Battery-Ultracapacitor Hybrid Energy Storage System to Increase Battery Life under Pulse Loads

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ABSTRACT This work presents a battery-ultracapacitor hybrid energy storage system (HESS) for pulsed loads (PL) in which ultracapacitors (UCs) run the pulse portion of the load while the battery powers the constant part of the load. Energy stored in UC depends upon the square of its voltage that’s why an active parallel hybrid topology with two bidirectional converters (BDC) is employed here that assigns UC a separate BDC to control its voltage between an upper and lower limit as per-requisite. The other converter is connected between the battery and DC-link to provide a distinct control of the battery. A MATLAB/Simulink model is developed to minimize the factors affecting the battery life such as capacity rate (C-rate), depth of discharge (DoD), and temperature rise due to PL by controlling the operating modes of the BDCs in which voltage of the UC and state of charge (SoC) of the battery are control variables. A constant output voltage across the load is maintained through feedback control. A detailed comparative analysis, among battery-alone, UC-alone, and battery-UC hybrid modes is performed which signifies that the proposed system is 55% lower in cost than its counterparts. The analysis shows that the proposed HESS reduces 50% capacity of a lead-acid battery, which is otherwise necessary to withstand the pulsating loads. Moreover, the performance of the HESS is also tested for electric vehicle (EV) load by hybridizing a high-voltage lithium-ion battery pack with a UC bank which confirms its suitability for EV applications.

INDEX TERMS pulsed load, battery life improvement, ultracapacitors (UCs), bidirectional converter, hybrid energy storage system (HESS), and electric vehicles (EVs).

I. INTRODUCTION

Batteries are widely used energy storage devices (ESDs) in photovoltaic (PV) systems, hybrid electric vehicles (HEVs), DC microgrids, and domestic electronics applications [1][2]. The load that extracts pulsating current from the batteries has small average power [3]. A battery capacity is normally measured by the predicted average power consumption of a typical electronic appliance. A pulsed load (PL) with a peak greater than the projected average value causes a current/voltage ripple that rapidly discharges the battery [4]. Battery lifetime is specified in charge/discharge cycles; the PL increases these cycles per day which eventually decreases the battery lifetime. Therefore, the PL needs a higher power rating of the battery than the designated rating [5]. In addition, low power density and thermal runaway due to internal heat generation in high current discharge conditions are major challenges [6]. Thus, it is essential to have an additional energy storage system that is enough robust in managing PL. Electric double-layer capacitors (EDLCs) or simply ultracapacitors (UCs) are energy storage capacitors. Unlike batteries, they have high power density, but less energy density. Low internal resistance and long life are the main advantages [7][8][9]. Thus, to attain substantial advantages in power and energy densities, a hybrid battery–UC storage system design is the most effective choice. The benefits in hybrid mode can be maximized by operating short-time high power pulses through UCs due to their high-power density and a nearly constant but long-run load by batteries due to their high energy density. A hybrid energy storage system (HESS) to enhance battery life is presented for plug-in HEVs in [10] and a wind-solar hybrid energy system in [11]. Different control strategies of HESS for EVs are presented in [12] which
uses a semi-active hybrid topology in the study. A home energy management system (HEMS) with different load outlines is presented in [13] without considering the effect of load on battery life. Adaptive passive control of a hybrid power source is proposed in [14] to regulate the voltage across the load under varying temperatures and load conditions. The battery provides power to the connected load only when the voltage across UC’s terminal drops below the voltage across the battery’s terminal but the output voltage is not constant. A supervisory energy management controller is proposed to enhance the energy management control strategy for a UC-battery HESS configuration [15]. It prolongs the battery service life in comparison to the battery-alone system. A semi-active battery-UC hybrid system extracts almost average current from the battery despite a PL [16]. However, lower limits on UC voltage and state of charge (SoC) of the battery are not considered which results in complete discharge of ESD. A model predictive control of a battery-UC HESS is experimentally verified by allocating the fast load current variation to the UC and slow current changes to the battery [17]. A comparison between a conventional passive hybrid topology and a capacitor semi-active HESS depicts that the latter requires less capacitance [18]. A UC-battery HESS is proposed for EVs in which the dynamic performance of both the ESDs is evaluated [19]. However, the control of the output voltage is not considered in [17]–[19]. The system is not feasible for a load that requires a constant voltage across it to function properly. A battery-UC HESS applying a constant-current charger in its operation is employed [20]. A comparative analysis between a constant load and pulsed load extraction from the battery shows that battery service life is lower in the PL case. However, the economic benefits and a detailed service-life analysis of HESS are not taken into account by these methods [21]. Therefore, a new strategy to control HESS by considering technical and economic limitations/benefits is still in need of the hour. The main objective of this work is to study the effect of PL on battery life and to analyze the performance of a battery-UC hybrid system for technical and economic limitations/benefits. Output voltage stabilization and energy distribution management are difficult when the UC is directly linked to the battery [22]. That’s why to provide UC’s voltage a wide range to vary, an active hybrid topology that parallels the output of two bidirectional DC-DC converters to a common DC-link is used in the study. The battery current is lowered to a minimum to improve the discharge persistence of the battery current. A MATLAB/Simulink model is developed that runs the pulsed part of the load through UCs and the constant part of the load via the battery by controlling the UC’s voltage and SoC of the battery. To verify the advantages of the proposed system a 12 V lead-acid battery and a high-voltage lithium-ion battery pack for EV load are considered in this study. A comparative analysis, among battery-alone, UC-alone, and battery-UC hybrid modes shows that the battery requirement reduces to 50% of its required capacity in the hybrid mode under PLs as compared to its counterparts. The system helps in reducing the use of toxic lead in lead-acid batteries with saved costs and fewer numbers of batteries to be replaced in EVs. Voltages of both the ESDs are kept less than the voltage of the DC-link. The rest of the study is arranged as follows; the impact of pulsed load on the battery service life is presented in Section II. Section III is all about the system description and the results are presented in Section IV. The conclusion is given at the end of Section V.

