A New Hybrid Energy Storage System for Electric Vehicle Drive System

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ABSTRACT

In this paper, a new Hybrid Energy Storage System (HESS) for Electric Vehicle (EV) drive systems is proposed to increase their battery lifespan, with the potential to meet peak power demands without heavily straining the batteries. The developed feedback control circuit works as a controller to maintain the voltage of the Supercapacitor (SC) at a value higher than the battery voltage during the high acceleration periods of the driving cycle, creating a relatively constant load profile for the battery. The battery is not used to directly harvest energy from the regenerative braking, being, thus, isolated from frequent charges during high acceleration/deceleration periods, which increases its lifespan. The simulation results demonstrate HESS's effectiveness in significantly reducing battery discharge/charge rates compared to a standalone system.

Keywords—battery; control; DC/DC converters; electric vehicles; energy storage; hybrid electric vehicles; power electronics; propulsion systems; supercapacitors

I. INTRODUCTION

EVs are gaining major popularity because of the soaring greenhouse gas emissions, which may cause serious health problems to the population as well as severe climate changes, all of which inevitably need to be solved [1]. The transportation industry is responsible for almost a third of the total emissions of carbon dioxide (CO_2), with over 70% of them being ascribed to vehicle transportation [2]. Compared to Internal Combustion Engine (ICE) vehicles, EVs are the most suitable solution in the transport sector for the zero-emissions objective to be achieved, while they also comply with modern world pollution demands [3]. However, EVs exhibit significant energy storage-related challenges, such as driving distance, battery expenses, charging period, volume, and weight [4], which have led to the adoption of HESSs that incorporate batteries and SCs for EVs, as well as other electric propulsion (transport) applications. Some of the most widespread objectives of HESSs are the regenerative-breaking recovery and the response to the acceleration performance and capability requirements of driving cycles [5, 6]. Equally important goals are energy loss mitigation as well as the enhancement of battery life, system efficiency, and dynamic performance. In parallel, weight, volume, and price are taken into consideration when choosing to develop an optimal energy management strategy in HESSs for EVs [7]. An EV's production process leads to significantly increased energy demand and greenhouse gas emissions compared to that of an ICE vehicle although it has a significantly lower overall environmental impact during operation. Therefore, EVs should be used as long as possible to minimize the harmful effects of the production process on the environment [8]. Other Energy Storage Systems (ESSs) are incapable of delivering all the features required by EVs to perform at the highest standards. To optimize features, such as power density, energy density, discharge rate, life cycle, and cost, HESSs combine two ESSs that have complementary characteristics, and as a result, ensure the best possible ESS performance [9].

HESSs can be configurated according to passive, semi-active, and active topologies, based on the energy demand and the configuration of the DC-DC converters. In the passive configuration, the ESS is linked to the load in parallel with no power control circuits involved, while for the semi-active hybrid, a single DC-DC converter is employed. In active hybrids, two DC-DC converters are used for the circuitry configuration [10]. In addition, regarding the Energy Management System (EMS), there are two types of strategies to be followed [11]. The first one is the online strategy, entailing the rule-based control strategy, the fuzzy logic control strategy, the model predictive strategy, and the filtration-based strategy. It is also known as the all or nothing control strategy and is simple to be implemented in real-world applications. Since this online approach is frequently developed empirically, it is unable to reach global optimization performance. The second type is the off-line strategy (Pontryagin's minimum principle, the dynamic programming approach), which can accomplish globally optimal performance. However, due to its high computing cost, it is challenging for it to be used in practical applications [12].

