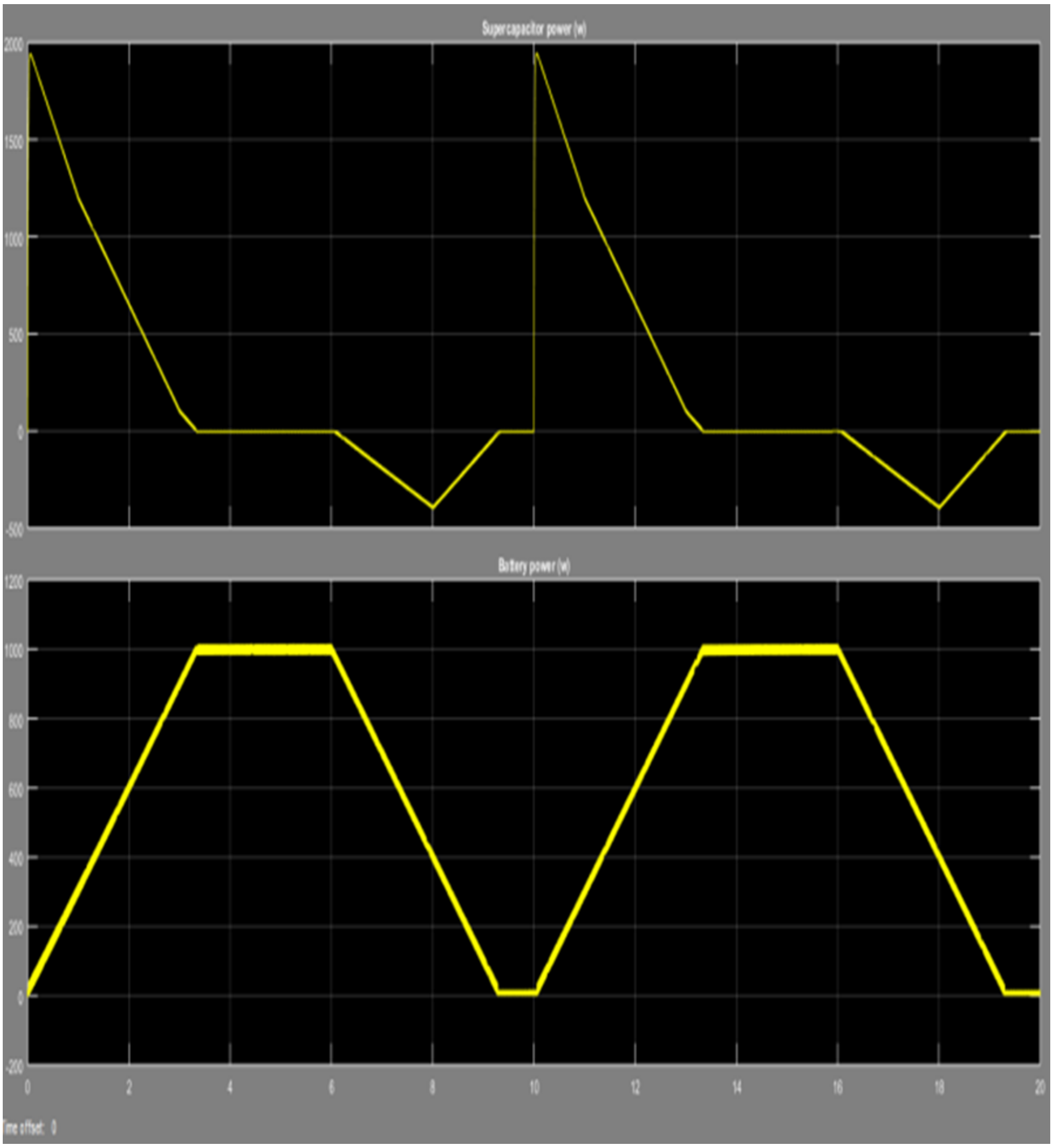

Figure 14. Ultracapacitor power (1) Battery power (2) in watt (W)

nificant when the battery is partially used up (Table 6). At -5°C 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.

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 (http://www.evpst.com.last). 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 is still higher though it is reducing day by day. Despite 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.

CONCLUSION

Benefits of hybridization as an energy storage device are presented in this paper. Different simulation results shows 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 (8%), first stored in the ultracapacitor which sufficiently reduces the battery ageing. In addition to it hybridization also reduces maximum battery current (12 A) and number of executed cycles. Hybridization increase the power preserving capacity (17%) of the system at all conditions hence increases the battery maintenance interval significantly.

NOMENCLATURE

Symbol	Abbreviation
η_1	Efficiency of boost mode
η_2	Efficiency of recovery mode
U_{max}	Maxium voltage od UCs
U_{min}	Minimum voltage of UCs
C	Capacity of UCs
V	vehicle instantaneous sped
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

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