II. IMPACT OF PULSED LOADS ON A BATTERY LIFE

The effects of PL on three main parameters that define the battery lifecycle are presented in this section. The first one is the capacity rate (C-rate), which is the amount of the discharge current rate compared to its highest capacity. The battery life is stated in charge-discharge cycles. A high current pulse rapidly discharges the battery which in turn reduces battery life cycles [23][24]. A comparison shows that a constant discharge current of 6C-rate reduces the efficiency by up to 60% as compared to the 1C discharge rate [25].

The second important factor which decides the battery life is temperature impact. The battery thermal model in (1) is employed for analysis [23]. It is the sum of heat transferred to the environment " \( h(T_b - T_{en}) = -h\Delta T_b \) ", irreversible heat generated by resistive dissipation " \( I_b^2 R_b \) " and reversible entropic heat coefficient " \( I_b T_b \frac{\partial \alpha_{oc}}{\partial T_b} \) " which depends upon battery’s SoC.

\[
C_{ib} \frac{d\theta}{dt} = -h(\Delta T) + I_b^2 R_b + I_b T_b \frac{\partial \alpha_{oc}}{\partial T_b} \tag{1}
\]

\( C_{ib} \): battery heat capacity, \( h \): coefficient of heat transfer, \( T_b, T_{en} \): battery and environmental temperature respectively, \( I_b, R_b \): the current and internal resistance of the battery respectively. If \( T_i \) is the battery initial temperature, then the increase in battery temperature \( \Delta T_b \) for the pulsed load is as stated in (2) [26][27]. This equation depicts that pulse current in combination with battery internal resistance produces more heat. As the temperature rises above a certain level due to PL, the cyclic performance of the battery deteriorates which ultimately shortens the service life of the battery. Every battery type has its own working temperature limits.