II. HYBRID ENERGY STORAGE SYSTEM

The dual-source HESS can overcome the drawbacks of deploying a solitary energy source by combining two energy sources in the vehicle's electric propulsion system [13]. HESS adoption presents several benefits, such as lengthening of system and storage life, cost and volume savings compared to using a single storage system, and an improvement in overall system effectiveness [14]. It often integrates high-energy and high-power storage components, with an overall improvement in power density and energy density being the main benefit of such hybrid systems [15, 16]. There are numerous additional potential energy storage configurations based on SMES, CAES, or flywheel [17], which manage solar and wind energy on a large scale [18, 19]. Also, there are microgrid systems, where local loads are powered by distributed power supplies, storage devices, controllable loads, and power-conditioning equipment [20, 21]. In the literature, several dual source combinations can be found, including battery and SC, battery and magnetic energy storage, battery and flywheel, battery and hydraulic accumulators, battery and fuel cell, SC and fuel cell, compressed air energy storage and battery, compressed air energy storage and fuel cell, etc. [22]. Most research is conducted on the combined usage of battery and SC storage to improve HESS overall performance, even if other configurations also offer certain distinctive advantages [19]. Thus, in the battery–SC combination, the components can make use of each other's complementing qualities. Due to its similar operating concept, wide availability, and affordable initial cost, this combination has gained popularity [19, 23]. Regarding converters, four varieties are available, including rectifiers, inverters, AC-AC converters, and DC-DC converters. The distribution of power among diverse power sources is coordinated using appropriate EMSs and topologies for HESSs. Additionally, by properly distributing output power throughout the system, these methods improve system economy and efficiency while extending HESS lifespan [24]. HESS can either be linked to the DC bus or the AC bus using a separate DC-AC converter. To utilize both and minimize their drawbacks, HESS is typically developed by connecting the SC and battery through a bidirectional DC-DC converter [25]. There are three types of interconnection topologies: passive, semi-active, and active. Based on the system requirements and the functions of the energy management system, a wide range of topologies can be chosen [25, 26].

In active HESS topologies, two bidirectional DC-DC power converters are used to connect the ESS elements to the DC bus and actively manage the flow of their power. The energy storage devices' voltage can be distinctive from the DC bus voltage due to DC-DC converters [26]. In EV applications, DC bus voltages must remain constant during the driving duration; therefore, a fully active topology is the primary option for these kinds of applications [27, 28]. A fully operational HESS can be deployed to implement the optimal control. However, this design compromises the efficiency, cost, and component size of the HESS. The former design is also more complex than a passive design [29]. There are two types of active topologies: parallel and series [30, 31].

III. PROPOSED HYBRID ENERGY STORAGE SYSTEM METHODOLOGY

The major cost component in EVs is the battery pack. From an economic point of view, it is necessary to increase the life span of battery packs which deteriorates due to various reasons, with the most common being the abnormal increase in temperature. When the EV motor is subjected to rapid acceleration the batteries will undergo a substantial increase in chemical reactions and the temperature will rise. To avoid the latter, batteries should not be subjected to a sudden increase in current. To overcome this, the SC is used in conjunction with the Battery pack to meet sudden inrush current demand. SC has a high power density and low energy density. Therefore, it can supply and absorb peak currents, increase the vehicle's overall efficiency and the lifetime of batteries, and handle the power output from a regenerative braking system [32, 33]. Due to these advantages, an SC/battery HES for EVs is proposed and analyzed in the current study. The overall block diagram of the proposed model is shown in Figure 1.

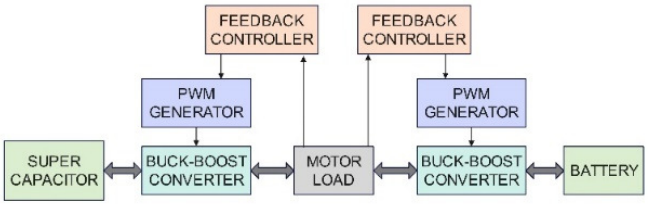

Fig. 1. Block diagram of the proposed HESS.

A. Battery Modeling

In recent decades, the popularity of Li-ion batteries has led to wide research on battery modeling. In this paper, the Equivalent Circuit Model (ECM) is applied in the HESS plant model. The considered battery model-block diagram of the subsystems which implements a generic Li-ion battery model within the MATLAB Simulink is shown in Figure 1.

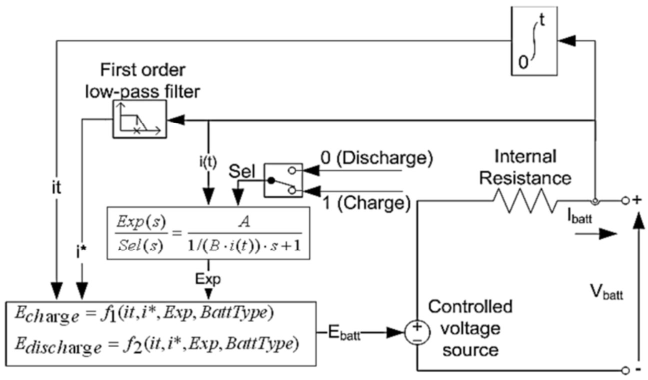

Fig. 2. Battery model-block diagram.

