A Modular Multi-Level Converter for Energy Management of Hybrid Storage System in Electric Vehicles

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Abstract - **This paper presents a novel energy management system (EMS) that for hybrid energy storage devices in Electric Vehicles (EVs). The use of ultra-capacitors as the power pulsating storage device in EVs mitigates the inefficiencies associated with the slow power dynamics of battery cells. Thus, Li-ion batteries can only supply the EV average power due to their high energy density characteristics. Such a hybrid system leads to challenging tasks in managing the energy between the individual battery and UC cells. Additionally, accounting for the motor loading conditions and extending the maximum torque per ampere operation is desirable for an EV drive powertrain. Thus, a modular multi-converter is configured to manage the energy between the different storage cells for an EV application. Furthermore, the use of MMCs eliminates the need for a system-level drive inverter feeding the EV motor. The presented results verify the proposed configuration effectiveness.**

Index Terms* – *Energy management, Battery management, DC-DC Converter, Electric Vehicles, Flux Weakening, Hybrid energy storage, Maximum torque per ampere operation, Multi-level modular converter.

I. Introduction

Batteries are the key enabling devices that facilitate our reliance on sustainable energy solutions. In high voltage applications, battery packs are composed of a large number of cells connected in series, which entail higher risks in terms of reliability and safety. Depending on the cell chemistry, there are thermal and voltage constraints that need to be accounted for during the design of battery modules. Moreover, factors such as the self-discharge rates and the internal impedances of the battery cells may vary from one cell to another due to manufacturing imperfections. In such a scenario, overcharging of battery cells can cause system failures while deep discharging can cause heating issues that deteriorate the battery life span [1]. Thus, a battery management system (BMS) is necessary to maintain the battery charging/discharging rates within the desirable operating limits. Additionally, a well-designed BMS extracts that the maximum available power from the connected battery cells at different operating conditions.

The usage of battery as the sole storage device in an electric vehicle (EV) limits the system power density due to the low pulsating power of Li-ion batteries. The power density of the storage system determines the acceleration and regenerative braking limits of the EV. The relatively low power density of a fully battery based system can be mitigated by integrating ultra-capacitors (UCs) with battery cells. Employing such hybrid energy storage system (HESS) can vastly improve the efficiency of power processing during the rapidly changing drive profiles of an EV [2-3].

The sensitive operation of the HESS necessitates a charge equalization mechanism as part of the EVs' energy management system (EMS). Numerous schemes were put forward [4-8] but their implementation is limited to either battery cells or UC cells. The modularity of the system is predicated on the choice of DC-DC converters that feature low power losses and easy scaling. Modular systems with cascaded cells and interfacing converters were shown in different configurations with promising results [9-11]. Besides modularity, these systems have the added advantage of reduced control complexity.

In this paper, the authors propose a modular multilevel converter (MMC) architecture with cascaded battery and UC cells to enhance the power processing capabilities of conventional EV battery packs. The stress on battery cells is reduced by throttling the high C-rate current drawn from the battery cells. Instead, the UCs are used for supplying peak power during traction or regenerating power during braking. Consequently, the energy density of battery cells can be leveraged for long-term power processing, and the power density of UCs is utilized for pulsated power processing. The need for a system-level drive inverter is eliminated with the proposed HESS configuration. The control strategy for the proposed HESS is deployed in accordance with the power requirements set by the EV motor. Many IPM motor applications rely on maximum-torque-per-ampere (MTPA) control for producing the desired torque from minimized current magnitudes. In the proposed configuration, the MMCs are controlled to extend the MTPA operation for increased system efficiency. Moreover, reduced number of switches are used in every operational mode if compared to conventional MMC configurations.

The novel configuration of the MMC based HESS is presented in Section II, while the system structure is illustrated in Section III. Section IV delineates the system's core energy management functions and the verification results are collated in Section V.