\[
\Delta T_b = \frac{1}{C_{ib}} \int_t^T \left[ -h(T_b - T_{en}) + I_b^2 R_b + I_b T_b \frac{\partial \alpha_{oc}}{\partial T_b} \right] dt - T_i \tag{2}
\]

The third factor is the depth of discharge (DoD) impact [11][28]. A reduction of 6-10 times battery life is observed if the DoD increased from 20% to 100% [19]. So, for each charge-discharge cycle, the DoD should be kept minimum to optimize the lifetime of the battery. The effect of DoD on battery service life illustrates that the same battery can function for 1200 cycles with 30% DoD instead of just 200 cycles with 100% DoD [29]. Hence, battery service life can be increased by decreasing temperature, C-rate, and DoD. It is possible by putting a limit on DoD, C-rate, and, current drawn from the battery.
III. SYSTEM DIAGRAM AND DESCRIPTION

The complete design of the proposed system is shown in a block diagram in Fig. 1. The HESS is a combination of a battery system and an array of ultra-capacitors. Both ESDs are connected to a DC-link capacitor through their respective bi-directional (BDC) DC-DC converters. If the load needs to be powered, the HESS provides the required power to the attached load otherwise ESDs get charged via a control. Battery SoC and UC voltage are monitored by their respective control programs in MATLAB. The program compares the SoC of the battery with its reference SoC and UC voltage with its reference voltage. The program compels the system to work within the pre-set SoC and UC voltage reference limits. The power supplied by the battery is limited within the constant range, so the battery delivers power within that limit while UC handles the remaining pulse load.

A. COMPONENTS MODELING: BI-DIRECTIONAL DC-DC CONVERTER

A multiple converter topology with two simple half-bridge non-isolated bidirectional converters (BDCs) is applied here. A BDC is composed of an inductor L, two power MOSFET switches S1, S2, and, the two diodes D1, and D2. The low-side voltage of one of the BDC is the same as the UC voltage (V_{UC}) and the other BDC has a low-side voltage equal to the battery terminal voltage (V_{Batt}) [30]. The high-side voltage of both the BDCs is the voltage of the DC-link as shown in Fig. 2. The V_{UC} can swing in a wider range as it is coupled with the DC-link through a BDC. The stored energy of the UC is fully controlled to improve its utilization factor. The converter serves two purposes here, it performs as a boost mode by taking power out from the ESDs to power the load and as a buck mode to charge the ESDs. Moreover, a DC-link capacitor is attached between the two converters. One of the major advantages of this topology is to maintain a lower voltage at both UC and the battery than the DC-link. The other benefits are a reduced number of MOSFETs, less passive components, and a simple circuit [19]. The higher energy can be obtained from the UC as its voltage has a wide range to vary due to the BDC [19][31].

1) Basic Modes of the System

Table I describes converter modes and states of the ESDs.

| Battery state and BDC_{Batt} modes | Attributes | Battery | BDC_{Batt} modes |
|-----------------------------------|-----------|---------|-----------------|
| SOC > SOC_r                      | Discharging | Boost mode |
| SOC < SOC_r                      | Charging   | Buck mode |

| UC state and BDC_{UC} modes | Attributes | BDC_{UC} modes |
|-----------------------------|------------|----------------|
| V_{UC} > V_r               | Discharging | Boost mode |
| V_{UC} < V_r               | Charging   | Buck mode |

If the SoC of the battery is within its pre-set limits then it will deliver energy to the load, and the bi-directional converter associated with the battery (BDC_{Batt}) will act as a boost converter. At the same time, a bi-directional converter connected to the UC (BDC_{UC}) will act as a buck or as a boost converter depending upon the preset voltage limits of the UC as each converter is independent of the other converter mode. Therefore, the system operation is controlled into four

![FIGURE 1: Block diagram of the proposed system](image1)

![FIGURE 2: Bi-directional converters with DC-link capacitor](image2)

![FIGURE 3: BDC_{Batt} mode controller flow chart](image3)
different modes that are “UC Stand-alone Mode”, “Battery Stand-alone Mode”, “Battery-UC Hybrid Mode”, and “Charging Mode”. Battery-UC Hybrid Mode” is used when the battery’s SoC and UC’s voltage are in their pre-set limits both the converters operate in boost mode. “Charging mode” is used when the control variables are below their respective reference limits both the converter function as buck mode.

