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Control of Hybrid Energy Storage for Extended Battery Life in Electric Vehicles

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Abstract: This paper aims at the development of a power split control for energy management of multiple energy sources in a typical Electric Vehicle (EV) drive. A source selecting switching circuit is developed so as to connect either battery, the high energy density source or ultracapacitor (UC), the high power density source to a 48V, 60W traction DC motor drive. Power split control is designed based on the rate of rise of motor drive power demand. This rate of demand, if makes the battery current to exceed its maximum limits, then the power split control will switch the high power source to deliver the load demand instead of the battery. A boost converter receives one of these sources and acts as the drive for the traction motor with a closed loop control to accomplish the speed tracking ability. A typical vehicle drive cycle is used for testing the developed converter, the motor drive system and its associated control in MATLAB simulation. Further, experimental validation is carried out in hardware circuit with Arduino evaluation board used for implementation of both the power split control as well as the speed control algorithms. Various test conditions depicting typical Electric Vehicle drive cycles were formulated to test the hardware system. The ultracapacitor is observed to support the traction motor drive during the high rate of power demand periods in the vehicle drive cycle. The simulation as well as the experimental results for various speed profiles were presented and analyzed.

***Index Terms*: Battery, boost converter, controller, DC motror, ultracapacitor.**

I. INTRODUCTION

The outbreak of environmental crisis in the past decade paved way to the recognition of Electric Vehicles (EV), which are foreseen to accomplish zero emission roads in the near future [1]. EV technologies manifest a multidisciplinary research in which the solutions for energy source related issues are much sought, as they directly reflect the customer concerns on the range anxiety. There is a trade-off between the energy and power needs of electric drives which makes the selection of the on-board energy storage a crucial factor in satisfying the range anxiety [1-2]. Battery being the reliable and cost-effective energy storage, they are preferred in EVs too. But the peak power demands of electric drives and sizing of the on-board storage to meet this demand is always challenging. High energy density battery can store large capacity of energy and can provide long drive range. But the electric traction drive demands peak power support frequently during its operating range like acceleration, hill climbing etc. When the battery is designed for average power demand of the drive, then peak power support will suffer; in contrary if the battery is designed for peak demand will make the system bulky and economically unrealistic. This anomaly can be comfortably combated by opting for multiple on-board energy storage to relieve the burden on the main battery of the EVs. When multiple energy sources are to power a common load, then power converters are to be restructured to have multiple input ports, with corresponding reformations and coordination in their control. Furthermore, an energy management system has to be in place for optimized utilization of these sources in a coordinated way so as to increase the drive range. Such an energy management system is expected to control the power delivery of the sources as dictated by the drive demand thus realizing an effective hybridization. However, the coordination of two energy sources, one with High Specific Energy (HSE) like Battery and the other with High Specific Power (HSP) like Ultracapacitor, has to be scheduled in such a way that their unique advantages can be fully utilized. This paper utilizes a source selection switching circuit which will precede a dc-dc converter which serves as a drive for a PMDC motor in EV application. The source selection strategy is formulated in order to cater the drive cycle demand of the vehicle from multiple sources in typical drive ranges. Section II presents the description of the multiple energy source and its energy management system, Section III and IV elaborates the simulation and hardware implementation respectively.

II. SYSTEM DESCRIPTION

There are several possible control strategies available in the literature to coordinate the two energy sources viz. HSE and HSP, in EVs [3]. It is a natural choice that the HSE source always works at its rated output power level, while the HSP energy source serves to support and accept the power difference during acceleration and braking. The power delivered to the load will be the summation of the output power of each energy sources.

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This paper is based on Multi-Input converter topology which engages one source at a time and controlled by the peak discharge restrictions of the battery while handling multiple energy sources in EVs. This topology eliminates the need for multiple converters to drive multiple sources and the corresponding control for their parallel operation. Moreover, this topology also extends the flexibility that the two sources need not have matched voltage levels.