The aforementioned battery model uses the discharge and charge models of (1) and (2), respectively:

$$(i^* > 0) = f1(it, i^*, i) = E_0 - K\left[\frac{Q}{Q-it}\right] i^* - K\left[\frac{Q}{Q-it}\right] it + A.\exp(-B.it) \quad (1)$$

$$(i^* < 0) = f2(it, i^*, i) = E_0 - K\left[\frac{Q}{it+0.1Q}\right] i^* - K\left[\frac{Q}{Q-it}\right] it + A.\exp(-B.it) \quad (2)$$

where E_{Batt} (V) is the nonlinear voltage, E_0 (V) is the constant voltage, Exp(s) (V) is the exponential zone dynamics, in V, Sel(s) represents the battery mode, with Sel(s) = 0 during battery discharging and Sel(s) = 1 during battery charging, K (V/Ah) is the polarization constant, or polarization resistance (Ω), i* (A) is the low-frequency current dynamics, i (A) is the battery current, it (Ah) is the extracted capacity, Q (Ah) is the maximum battery capacity, A (V) is the exponential voltage, and B (Ah^{-1}) is the exponential capacity.

The parameterization of Li-ion cell models is a complex task, especially for electrochemical models. Owing to their complexity, Li-ion cell models are governed by partial differential equation sets. The proposed model uses the parameters obtained at a constant temperature, assuming that the temperature impact is neglected.

B. Supercapacitor (SC)

The SC model block diagram of subsystems within the MATLAB Simulink, which implements a generic model parameterized to represent the most popular types of SCs is shown in Figure 3:

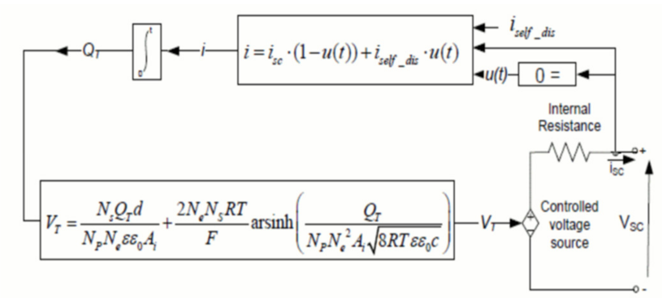

Fig. 3. SC model-block diagram.

The SC output voltage is expressed using a Stern equation:

$$V_{sc} = \frac{N_s Q_r d}{N_p N_e \varepsilon \varepsilon_0 A_i} + \frac{2N_e N_s RT}{F} \sin h^{-1}\left(\frac{Q_T}{N_p N_e^2 A_i \sqrt{8RT\varepsilon\varepsilon_0 C}}\right) - R_{sc} \cdot i_{sc} \quad (3)$$

with:

$$Q_r = \int i_{sc}\, dt$$

To represent the self-discharge phenomenon, the SC electric charge is modified to (4) when $i_{sc} = 0$:

$$Q_r = \int i_{self\_dis}\, dt \quad (4)$$

where:

$$i_{self\_dis} = \begin{cases} \frac{C_r a_1}{1+sR_{sc}C_r} \text{ if } t - t_{oc} \le t_3 \\ \frac{C_r a_2}{1+sR_{sc}C_r} \text{ if } t_3 < t - t_{oc} \le t_4 \\ \frac{C_r a_3}{1+sR_{sc}C_r} \text{ if } t - t_{oc} \ge t_4 \end{cases}$$

The constants α_1, α_2, and α_3 are the rates of change of the SC voltage during time intervals (t_{oc}, t_3), (t_3, t_4), and (t_4, t_5), respectively.

C. Bidirectional DC/DC Buck-Boost Converter

A bidirectional half-bridge DC-DC buck-boost converter employs two switches to facilitate both buck and boost operations [34]. The switches operate in a complementary fashion, ensuring that only one is active at a given time. A non-isolated bidirectional DC-DC buck-boost converter was designed and modeled in MATLAB/Simulink. The DC-DC converter encompasses internal resistance R=0.0001 Ω, inductance L=8 mH, capacitor C=0.0047 F, and two MOSFET switches, S1 and S2. This configuration enables bidirectional power flow. The converter operates in two distinct modes, as seen in Figure 4.

IV. MATLAB MODELING

A. Standalone Battery connected to Load through Bidirectional DC/DC Buck-Boost Converter

Initially, a MATLAB/Simulink model of a bidirectional DC/DC buck-boost converter, delivering energy to load using only the battery, is developed. During the next step, a MATLAB/Simulink model of a bidirectional DC/DC buck-boost converter, delivering energy by employing the proposed HESS is built. Then, the results obtained from the aforementioned two circuit models are compared. The MATLAB/SIMULINK model of a Standalone Battery connected to load through a bidirectional DC/DC buck-boost converter is illustrated in Figure 5. Here, a fictitious load having step responses is considered instead of the actual motor. The considered fictitious load consists of a summation of various step responses and is shown in Figure 4.