B. BATTERY AND UC POWER CONTROLS

A MATLAB function is programmed to control the modes of BDCs described in the previous section. The program is built on the mode selector algorithms for the BDC_Batt presented in Fig. 3, and for BDC_UC as depicted in Fig. 4. By controlling the SoC of the battery and V_UC, a limit is laid on power drawn from the ESDs. That’s why the V_UC and SoC of the battery are used as control variables. A mode selector has three variables. In the case of BDC_UC, the variables are; the UC voltage, the required power, and an internal dummy variable U_X. The U_X controls the charging and discharging of the UC. If V_UC is lower than the reference voltage (V_r), U_X=1. This bounds the converter for buck mode till the full charging of UC and transforms the U_X to zero (U_X = 0).

At the start, the mode selector reads the values of input control variables. If there is NO power requirement, it compares the V_UC with the full capacity voltage of the UC (here 13.5V) and it turns the U_X to 0 and shuts down the converter if both voltages are equal. If V_UC is lower than the maximum V_UC, it compares it with the V_r. If the V_UC is lower than the V_r, it locks the converter for buck mode and enables U_X =1, otherwise, it turns the variable U_X to zero. On the other hand, if the load needs to be powered the algorithm selects the boost mode if U_X=0. If not, it compares the V_UC with its lower limit V_r and turns the U_X to 1 for V_UC<V_r, and boost mode if V_UC>V_r. A similar algorithm is applied for BDC Batt but the control variable SoC of the battery replaces the V_UC, B_X replaces the U_X and, the rest remains the same. Each BDC can operate as boost, buck, or OFF mode depending upon the control strategy.

1) Boost Mode

If boost mode is selected energy is delivered from ESDs to the load. The voltage of ESDs is stepped-up to the voltage level of the DC-link. This is done by skillful maneuvering on S1 and S2 is set OFF permanently. When S1 is ON the inductor L accumulates the energy. When S1 is positioned to OFF the stored energy of the inductor is shifted to DC-link by an antiparallel diode of S2.

2) Buck Mode

In buck mode, the converter starts charging the ESD with energy from the charging source. In this mode, the voltage of the charging source is stepped down by the converter up to the level of the device being charged. When S2 is swapped to the ON position, the energy flows from the charging source to ESD, and inductor L accumulates some portion of the energy. When S2 is positioned to OFF the stored energy of the inductor is delivered to ESD by an antiparallel diode of S1.

C. FEEDBACK FOR VOLTAGE REGULATION

To keep the output voltage of the converters within the voltage range of the DC-link, a regulatory process is mandatory. As our input (voltage of ESDs goes down when the load is ON), as well as the load, both are varying. Therefore, it is essential to regulate the variation against the input voltage and line voltage [20]. In our control scheme, a difference between the converter output voltage and an external reference voltage is taken which is processed by a proportional-integral (PI) controller for compensation. An inner current control loop is added in outer output voltage closed-loop control. This inner-loop feedback the inductor current as shown in Fig. 5. The inductor current of a BDC is compared with the required current and a difference called error is passed through a PI controller for compensation. A PWM signal of the same frequency is obtained when the compensated signal is compared with the constant amplitude saw-tooth waveform. This signal controls the switches in the converter.
D. PULSED LOAD

A periodic rectangular pulsed load train is considered alternating between two power levels \( P_{\text{MIN}} \) the lower power limit and \( P_{\text{MAX}} \) the upper power limit with duty cycle \( DT \) for a period \( T \) [32]–[34]. Note that the \( P_{\text{MAX}} \) > \( P_{\text{MIN}} \) and \( P_{\text{MIN}} \) can be either zero or positive. A periodic non-sinusoidal pulsed load (PL) is given by (3),

\[
P(t) = \begin{cases} 
P_{\text{MAX}} = 130 \text{ Watts}, & 0 \leq t \leq DT \\
P_{\text{MIN}} = 50 \text{ Watts}, & DT \leq t \leq T 
\end{cases} \tag{3}
\]

The designed system powers a PL with \( P_{\text{MAX}} \) and \( P_{\text{MIN}} \) for 10 minutes in every hour as in Table II, 24 times a day in a life span of 10 years.

