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HYBRIDIZATION OF BATTERY AND ULTRACAPACITOR FOR LOW WEIGHT ELECTRIC VEHICLE

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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 is, the higher the hybrid system efficiency becomes. Data from real world is is covered by this study. Simulations are done considering a modified Bangladeshi drive cycle for low weight vehicles. Several issues like volumetric, gravimetric and cost issues of hybridization are present in this paper. Owing to 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 but it also increases the power train efficiency and the battery lifespan. This paper would help researchers in further development of this topic.

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

1. 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 a battery with an ultracapacitor energy storage systems not only increases the efficiency of the vehicle but iy 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 temperatures. [3].
2. The main source provides only average power while hybridization of the battery and capacitor provides large power pulse compared to the main source only [4].

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

From the literature (Tab. 1), it is clear that several works have been done on the battery and ultracapacitor hybridization. But there is no research about an efficiency increment using this kind of hybridization and how this system will work if implemented on a low weight vehicle (i.e. three-wheelers, small automobiles and etc.). In this paper, the first component modeling, topology and power management of the battery and ultracapacitor modeling is shown along with the total system simulation, the system is implemented on a low weight vehicle and the simulations were performed in the MATLAB platform. In the simulation, a modified Bangladeshi drive cycle is taken to see how compatible the system can be for Bangladesh.

2. 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 super-capacitor bank and electric loading which controls the power train. Those components are discussed below.

Tab. 1. Different examples of 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 of power train and showed advantages and disadvantages of the powertrains.	[5]
2009	Did a fuel cell vehicle hybrid comparison with battery or ultracapacitor.	Showed how efficient the replacement of a battery with an ultracapacitor ca be.	[6]
2009	Worked and reviewed on future necessities of energy storage hybridization technologies.	Showed previous and future importance of hybridization.	[7]
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 the battery and ultracapacitor hybridization.	[8]
2012	Optimized for efficiency or battery life in a supercapacitor/battery electric vehicle	Showed an increment of the battery life by implementing an ultercapacitor with the battery.	[9]
2013	Designed a semi active hybrid energy storage system using a battery and an ultracapacitor	Showed a voltage drop controlling method by using a battery/ultra-capacitor hybridization.	[10]
2014	Worked on battery-ultracapacitor materials for fast storage of electrochemical charge.	Worked on materials and showed that PTMA constituents a dominate in the hybrid battery charge process	[11]
2015	Worked on the merging of the battery and supercapacitor chemistries.	This review paper showed different merging procedures for the battery and ultracapacitor.	[12]
2016	Worked on different energy storage technologies for several high power applications.	In this study, the author discussed about different high energy storage technologies including the battery and the ultracapacitor.	[13]

2.1. Battery Bank

Modeling of batteries is highly 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 their function, namely a state change, a discharge rate, a temperature difference and etc. Its capacity depends upon the temperature of the system along with the discharge rate.

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

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

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

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

where 'σ' is a constant.

The Thevenin's equivalent circuit has been applied here to design the circuit of the model. Voltage and resistance are here functions of the 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 an open circuit voltage, then with respect to SOC it can function as: VOC = a1 + a2 SOC, at some specific temperature. In the battery, there exists both static and dynamic resistance, so the resistance measurement should be done with care.

2.2. 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 that is higher in value. The key difference between a normal and super-capacitor is efficiency. Super-capacitors are far more efficient than regular ones; i.e. in general series, resistance has much lower values than a shunt.

2.3. Electric Loading

Electric loading results mainly from motive/mechanical power from an inverter-fed induction motor. At the time of regenerative braking, induction motor works as a generator by lowering its terminal voltage frequency resulting in a power flow in a reverse direction and causing Brake Torque.