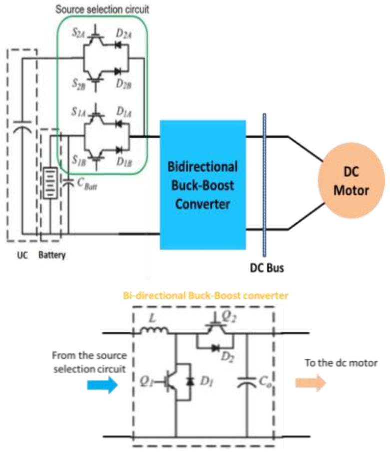

Fig. 1. Multiple-Input battery/UC system [4]

The battery and ultra-capacitor are connected as inputs to a boost converter which is common for both the sources through a source selection circuit consisting of two bi-directional switches as shown in Fig. 1. The two input sources work independently to deliver power to the output. The voltage levels of battery and UC is so selected that it is lower than that of the DC Bus voltage, and the bidirectional DC-DC converter will be operated in the boost mode when feeding the motor from either of the source. S_{1A} controls the power delivered by the battery, while S_{2A} is turned on when UC is required to support the peak inrush power. The inductor current is controlled by PWM control of switch Q_1 and the distribution of power between the battery and the ultra-capacitor is controlled by S_{1A} and S_{2A} respectively. Since battery and UC are connected to the load through a common converter, the cost, size and complexity is reduced. This topology has been selected to implement the parallel operation of battery and UC with a suitable control strategy.

III. PERFORMANCE EVALUATION

The identified multi input system is designed for a dc motor and the system performance is evaluated for different drive cycles both in simulation as well as in the hardware experiments. The system is tested under various operating conditions emulated to represent typical vehicular conditions which include acceleration, deceleration and cruising modes.

A. Simulation Studies

The multiple-input topology of Fig. 1 has been implemented in the MATLAB Simulink environment with various system component specifications as described in Table 1. The overall control scheme for the switch selection as well as the motor drive is presented in Fig.2. The input for the drive system is obtained from the drive cycles available in the online repositories of international agencies for EV. The rate limiter decides on which source will be selected under any given operating condition. The current error is utilized to obtain the rate of change of motor power demand and further the source selection decision is made by the source controller.

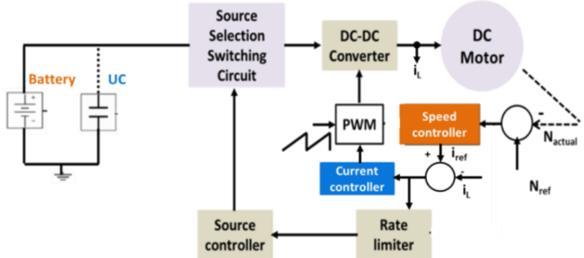

Fig. 2. Control scheme for the Multi-Input system

Table 1. Simulation System Specification

Battery parameters		**Ultracapacitor parameters**	**DC Machine Parameters**	**Value**
Voltage	120 V	120V	Armature Voltage, V_a	240 V
Capacity	66 Ah	1000 F	Power	5 HP
Boost Converter			Rated Speed	1750 RPM
L	6 mH		Field Voltage, V_f	300 V
C	8 mF			

B. Simulation Results and Analysis

The reference speed profile for the DC motor control has been taken from the drive cycle available at the repository of OAK RIDGE National Laboratory [5] and is shown in Fig. 3. This has been utilized to emulate the real filed vehicle drive condition in the simulation. The spread-sheet from the aforementioned repository has been imported in MATLAB and a speed-time graph is obtained. This is the speed intended to be tracked by the dc motor considered as the EV drive. Thus, this speed is compared with the actual speed of the DC machine and the error is compensated using a feedback controller as shown in Fig. 2 to generate gating pulse for boost converter. The circuit of Fig. 1 with the specifications of Table 1 is and with the controller of Fig.2 is simulated in MATLAB/Simulink and the results are presented in Fig. 4 to Fig. 7.

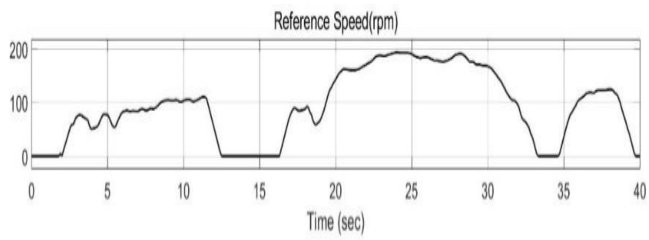

Fig. 3. Reference speed curve

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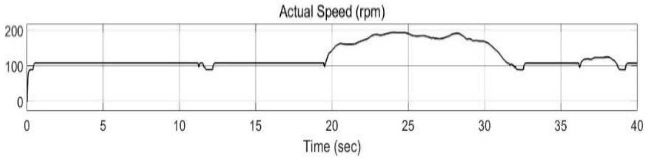