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II. Proposed System

The system framework of the proposed hybrid system for EVs is shown in Fig. 1. The high voltage battery is made up of low voltage sub-modules that store and supply energy to the EV motor. Within each sub-module, UCs cascade with battery cells via DC-DC converters enabling both series and parallel configurations of the energy cells. The modular multi-level H-bridge inverter $(S_1 - S_4)$ is used at the output of each sub-module and the modular multi-level half-bridge converter $(S_5 - S_6)$ is chosen for cascading the energy cells (Fig. 1). These converters belong to a class of Modular Multi-Level Converters (MMCs) that can operate with a high efficiency over a wide range of switching frequency thus resulting in low power losses [12]. Each sub-module is essentially a hybrid converter structure that combines different MMCs. The proposed system is developed to extend the MTPA operation, thus, a series connection of the UC with the battery is allowed. Consequently, two back-to-back switches $(S_7 - S_8)$ are placed along the alternate discharge path of the battery cell to prevent unanticipated charge sharing between the energy cells due to leakage current or SOC imbalance. However, if the proposed system is to be developed for regular power modes without accounting for MTPA control conditions, then S_8 can be excluded from the converter structure.

The UC is always maintained at a voltage level lower than the nominal voltage of the battery cell. This is set as a prior constraint in order to account, in advance, for low voltage levels required during peak power fluctuations. Additionally, maintaining the UC voltage less than the battery cell voltage prevents mutual charge sharing since the anti-parallel diode of S_6 tends to form a parallel conduction path between the UC and battery cell. The UC is placed close to the H-bridge output to minimize conduction losses while supplying peak power during traction or accepting power during regeneration. For n sub-modules, there are n battery cells, n UCs, and $8n$ switches. The corresponding control strategy is developed in such a way that minimum number of converter switches are used for a given voltage level.

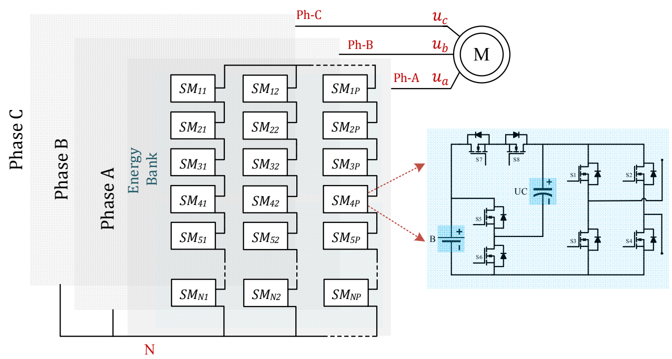

Figure 1: Novel Hybrid Storage System for Electric Vehicles

Moreover, the simple structure of sub-module converter allows easy scaling of the HESS depending on the application requirement while establishing absolute control over the power contributions of each energy cell. The signals reaching the motor from the HESS are alternating waveforms that do not require any other form of inversion. This eliminates the need for a system-level drive inverter present in conventional motor drives sized to invert high voltage DC signals. The three-phase connections in the main system framework carry three-phase alternating voltage and current waveforms to feed the motor. For higher current discharge, more parallel sub-module strings can be added for each phase. Sizing of the HESS is done based on the maximum, average and minimum power demands of the EV motor.

III. Converter Control Strategy

The DC energy source(s) of each sub-module is fixed with a multi-level H-bridge inverter at the sub-module output that performs DC-AC conversion. There are three alternatives for the DC source of a sub-module: battery only, UC only, battery and UC. The corresponding conduction paths of the three modes are featured in Fig. 2.