3. TOPOLOGIES OF HYBID ENERGY STORAGE

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

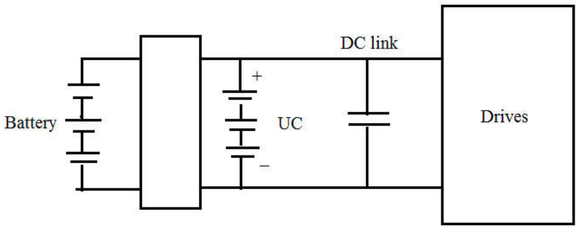

Fig. 1. Power train with battery semi-active hybrid

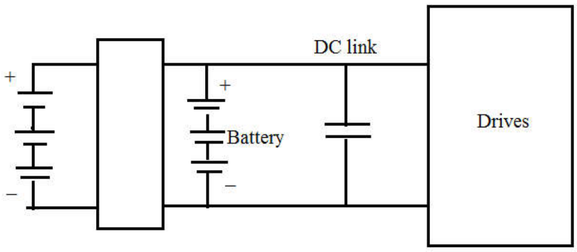

Fig. 2. Power train with ultracapacitor semi-active hybrid

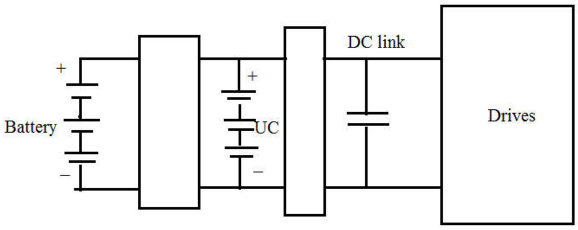

Fig. 3. Power train with battery fully active cascaded hybrid

For a city vehicle in the power train discussed, ultracapacitors serve as a high power low energy auxiliary storage device. UCs are engaged during regenerative braking and high power loads. Additional cost can be minimized by introducing an auxiliary storage device on the basis of an instantaneous vehicle speed, power demand and UCs charges. The power distribution is shown in Figure 5.

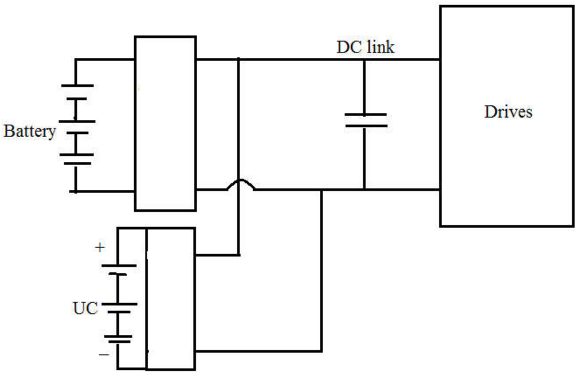

Fig. 4. Power train of fully active parallel hybrid

All energy from regenerative braking is captured by the ultracapacitor for balancing the UCs state of charge. Additional storage is recharged by the battery during the stop if necessary.