Fig. 4. Obtained speed curve

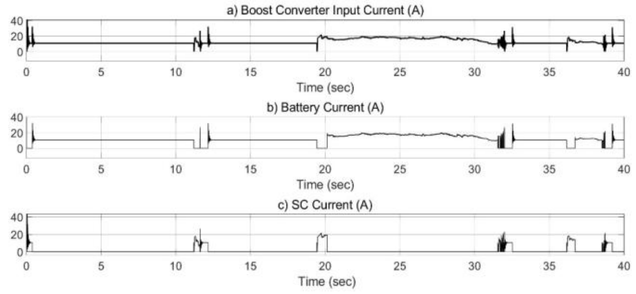

Fig. 5. The boost converter input current, battery and UC currents

The input current to the boost converter and the current delivered by each source are presented in Fig. 5 (a) to (c). It can be ascertained that the converter current in Fig. 5 (a) accounts to be the instantaneous sum of the battery current of Fig. 5 (b) and UC current of Fig. 5 (c). It can also be observed that the UC delivers the load only during the transient periods while battery delivers the steady demands.

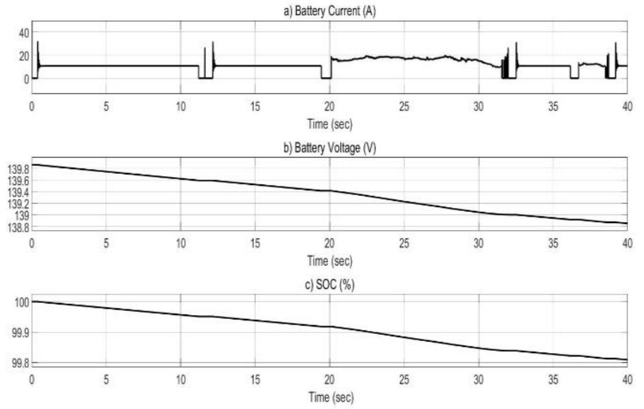

Fig. 6. Battery parameters

The current, voltage and State of Charge (SoC) of the battery are presented in Fig. 6 (a), (b) and (c) respectively corresponding to the same drive cycle of Fig. 3. It can be noticed that when the battery delivers power, its voltage and SoC has been found to reduce. The rate of fall of battery SoC follows the magnitude of current delivered by the battery, for instance after 20 s SoC and voltage are observed to fall as the battery delivers higher magnitude of current.

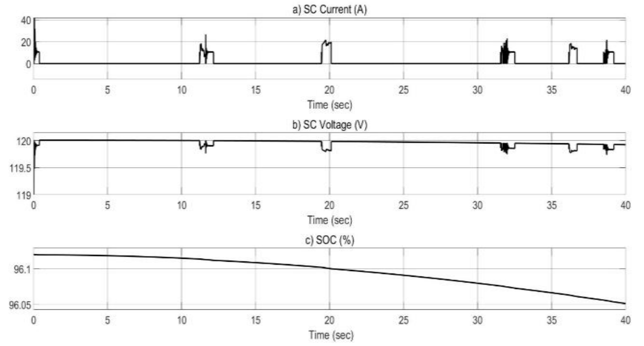

Fig. 7. Ultracapacitor parameters

Similarly, the current, voltage and SoC of the UC are presented in Fig. 7 (a), (b) and (c) respectively. It can be observed that the UC delivers to the load only during transient periods and immediately after such a transient period, its voltage has been found to reduce rapidly. As the energy stored in the capacitor is a function of its voltage, such a rapid fall in voltage is apparent.

C. Verification Through hardware experiments

The proof of concept for the power split control is established through a scaled-down hardware setup with a 60W, 48V PMDC motor. The motor is powered through a custom developed boost converter with both the control algorithms implemented in Arduino microcontroller [6]. The system specifications for hardware implementation are presented in Table 2.