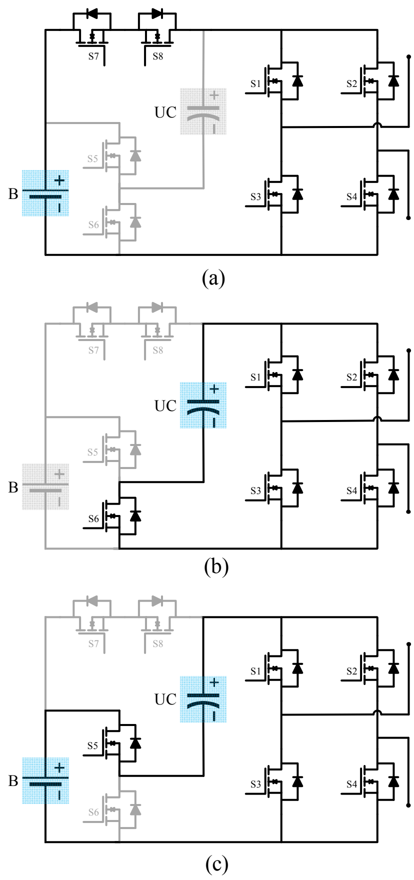

Figure 2: Conduction Modes: (a) Battery only (b) UC only (c) Battery + UC

The modularity of these units coupled with easy switching control make their use appropriate in high voltage drive applications that demand variable speed and consequently variable power. During regular speeding conditions when the power demand ranges from average to low, the current is drawn from the battery cells while bypassing the UCs (Fig. 2(a)). During peak power fluctuations that occur at high speeds, the low voltage UCs are connected to the output inverter while bypassing battery cells (Fig. 2(b)). For speeds above the nominal motor speed, high voltage levels are to be maintained in order to keep the motor operating at maximum-torque-per-ampere (MTPA). This is achieved by connecting both the battery cell and UC in series to serve as the DC source to the H-bridge inverter (Fig. 2(c)).

Table 1: Sub-module Converters Switching States

Source : Mode	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*Output*
Battery : Low/Average Power	1	0	0	1	0	0	1	1	+Vdc
	1	1	0	0	0	0	1	1	0
	0	1	1	0	0	0	1	1	-Vdc
UC : High Power	1	0	0	1	0	1	0	0	+Vdc
	1	1	0	0	0	1	0	0	0
	0	1	1	0	0	1	0	0	-Vdc
Battery + UC : Maximum Torque Per Ampere	1	0	0	1	1	0	0	0	+Vdc
	1	1	0	0	1	0	0	0	0
	0	1	1	0	1	0	0	0	-Vdc

The switching states of the sub-module converters are detailed in Table I with respect to Fig. 2. Analysis of the switch conduction losses reveal the efficiency merits of the proposed converter design. For a given voltage level, 4 switches are conducting in the battery only mode, and only 3 switches are conducting in UC only and combined energy cell modes. Consequently, the minimum number of switches used per module reduces the conduction losses associated with high power transfer in the UC only mode. This design merit extends to the combined battery cell and UC mode as well. In a conventional hybrid system, that has a single battery or UC for each H-bridge module, a minimum of 4 switches have to conduct to establish a series path between two modules in order to obtain increased voltage levels. In the proposed converter design, only 3 switches are conducting when the battery and UC are in series (Fig. 3). A significant reduction in sub-module conduction loss by approximately 25% is observed during MTPA operation, thereby, improving the system level efficiency. The switching states remain the same during discharging, charging and regeneration cycles signifying low complexity in control. Moreover, if any of the sub-modules have sources with extremely low levels of charge, the bypass modes are activated to remove those modules from the main conduction path. There are multiple switch combinations by which the 0Vdc bypass mode can be activated although Table I enlists one of them.

Once the sub-module DC source is selected based on the mode of operation, the H-bridge inverters are switched using a pulse width modulation (PWM) scheme. A multi-carrier technique called Phase Disposition PWM (PDPWM) is chosen for switching the H-bridge inverters (Fig. 4). This method has been widely used for performing balancing and control of cascaded H-bridge inverter topologies [13]. High frequency carrier signals are stacked above and below the zero reference with 0° phase shift. To obtain p levels in the output waveform, p-1 carrier signals have to be used. The carrier signals are assigned to different sub-modules based on their SOC levels. Reference signals with appropriate parameters (amplitude, frequency and phase) for the three-phase waveforms are defined and passed though the stacked carrier signals. The reference voltage waveform can be generalized for the three phases as follows:

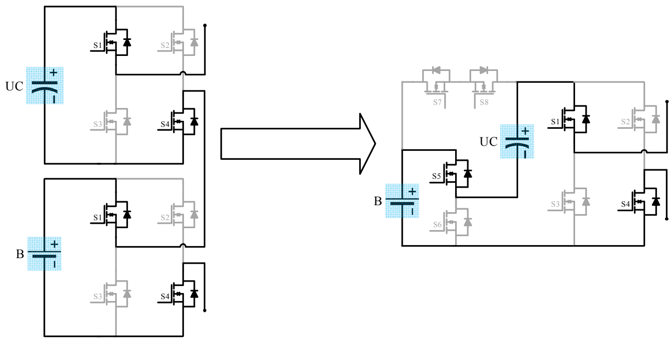

Figure 3: Comparison of conventional and novel converters for series-connected battery cell and UC