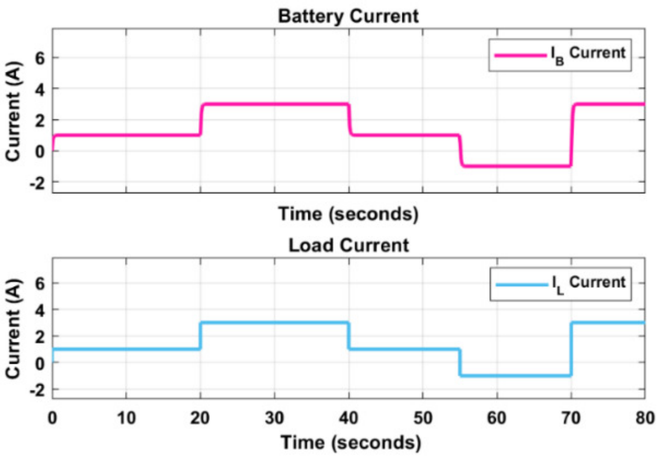

Fig. 4. Waveforms of battery current and load current.

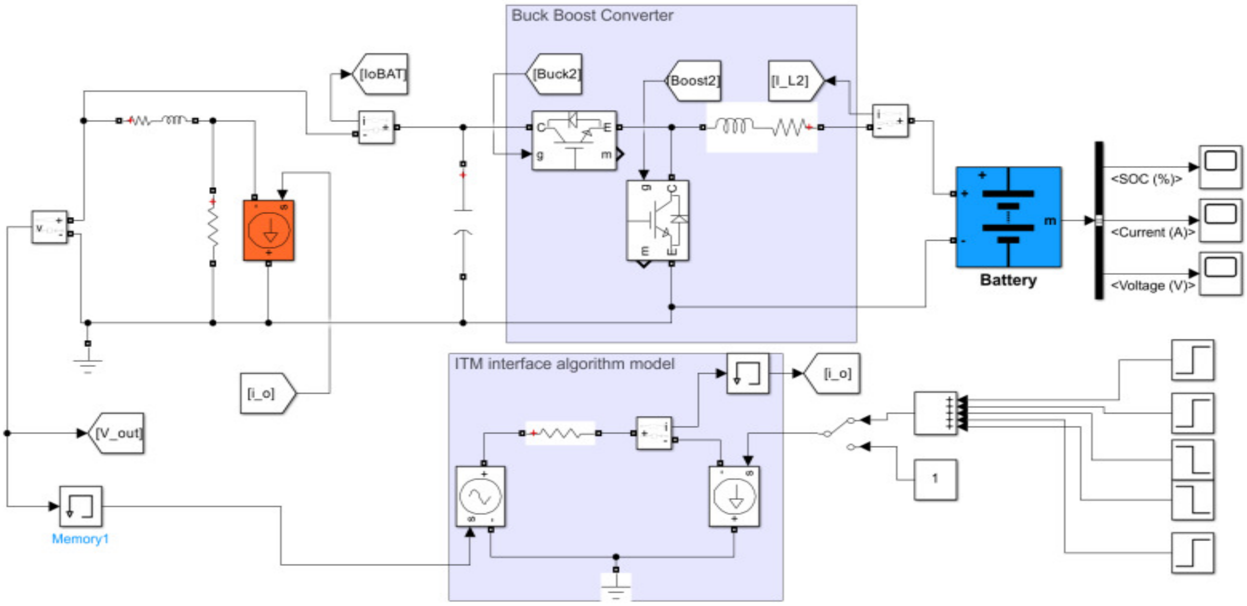

Fig. 5. MATLAB/SIMULINK model of standalone battery.