Table 2. System Specifications

DC motor		Boost Converter	
Rated Capacity	60W	Current ripple (%)	5 %
Rated Voltage	48V	Voltage Ripple (%)	1%
Rated Current	1.2A	Inductor	6 mH
Rated Speed	1500rpm	Capacitor	60 **µF**
Insulation Class	F		

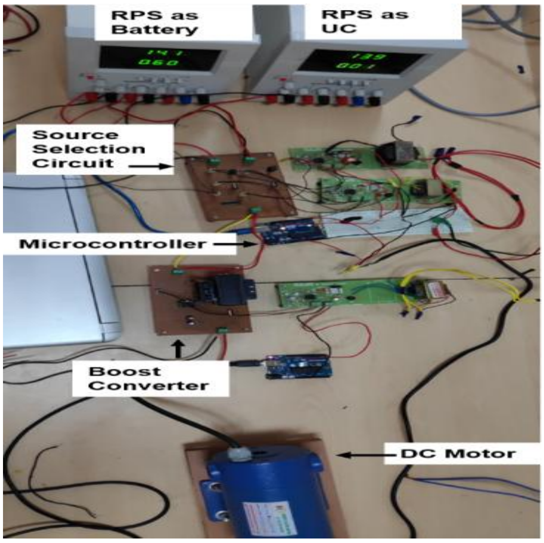

Fig. 8. Snapshot of experimental setup

The snapshot of the developed experimental set up is presented in Fig. 8. The selected topology has been implemented in hardware with two Regulated Power Supplies (RPS) one representing the battery and the other representing the UC. The objective of this research work is to validate a multi input converter configuration with the proposed power split logic for their control, so RPSs are considered instead of the actual sources. The boost converter powers the DC motor, with the speed control and the power split algorithm implemented in the same Arduino UNO microcontroller.

Speed encoder (LPD3806-600BM) is used to measure the actual speed of the DC motor and the speed computations are also carried out in the microcontroller. In an electric motor, the rate of change of speed is proportional to the rate of change of power if the load torque is maintained constant. So, the rate of change of speed is computed and is used to determine which of the two sources should supply the load at a given instant.

D. Source Selection Control Logic

The source selection logic is developed based on the rate of change of speed as explained in section c and the same is realized through the process as depicted in the flowchart of Fig. 9. This logic when implemented in the Arduino UNO is intended to generate the gating signals for the source selection switches.

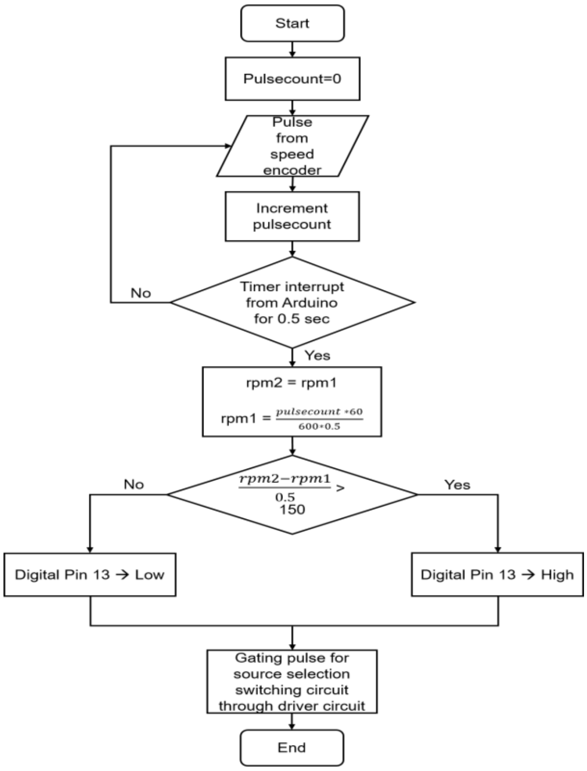

Fig. 9. Flowchart of generation of gating pulse for source selection circuit

E. Results from Hardware Experiments and Inferences

The same drive cycle from OAK RIDGE National Laboratory is utilized to obtain the speed profile for the hardware experiments too. But the duration is curtailed to 9 s and the segment considered for the hardware testing is presented in Fig. 10. The corresponding battery and the UC currents are shown in Fig. 11. (a), in which the red encircles indicate the complementary current support observed across the two sources, while the constant power region is encircled with blue color, where the battery alone delivers a constant current. The armature voltage and current of the DC motor are presented in Fig. 11. (b) for the same speed profile. The region encircled in red indicates the sudden change in the speed of the DC machine and the subsequent increase in the armature voltage. Whenever the speed encounters a change, the armature voltage has been observed to follow it and at the same time the armature current undergoes transient state. It can also be observed from the above results that, whenever the rate of change of speed of the DC motor exceeds the preset value of 150 rpm for duration of 0.5 s, battery is cutoff from the load and UC is made to deliver the required power. On the other hand, when the change in speed is within the limit, battery supports the load.