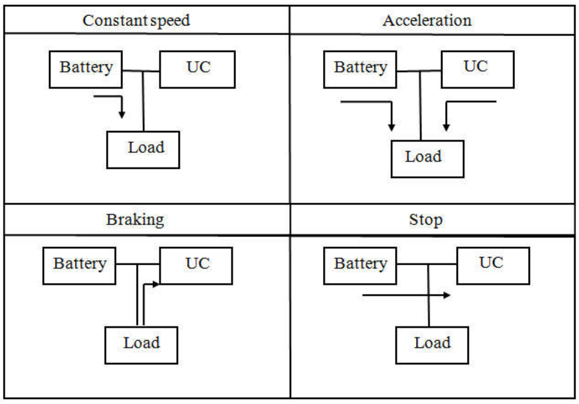

Fig. 5. Energy flow diagram at nominal stages

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

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

$$U_{ref\text{-}up} = \sqrt{U_{max}^2 - \frac{mV^2\eta_2}{c}}. \tag{4}$$

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

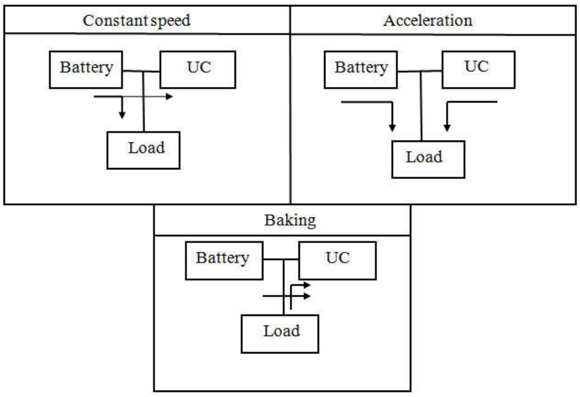

Fig. 6. Energy flow diagram at low SOC and low speed of ultracapacitor

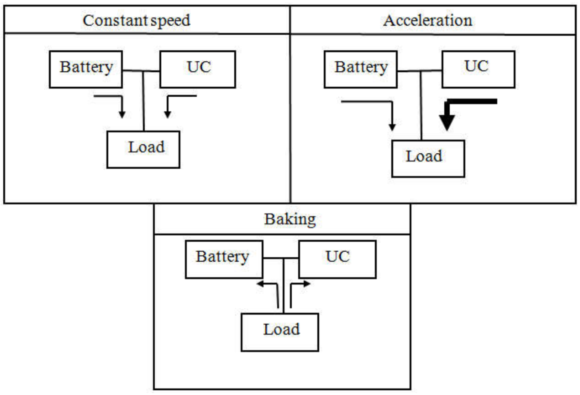

Fig. 7. Energy flow diagram at high SOC and high speed of ultracapacitor

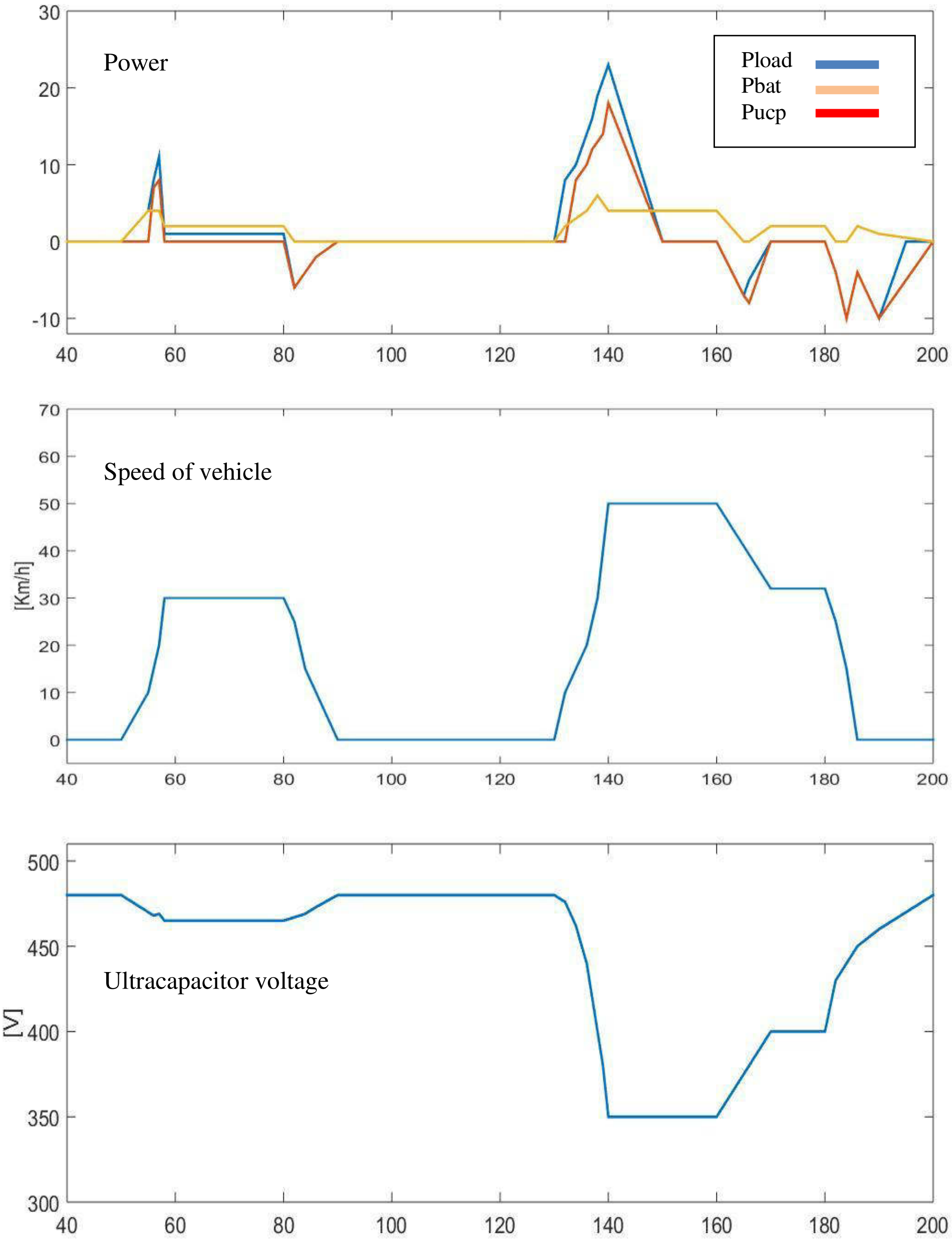

Fig. 8. Power distribution in HES

4. SIMULATIONS AND RESULTS

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

4.1. Battery and ultracapacitor model

The battery model is shown in Figure 9. A resistor is connected in series. Considering the charge in the discharge current and temperature, a discharge capacity is modeled using method [20, 21]. 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 caused by the non-zero internal resistance of an ultracapacitor and capacitor C, which is the ultracapacitors capacitance [22]. This model is sufficient to evaluate power losses.

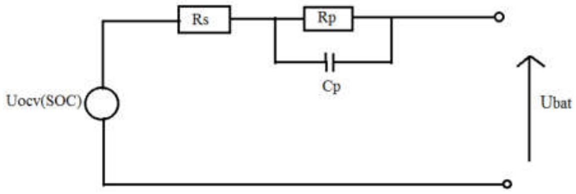