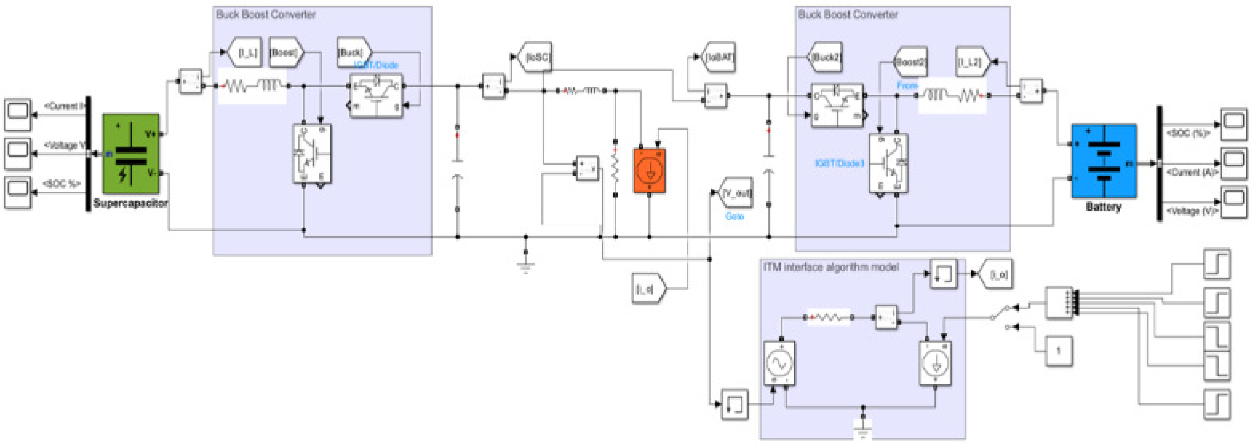

Fig. 6. MATLAB/SIMULINK model of battery in conjunction with the SC.

The Ideal Transformer Method (ITM) is also presented in the simulation model, and is used for impedance matching purposes when interfacing the software with hardware equipment. Upon simulating the Simulink model, depicted in Figure 4, the battery discharge current is like that of the load current and is demonstrated in Figure 4. In this model, as the battery discharge current demand rises steeply, the battery is subjected to an enormous rise in chemical reactions, which leads to an exponential rise in temperature, resulting in an increase in battery deterioration, thereby reducing battery life. The proposed HESS model of Figure 6 aims to overcome these battery current alterations, despite the steep current demand from the motors.

B. Battery in Conjunction with SC Connected to Load through a Bidirectional DC/DC Buck-Boost Converter

The MATLAB/SIMULINK model of the Battery in conjunction with an SC connected to the load through a bidirectional DC/DC buck-boost converter is exhibited in Figure 6. In this model, the same fictitious load is the sum of step responses, as evidenced in Figure 4. The SC is added to the Simulink model. The battery and the SC are the considered energy sources, and their internal block diagrams are manifested in Figures 2 and 3, respectively.

The two energy sources, battery and SC, are connected to load through an individual bidirectional DC/DC Buck-Boost converter. The pulses to the Buck-Boost converter are given in such a way that, the duty cycle of the SC is added to the battery when there is a sudden demand of current from the motor. This results in greater current from the SC during high acceleration periods. When the rate of change in the current demanded by the motor is less, then the duty cycle of the battery is set to high, and the SC suitably adjusts the PWM pulses to the Buck-Boost converter. The block diagram of a feedback control circuit for the generation of PWM pulses to the Buck-Boost Converter associated with the SC and the battery is illustrated in Figure 7. The output current of the SC is converted to a voltage signal, which is compared to the reference voltage signal, and an error is generated. This error signal along with V_{out} is compared to the V_{out} and then sent to Voltage Control with Saturation Feedback (VCSF). The output of VCSF is subsequently compared to the load current and sent to Current Control with Saturation Feedback (CCSF).

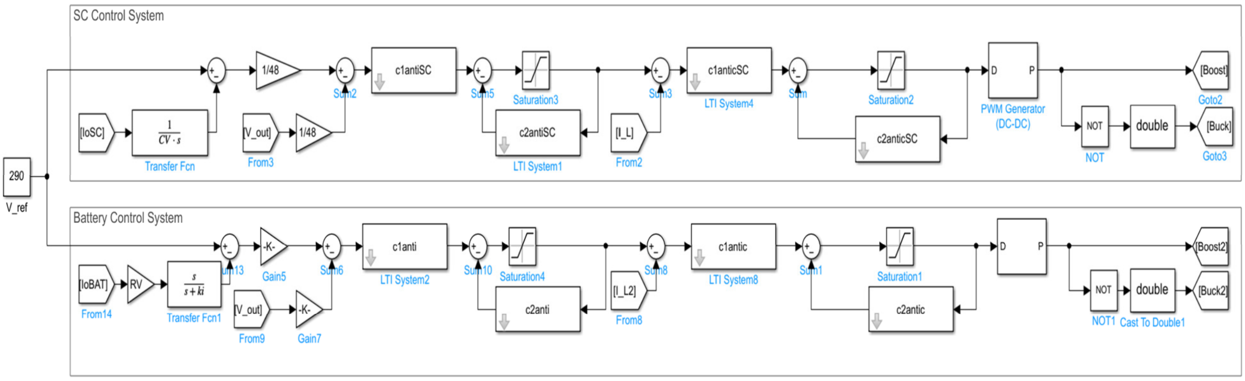

Fig. 7. MATLAB/SIMULINK block diagram of the feedback control circuit.