### TABLE II: PULSED LOAD DESIGN PARAMETERS

| Parameter     | Value | Unit | Parameter     | Value | Unit |
|---------------|-------|------|---------------|-------|------|
| \( P_{\text{MAX}} \) | 130   | W    | DC-link voltage | 16    | V    |
| \( P_{\text{MIN}} \) | 50    | W    | Voltage ripples | 2     | %    |
| Time/hour    | 10    | min  | Time Period (T) | 4     | s    |
| Cycles/day   | 24    | Nos. | Duty Ratio (DT) | 0.25  | ---  |
| Life span    | 10    | Year | Settling Time | 65    | ms   |

IV. RESULTS: BATTERY STAND-ALONE MODE

Battery (12 V, 7.2 Ah) performance is examined under different C-rates and varying loads. Simulation results in Fig. 6 (a) show that if a constant power of 180 W at 12 V (~@ 2C-rate) is drawn, the battery supplies power for approximately 1100 seconds with 100% DoD. However, if the pulsating power (average ~@ 2C-rate) as shown in Fig. 6 (b) is drawn, then it only supplies the power for 900 s for the same DoD. The battery supplying capacity is reduced by more than 18%. When a 4C-rate constant load is applied, the battery powers the load for approximately 275 s as depicted in Fig. 7 (a). However, the same battery is unable to withstand the PL of average 4C-rate for just 4 seconds as shown in Fig. 7 (b). The terminal voltage drops too early since too much voltage dip on the battery’s internal resistance occurs. The battery must be charged early which increases the charging-discharging cycles within a specified time that cuts the battery service life. If only a battery power a PL, it should be capable to deliver the needed energy while supporting the pulsed load. The pulsed power demand causes a sharp decrease in the terminal voltage in the battery due to its higher internal resistance than UC. The battery does not meet the energy and power requirements at the same time under PL and gets discharged prematurely. Therefore, load interruption occurs. A well-known solution to this problem is to increase the size of the battery by increasing the quantity or by using a higher-capacity battery. However, it will increase the volume, cost, and weight of the overall system. The high energy to meet the required power can also be obtained by the parallel interconnection of the cells that will oversize the battery system in terms of energy content. HESS often condenses the weight and size of ESS while improving the overall performance. The system is simulated and the outcomes for PLs are specified in the given Table III. The system requires approximately 5 batteries per year and 46 numbers in total for the life span of the stated duration. A cost of 736$ is to be paid if a battery-alone mode is utilized for the designed system [23].

### FIGURE 6: (a) 2C-rate constant load, (b) 2C-rate pulsed load

### FIGURE 7: (a) 4C-rate constant load, (b) 4C-rate pulsed load

### TABLE III: BATTERY STAND-ALONE MODE SPECIFICATIONS

| Parameters                  | Value | Unit | Parameters                  | Value | Unit |
|-----------------------------|-------|------|-----------------------------|-------|------|
| Battery voltage             | 12    | V    | Battery capacity            | 7.2   | A h  |
| Voltage variation           | ±10   | %    | Battery DoD                 | 100   | %    |
| Battery type                | Lead Acid | --   |                             |       |      |
| Required Attributes         |       |      |                             |       |      |
| Batteries/year              | 5     | Nos. | Total batteries            | 46    | Nos. |
| Cost/battery                | 16    | $    | Total cost                  | 736   | $    |
A. UC STAND-ALONE MODE

If the same load of 42 kJ of energy specified in battery-alone mode is driven by the UC only, a 630 F capacitance is required. This capacitance would involve 45 numbers of cells of 350 F capacity. We calculated that 720$ is to be paid if a UC-alone system is used in the designed system. This mode is off-the-board because of its unreasonably higher cost than the battery-alone system.