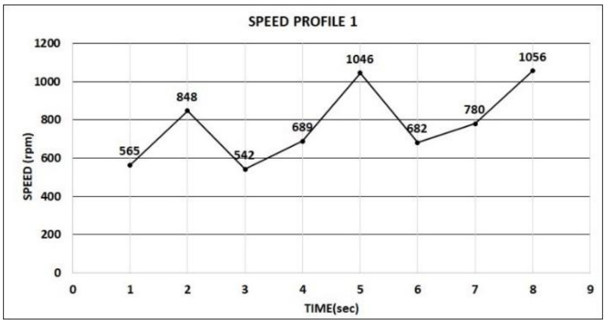

Fig. 10. Speed profile 1

Fig. 11. (a) Battery and UC current obtained for speed profile 1

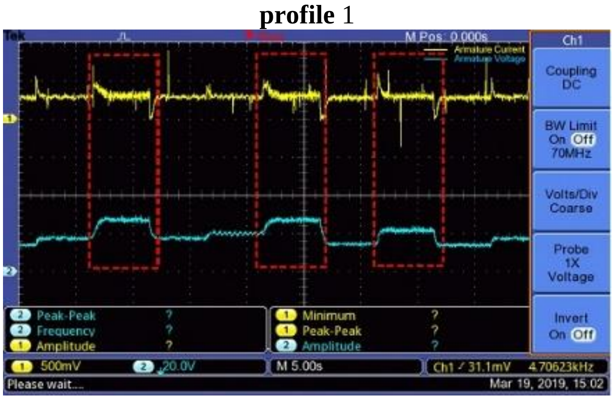

Fig. 11. (b) Armature voltage and current for speed profile 1

Similar testing has been carried out with two more speed profiles which are presented in Fig. 12. (a) and (b) and the corresponding battery and UC currents are presented in Fig. 13. (a) and (b). The same trend of current sharing occurs even here with UC supporting the transient durations and the steady current is supplied by the battery. Finally, the steady state results obtained from the hardware experiments is presented in Table 3 for speed profile 1. Under steady state the system exhibits power balance for all the speed values with highest efficiency being 81.14 %.