$$V_{ref} = A \times m \times \sin\left(\omega t - \varnothing\right) \tag{1}$$

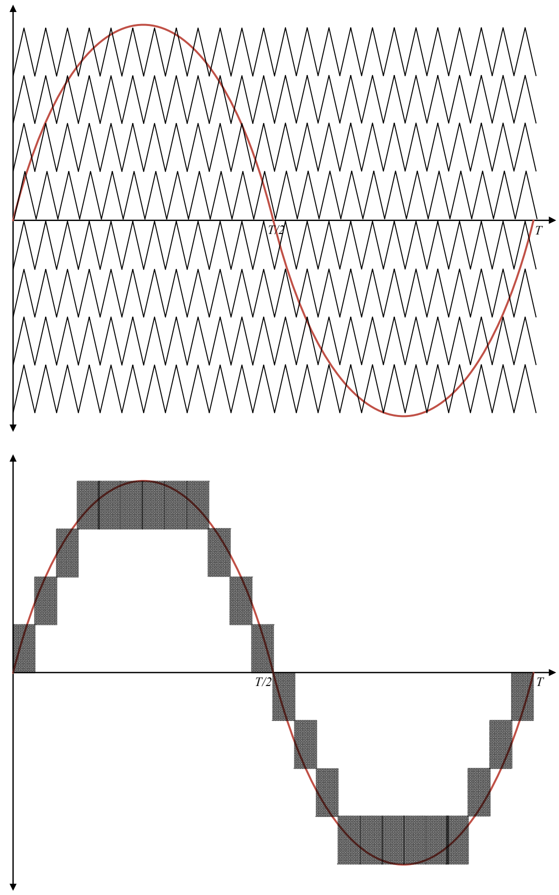

Figure 4: PWM Signals with Output Waveform

A is amplitude of the reference waveform that is set as the maximum of all the carrier signals. m is the modulation index that allows selective switching of sub-modules by proportioning the amplitude of the reference wave. The frequency of the reference wave, ω, is the required frequency of the output waveform. $\varnothing$ is phase shift in radians (0, 2π/3, 4π/3) to produce three-phase reference signals. Stair-shaped waveforms that are sinusoidal can be obtained from series connected versions of these sub-modules for each of the three phases. The waveform of a 9-level (8 non-zero levels and 1 zero level) voltage signal is demonstrated in Fig. 4.

IV. SOC Estimation and Balancing

The proposed HESS incorporates SOC estimation and charge balancing functions as the part of the EMS. Energy cell status is determined based on states of charge (SOC) because it can be generalized for any cell chemistry. Using high precision sensors, the coulomb counting method is sufficient in performing SOC estimations. The battery and UC cell SOCs are determined as follows:

$$SOC_B(t) = SOC_B(t-1) - \frac{I_B(t).T}{Q_{B\_Nom}} \quad (2)$$

$$SOC_{UC}(t) = \frac{V_{UC\_OC}(t)}{V_{UC\_Nom}} \quad (3)$$

Eqn. (2) and (3) represent the SOC of a battery cell and UC cell respectively. The cell SOC is estimated for discrete time steps of $t = kT$, where k is the discrete step and T is sampling time in seconds. I_B and Q_{B_Nom} are the battery current and nominal capacity respectively. V_{UC_OC} and V_{UC_Nom} are the ultra-capacitor open circuit voltage and nominal voltage respectively. The order of precedence of charging and discharging of the energy cells is set based on online estimation of SOC. For discharge, the sub-modules are ordered from highest to lowest based on SOC. The corresponding PWM signals are updated every half cycle of the modulation wave when there is no current flow in the circuit. This is done to reduce harmonic distortions during converter switching. Consequently, the cells with high SOC are discharged more than the cells with low SOC. The order of precedence is reversed during battery charging and regeneration, i.e., the cells with low SOC will have higher precedence and will be charged more than the cells with high SOC. The algorithm is generalized in Fig. 6.