Fig. 9. Electrochemical battery model

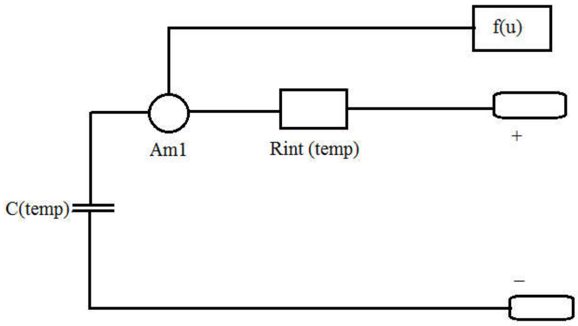

Fig. 10. Ultracapacitor model

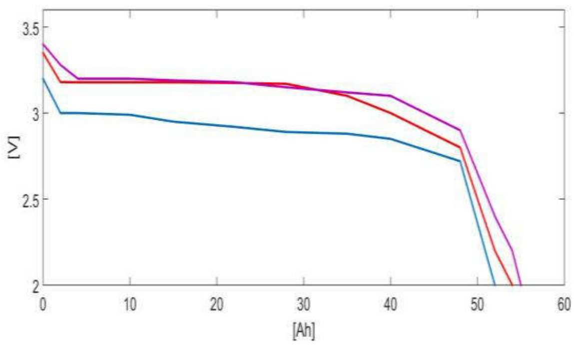

Fig. 11. Discharge characteristics of battery (5C – blue, 1C – red, 2C – purple.

Tab. 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

Tab. 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

4.2. 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:

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

$$E_{sw} = E_{on} + E_{off}, \tag{6}$$

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

$$Ptr = P_{cond\text{-}tr} + P_{sw\text{-}tr}. \tag{8}$$

Losses per diode:

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

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

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

Total loss:

$$P_{tot} = P_{tr}+P_d. \tag{12}$$

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 a 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 the dry asphalt of concrete road [23].

Tab. 4. Vehicle model parameters

Parameter	Value
Vehicle total mass	700 kg
Aerodynamic coefficient	0.34
Vehicle fontal area	2 m^2
Rolling friction coefficient	0.013
Converter switching frequency	14 kHz
Efficiency of powertrain	82%