The required attributes can be observed in Table IV. The system performance is good for high power load due to UCs' high-power density, but it is not suitable for long time energy requirements. The other problem is the linear voltage drop of the UC. It can’t maintain a required voltage across the load after some period. The energy stored in the UC is proportional to the square of its terminal voltage. As the energy drawn from the UC is increased, the voltage drop becomes faster. Therefore, some of the cells/modules become useless due to excessive voltage drops.

| TABLE IV: UC STAND-ALONE MODE SPECIFICATIONS |
|-----------------------------------------------|
| Parameters | Value | Unit | Parameters | Value | Unit |
| UC initial voltage | 13.5 | V | Voltage variation | 50 | % |
| UC final voltage | 6.75 | V | Voltage/cell | 2.7 | V |
| Capacitance/Cell | 350 | F | Manufacturer | Maxwell Series |
| Required Attributes |
| Total capacitance | 630 | F | Total UC cells | 45 | Nos. |
| Cells in series | 5 | Nos. | Cells in parallel | 9 | Nos. |
| Cost/UC cell | 16 | $ | Total cost | 720 | $ |

B. BATTERY-UC HYBRID MODE

The equivalent system described in the previous section is planned for battery-UC HESS. The objective is to extract a constant power from the battery so that the PL could not affect its performance. Therefore, the battery power delivering capacity is limited to a constant rate of \( P_{\text{MIN}} \) which can be observed in Fig. 8 (b). The battery is supplying a constant power of 50 watts \( (P_{\text{MIN}}) \) out of 130 watts \( (P_{\text{MAX}}) \) irrespective of the pulsed load and the remaining 80 watts including pulses are provided by the UC which is given in Fig. 8 (a). A little bit of a jerk is observed when the power transition takes place from \( P_{\text{MAX}} \) to \( P_{\text{MIN}} \) or vice versa.

The specifications of the designed components required for a battery-UC HESS have described in Table V. The system is more efficient than battery-alone mode as the total batteries are reduced to 5 from 46. The total capacitance is reduced to 180 F as compared to 630 F in UC-alone mode reducing the cost to 320$. The cost comparison shows that the HESS cost is reduced to 55% as compared to the battery-alone and the UC-alone mode. The improvement in battery life is approximately 50%.

The Simulink results for the output voltage show that the output voltage reaches up to 16.1 V which can be observed in Fig. 9. The ripples are a mere 0.1 V which is only < 1% of the output voltage at the settling time of 65 milliseconds. HESS performance is observed under 33% DT, 50% DT, and, 75% DT of the variation in load shown in Fig. 10. The system is capable of supplying the load with different pulsed loads. Any change in the load within the limitations is acceptable for the battery and UC but the load exceeding the limits is not served.

| TABLE V: HESS DESIGN PARAMETERS |
|---------------------------------|
| UC Required Attributes |
| Total Capacitance | 180 | F | Total UC cells | 15 | Nos. |
| Cells in Series | 5 | Nos. | Cells in parallel | 3 | Nos. |
| Cost/UC cell | 16 | $ | Total cost | 240 | $ |
| Batteries/Year | 0.5 No.s. | Total batteries | 5 No.s. |  
|---------------|---------|----------------|-------|
| Battery DoD   | 40 %    | Total cost     | 80 $  |

**Common Attributes**

| DC-link voltage | 16 V | Settling time | 65 ms |
|-----------------|------|---------------|-------|
| Ripple voltage  | < 1 %| Total ESDs cost | 320 $ |

**i. HESS under 2C-rate Load**

The performance of HESS under 2C-rate pulsed load is analyzed and presented in Fig. 11. The system is pushed to its discharge limits. The battery DoD is limited to 40% and UC voltage DoD to 50%. It can be observed that the UC is supplying the pulsed load and the battery is providing an almost constant part of the load. When the lower limit of the UC voltage is reached at 460 s, the system shuts down the BDC and the load is shifted to the battery.