After that, the output of the CCSF is given to the PWM generator and subsequently to the Buck-Boost Converter, as outlined in Figure 7. A similar type of control circuit is used for the generation of PWM pulses to the Buck-Boost converter associated with the battery. Upon simulating the model shown in Figure 6, it is observed that the rate of discharge current from the battery is decreased, as outlined in Figure 8, for the same output load current when compared to the Simulink model. When the battery current waveforms with and without the SC are compared, as depicted in Figure 9, for from 19.9 to 21.4 s, it is obvious that the battery discharge current rate is significantly reduced with the proposed HESS. The former has been reduced from 11 to 1.39 A/s. This reduction is achieved using the transfer function model-based feedback control circuit.

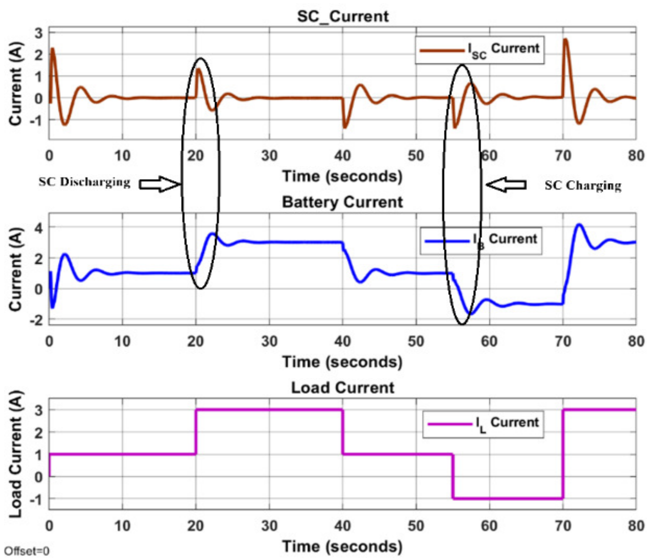

Fig. 8. Waveforms of SC current, battery current and load current.

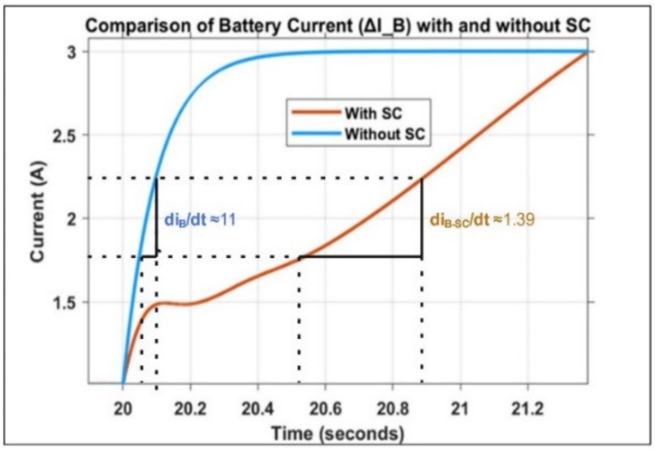

Fig. 9. Comparison of battery current waveforms with and without SC.

V. CONCLUSIONS

This paper investigates the behavior of battery packs and supercapacitors (SCs) during high discharge rates for connected Ideal Transformer Method (ITM) loads. Many configurations of Hybrid Energy Storage System (HESS) have been introduced in the literature. The proposed HESS utilizes a transfer function model-based feedback control circuit to predict the rise in the battery current and provide a duty cycle for the respective bidirectional DC/DC buck-boost converter. A MATLAB simulation comparison of battery current drawn in two circuit configurations was conducted. The first circuit uses a standalone battery as the energy source, while the second incorporates a battery and an SC. As illustrated in Figure 9, the rate of the battery discharge current is substantially reduced by integrating the SC, from 11 to 1.39 A/s. This reduction is achieved by deploying the proposed transfer function model-based feedback control circuit. The integration of the proposed HESS in an Electric Vehicle (EV) system increases the lifespan of the battery pack due to the substantial reduction in the rate of discharge current.

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