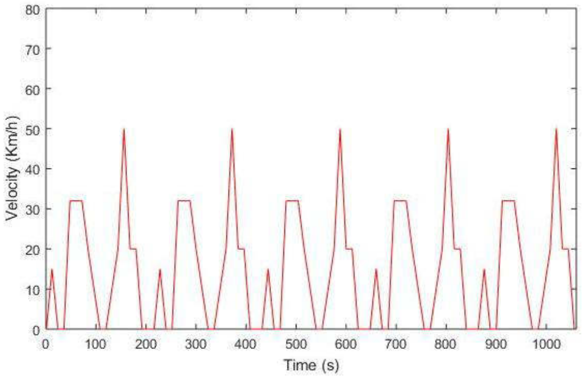

Fig. 12. Modified Bangladeshi urban drive cycle

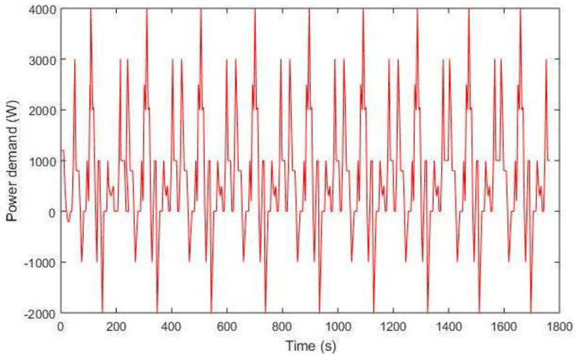

Fig. 13. Drive power demand of the vehicle

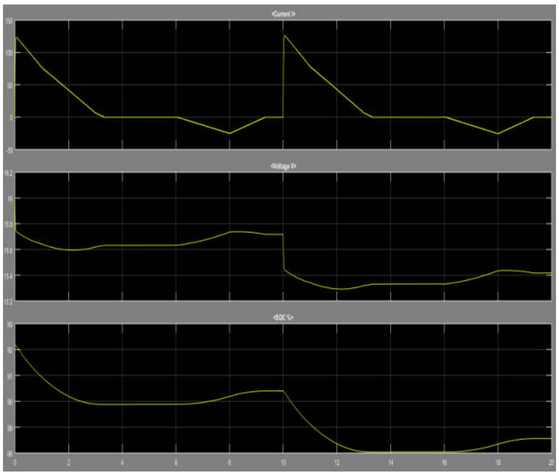

Fig. 14. Current (1), voltage(2) and SOC (3) of ultracapacitor

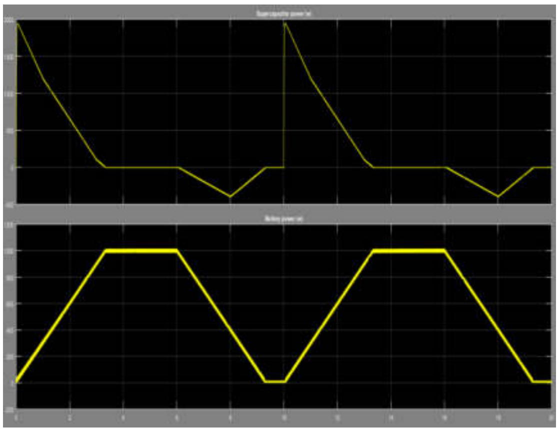

Fig. 15. Ultracapacitor power (1) Battery power (2) in W

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 from Table 5 clearly show the effect of hybridization on improving the performance of the vehicle. In a larger case, a hybrid source gives not only increased efficiency but also a smaller decrease in capacity.

Tab. 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

Supporting of the ultracapacitor is more significant when the battery is partially used up (Table 6). At -5°C, the vehicle is not able to run by battery only in accordance with the drive cycle. But the hybrid system eliminated this problem, where the 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.

Tab. 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

5. ISSUES OF HYBRIDIZATION

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

6. CONCLUSIONS

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

Nomenclature

Symbols

C	capacity of UCs
D	duty cycle
E_{off}	energy dissipation during turn-off time
E_{on}	energy dissipation during turn-in time
E_{rr}	energy dissipation during reverse recovery
f_{sw}	switching frequency
I_d	diode current
I_{rated}	rated current
r_T	forward slope resistance
T_{tr}	transistor current
U_{max}	maximum voltage od UCs
U_{min}	minimum voltage of UCs
V	vehicle instantaneous sped
V_d	diode voltage
V_T	threshold voltage
V_{tr}	transistor voltage
η_1	efficiency of boost mode
η_2	efficiency of recovery mode

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