**ii. HESS under 4C-rate Load**

The performance of HESS under 4C-rate pulsed load is analyzed and presented in Fig. 12. The battery DoD is limited to 40% and UC voltage DoD to 50%. It can be seen that the UC is supplying the pulsed load and the battery is providing an almost constant part of the load. When the lower limit of the UC voltage is reached at 460 s, the system shuts down the BDC and the load is shifted to the battery. It can be observed that the HESS is capable of supplying power to a 4C-rate load contrary to the battery-alone mode which shuts down the system due to low power density.

**iii. HESS under Electric Vehicle Load**

HESS performance for an electric vehicle is also tested and compared with that of the battery-alone mode. Its Simulink results are shown in Fig. 13 with the following observations.

1) As previously stated, the battery discharging current is limited hence the HESS battery's peak current is significantly reduced when compared to the battery-only mode. The maximum discharge and discharge current of the battery in the HESS is limited to 10 A which reduces the stress on the battery due to high current pulses as compared to battery-alone mode. The battery cycle life is significantly enhanced by taking advantage of the reduced peak current.

2) When compared to the battery-alone mode, the HESS battery voltage has a more stable performance. It can be observed from Fig. 13(a) that the voltage drop is more in battery-alone mode than HESS during acceleration. Moreover, due to the enormous power demand from the battery-alone mode, the cell voltage balance problem is still a challenge for actual battery management systems.

3) The UC successfully delivers peak currents and provides a fast reaction for high-frequency current variation as shown in Fig. 13(c). Furthermore, the UC's voltage is always kept within a safe fluctuation range. As a result, the UC always has enough space to absorb regenerative braking energy from the vehicle while meeting the acceleration demand.

4) It is obvious that the higher energy consumption of the driving cycle leads to
larger battery size. Combining a battery with a UC pack reduces the battery's energy capacity significantly.

C. BATTERY SOC CONTROL PROGRAM TEST

DoD of the battery is restricted to approximately 20% to test the program. When the SoC of the battery reaches its lower cutoff limit the control program shuts down the converter and the current drawn from the battery goes to zero as shown in Fig. 14. When the battery’s current becomes zero at a time of 6.5 seconds, the load is shifted to UC as in Fig. 14 (c). A small abrupt jerk is observed, but the system regains its originality in a settling time of just 65 ms and starts a smooth run. The system makes available the mandatory power to the load from UC while shutting down the BDC_Batt.

D. UC Voltage Control Program Test

The UC is supplying pulsed power to the load and the battery is supplying constant power to the load. V_{UC} is restricted to its reference lower limit of 10.3 V to test the program. When the V_{UC} reaches its lower limit, the control program shuts down the BDC_{UC} and the current drawn from the UC goes to zero. The load is shifted to the battery which can be observed in Fig. 15. The battery is unable to run the load in an effective way when the BDC_{UC} shuts down. Any change in the load within the limitations is acceptable for the battery, but the load exceeding the limits is not served.

V. CONCLUSION

This work aimed at the development of a hybrid battery-ultracapacitor ESS suitable for PLs. The objective of designing the hybrid mode was to improve the battery life and to run the PLs by battery-UC HESS. To accomplish the task, a hybrid ESS is developed and performance is confirmed by the simulation results. The three main parameters which significantly cut the battery life are analyzed and controlled. The C-rate impact is reduced by limiting the battery power deliverance capability to a constant C-rate. The SoC is controlled by developing a MATLAB program that shuts down the power drawn from the battery when a lower pre-set limit on SoC is reached. The temperature impact due to PLs is diminished by transferring the pulses to the UC. Hence, the proposed HESS improves the battery service life and reduces 50% of its required capacity, which is otherwise necessary to withstand the pulsating power. The cost comparison signifies that the proposed system is 55% lower in cost as compared to its counterparts.
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