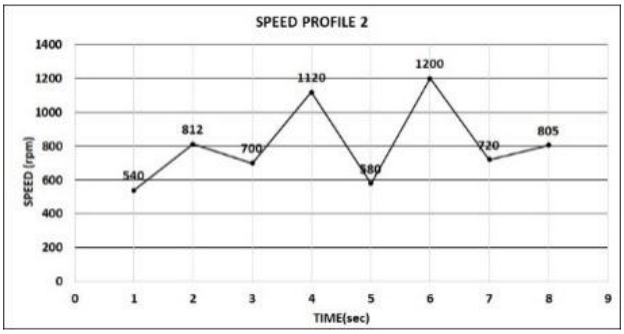

Fig. 12. (a) Speed profile 2

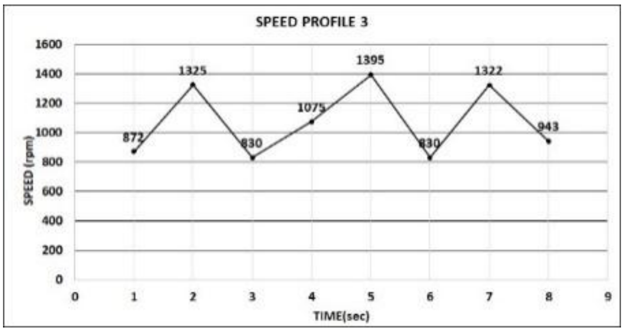

Fig. 12. (b) Speed profile 3

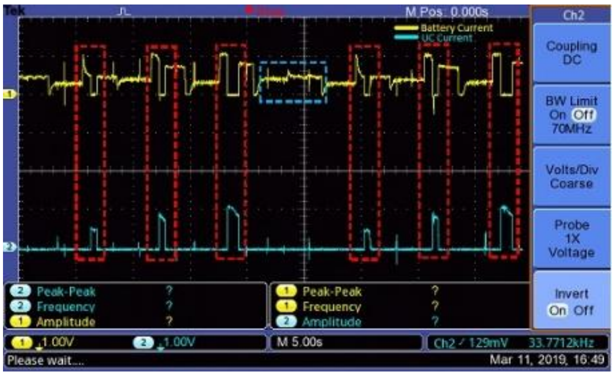

Fig. 13. (a) Battery and UC current obtained for speed profile 2

Fig. 13. (b) Battery and UC current obtained for speed profile 3

Table 3. Experimental Results for Speed Profile 1

Motor drive		**Armature**		**N**	**Motor drive**		
V_{in} (V)	**I_{in} (A)**	**V_a (V)**	**I_a (A)**	**(rpm)**	**P_{in} (W)**	**P_{out} (W)**	**η(%)**
14	0.63	14.5	0.48	565	8.82	6.96	78.9
14	1.02	21.3	0.53	848	14.28	11.28	79.05
14	0.6	14.2	0.48	542	8.4	6.816	81.14
14	0.78	17.5	0.5	689	10.92	8.75	80.12
14	1.38	24.8	0.55	1046	19.32	13.64	70.6
14	0.79	16.5	0.49	682	11.06	8.085	73.1
14	0.93	18.6	0.51	780	12.6	9.486	75.28
14	1.38	24.8	0.55	1056	19.32	13.64	70.6

Table 4. Experimental Results for Speed Profile 2

Motor drive		**Armature**		**N**	**Motor drive**		
V_{in} (V)	**I_{in} (A)**	**V_a (V)**	**I_a (A)**	**(rpm)**	**P_{in} (W)**	**P_{out} (W)**	**η(%)**
14	0.57	13.9	0.48	540	7.98	6.672	83.6
14	0.91	20	0.81	812	12.74	10.2	80.06
14	0.76	17.4	0.5	700	10.64	8.7	81.76
14	1.43	27.2	0.55	1120	20.02	14.96	74.72
14	0.61	14.7	0.47	580	8.54	6.909	80.9
14	1.57	29	0.56	1200	21.98	16.24	73.88
14	0.79	17.9	0.49	720	11.06	8.771	79.3
14	0.9	19.8	0.5	805	12.6	9.9	78.57

Table 5. Experimental Results for Speed Profile 3

Motor drive		Armature		N	Motor drive		
V_{in} (V)	I_{in} (A)	V_a (V)	I_a (A)	(rpm)	P_{in} (W)	P_{out} (W)	η(%)
14	0.97	21.1	0.5	872	13.58	10.55	77.68
14	1.77	31.3	0.6	1325	24.78	18.78	75.78
14	0.91	20.4	0.5	830	12.74	10.2	80.06
14	1.28	25.5	0.53	1075	17.92	13.515	75.41
14	1.92	33.2	0.62	1395	26.88	20.584	76.57
14	0.91	20.2	0.49	830	12.34	9.898	77.69
14	1.76	31.4	0.6	1322	24.641	18.78	76.21
14	1.07	23.1	0.571	943	14.98	11.781	78.64

IV. CONCLUSION

A power converter circuit for which the provision to receive multiple energy sources is identified and used for powering a 60W traction DC motor drive in EV applications. Power split control strategy for the selective operation of two energy sources, the battery and the ultracapacitor is formulated and implemented in both simulation and in hardware experiments. A closed loop speed control is achieved for the DC motor to track the drive cycle requirement. A rate limiter algorithm is used to manage the power split across the two sources. The battery has been observed to deliver the load power during constant speed operations and also when the rate of change of current doesn't exceed the battery limitations as per the design. Ultracapacitor is noticed to supply the load during peak demands, i.e. when the rate of change of current exceeds the battery limitations. Hardware implementation of the same multiple source traction system has been performed and validated through various speed profiles. Whenever a rise in speed is introduced, the ultracapacitor has been found delivering the load, while the steady speed periods are found supported by the battery.

Such multiple energy sources will relieve the traction battery from being oversized just for the sake of delivering the peak inrush currents. Also, the regenerative recapture energy if pumped to the ultracapacitor can save the battery from harsh transients thus preserve the battery capacity as well as the life cycle.

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