V. Simulation Results

The proposed HESS structure and operation are verified for two and six sub-modules hybrid system. Simulations are performed for different modes of operation based on the power requirements of the EV motor. The main controller inputs include cell states of charge, bus current, instantaneous power demand, available battery power and available UC power. Discharging and charging (regeneration) cycles are identified based on these inputs. A threshold function that senses power fluctuation is configured that automatically switches the DC input of each sub-module during vehicle operation.

A. Five-level Voltage Waveform

The two sub-module system triggered by the PDPWM scheme produces a 5-level output waveform that draws current from different combinations of battery cells and UCs depending on the power mode.

<u>Battery only (Low/Average Power):</u>

During low and average power demands, current is drawn from the battery cells while the UCs are bypassed. The battery cells are initialized with 100% SOC and the switches along their discharge path are activated. This results in a 5-level alternating waveform with each cell contributing about 4V as shown in Fig. 6.

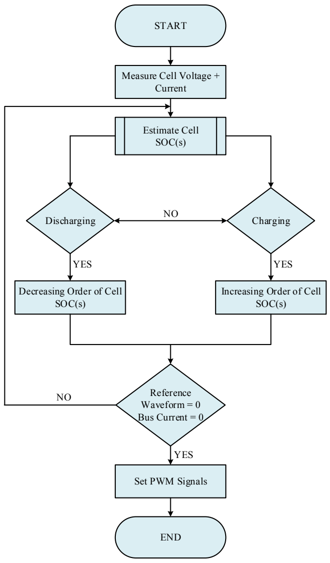

Figure 5: Cell SOC Estimation and Balancing Algorithm

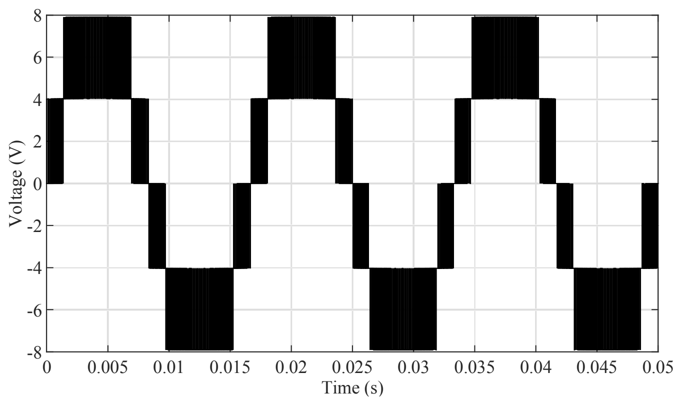

Figure 6: Five-level Voltage Waveform (Battery only)

<u>Ultra-capacitor only (High Power):</u>

During high power fluctuations, the battery cells are inactive and only the UC cells are discharging. The UC cells starts the cycle with 100% SOC and the switches along their discharge path are activated. This results in a 5-level alternating waveform with each cell contributing a voltage level of 3V as shown in Fig. 7.

<u>Battery and Ultra-capacitor (MTPA Extension):</u>

High voltage levels are required in order to maintain efficient motor operation under MTPA conditions. This is supplied by series-connected battery and UC within each sub-module with all the cells initialized at 100% SOC. The resulting 5-level alternating waveform consist of battery cells and UCs contributing about 4V and 3V respectively as shown in Fig. 8.

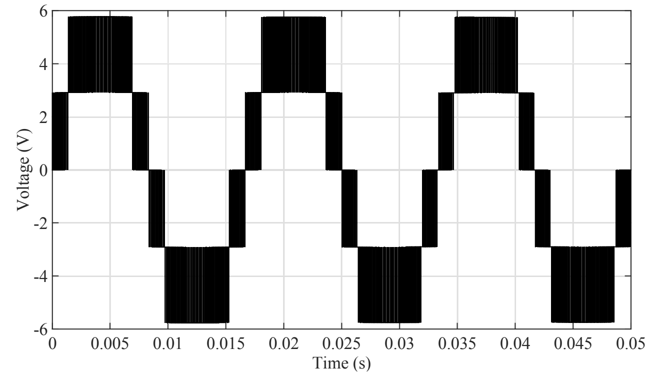

Figure 7: Five-level Voltage Waveform (UC only)

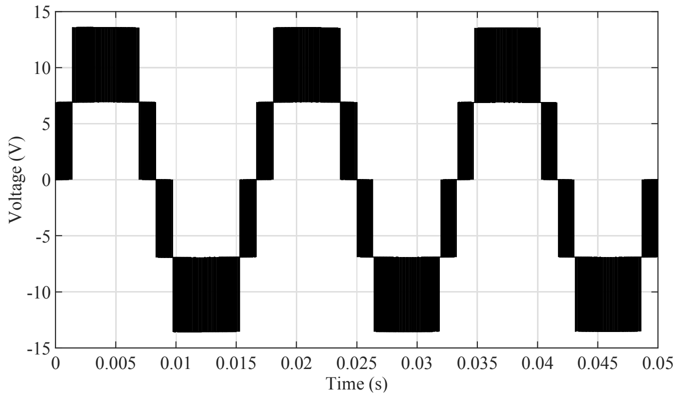

Figure 8: Five-level Voltage Waveform (Battery + UC)

B. *Three-Phase System*

In order to verify three-phase operation, the system is scaled up to include six sub-modules. The corresponding thirteen-level phase shifted waveforms can be used to power a three-phase EV motor (Fig. 9).

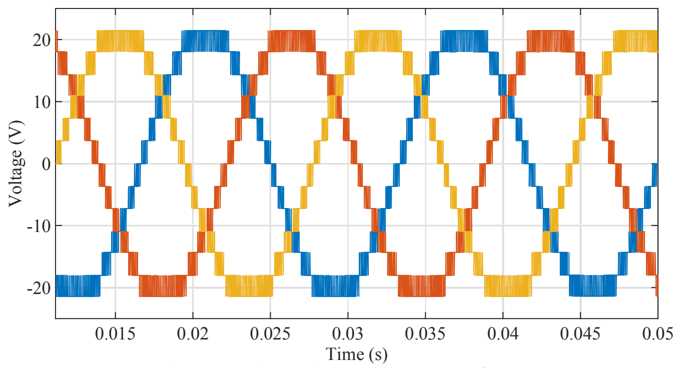

Figure 9: Three-Phase Voltage Waveform

C. *Energy balancing of six sub-modules*

The cell balancing action of the control scheme for six sub-modules is demonstrated in Fig. 5. The system is tested with UCs initialized at different SOCs and a diverse current profile that consist of high discharge and charge (regeneration) currents. Clearly, the cell with the high initial SOC discharges more than the cell with a lowest SOC. During regeneration, the low SOC cell charges faster and the cell SOCs converge in the advancing cycles of discharge. A similar behavior is exhibited by the battery cells during discharging and constant charging although the dynamics are slower and require long periods of simulation.

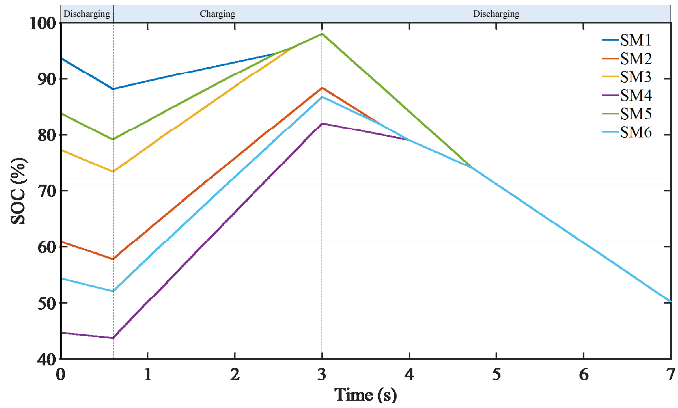

Figure 10: SOC Balancing of Six Sub-modules

V. CONCLUSION

The proposed HESS adopts a MMC based converter structure as to manage the energy between the battery and UC cells. Additionally, the proposed configuration eliminated the need for a system level inverter as the AC power signal is generated from the MMC modules. The system has the ability to switch between high power, high energy and MTPA extension modes seamlessly. The validation results prove that the system can cater to various power demands while ensuring that the energy cells are efficiently utilized. The simplicity of the novel converter structure can aid in the development of high voltage energy packs without compromising on power density. Moreover, the flexibility of control allows easy implementation of energy management functions, some of which are presented in this paper.

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