AN EFFECTIVE CONTROLLER DESIGN FOR SWITCHED CAPACITOR LUO CONVERTER USED IN HYBRID ELECTRIC VEHICLE APPLICATION

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Abstract: *In hybrid electric vehicle (HEV), power electronic interface and its control draws more attention towards better utilization of energy sources. To this purpose, an efficient hybrid switched-capacitor (SC) bidirectional DC–DC converter is designed and interfaced between the dual energy storage systems (ESS). A closed loop controller is designed to regulate the power flow and facilitate reverse power flow during regenerative braking. The performance of the converter is analysed with respect to power conversion efficiency, current ripple and robustness to operate in both quadrants. Simulation is carried out in MATLAB/SIMULINK environment to verify and validate the performance of the system in various operating modes.*

Key words: *Switched-capacitor bidirectional DC–DC converter; energy storage system; Hybrid electric vehicle; battery-ultracapacitor.*

1. Introduction

Hybrid electric vehicles (HEV) are expeditiously progressing as alternative power trains for green transportation to the need of reducing polluting emissions and fuel consumption of land transportation vehicles [1-2]. A hybrid electric vehicle combines one or more energy storage systems with supplementary operating characteristics to achieve load leveling or efficient power flow management results in hybrid energy storage system (HESS). In a HESS, one of the energy sources must be responsible to supply the high power demand, transients and the fast load fluctuations of the system characterized by fast response time, high efficiency and lifetime. Another energy source should be capable of supplying the high energy demand of the system characterized with low self-discharge rate [3]. Since HEV demands for high energy density for long run and high power density for acceleration and braking, the energy storage system should offer both. Conventionally, batteries and fuel cells are used [3-5] but recently, combined battery-ultracapacitor (UC) system has become potential candidates for energy storage system in HEV applications [6]. Battery together with ultracapacitor makes an excellent HESS for electric vehicle with high energy and power density, better acceleration performance, controlled regenerative braking and improves life time of battery by taking some stress off by sharing the load current [7-9]. A hybrid arrangement with a parallel combination of batteries and UCs, can significantly reduce the volume and weight of the overall HEV energy storage system [12].

There are different configurations to couple battery-ultracapacitor (UC) system. The simplest way is the passive configuration, which directly couples the storage units. The advantages include simplicity and low cost [10-11], while the drawback is inefficient utilization of the storage units. An active configuration regulates transfer of energy using power electronics interface. To this purpose, high efficiency converter topologies with effective control algorithms have been explored and continue to attract researchers [13-14]. An efficient bidirectional DC-DC converter (BDC) is necessary to interface the ultra-capacitor and battery combination to control the power flow [15]. Non-isolated topology is a suitable choice for high power application systems and systems having size and weight constraints [13-14]. But the most widely used converter is the bidirectional Buck/Boost DC-DC converter [15]. Due to its simple arrangement and few elements, this traditional converter is considered one of the most reliable bidirectional DC-DC converter. However this conventional DC-DC converter suffers from space constraint and has limitation with respect to gain [16].

Many approaches have been proposed to overcome these drawbacks of the buck-boost BDC. In order to increase the voltage conversion ratio, some attractive solution of coupled-inductor-based BDCs has been proposed [17]. In this aspect, a non-isolated bi-directional DC-DC switched capacitor Luo converter has also been preferred for high power HEV applications [18-19]. In addition, it has low electromagnetic interference (EMI), good regulation capability, ease of control , lower source current ripple, , and continuous input current waveform, in both buck and boost modes of operation, which are essential for HEV application [20-22]. In this perspective this work explores the suitability of an improved 4-Quadrant switched capacitor converter (SCC) for HEV applications and proposes a robust controller.

This paper is organized into six sections. The system description is introduced in section 2 followed by operating modes of 4-Quadrant switched capacitor Luo converter in section 3. Section 4 presents the controller design and in final section simulation results are presented to validate the converter performance.

2. System Description

The integration of Battery/ ultracapacitor energy storage system with non-isolated bidirectional dc/dc converter provides efficient electric power train for hybrid electric vehicle [10-15]. The block diagram of the electric power train with hybrid energy storage system and traction motor is shown in Fig.1. This electrical power train system incorporates the parallel active configuration of ultracapacitor and battery through a 4-Q switched capacitor bidirectional DC-DC Luo converter. Using this configuration, UC relieves high energy-density battery unit from the peak power transfer stress due to its higher specific power and efficiency [6-9].

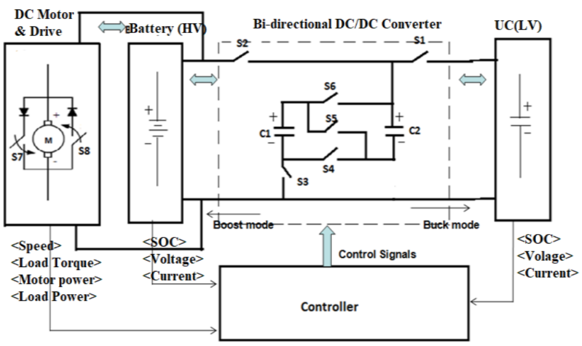


Fig.1. Block diagram of the electric power train with HESS

A switched capacitor (SC) bidirectional DC/DC Luo converter interfacing battery (HV) and ultracapacitor (LV) is a non-magnetic structure with the combination of switches and capacitors [18]. Fig.2. shows the schematic interface of Battery/UC modules using non-isolated switched capacitor DC/DC Luo converter. The combination of capacitors and switches results in voltage lift/current amplification. The transfer of energy between

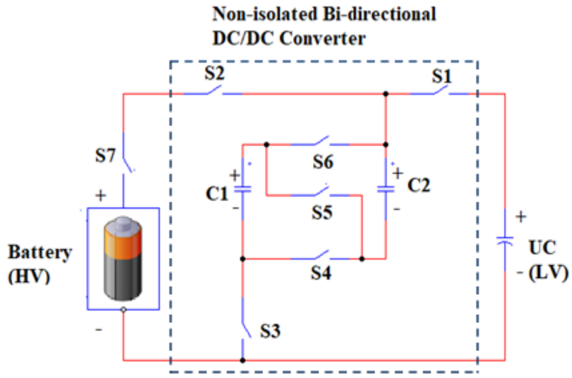


Fig.2. Schematic of SCC with HESS [1]

high voltage (HV) side or the low voltage (LV) side is controlled by charging and discharging of capacitors [20-22]. In the proposed configuration, the HV side consists of battery modules while the LV side consists of UC modules. The value of internal resistance (R_{bat}) of battery, internal resistance (R_{eq}) and equivalent capacitance (C_{eq}) of UC are given in table I. Each switch consists of two MOSFETs for bi-directional power flow.

A separately–excited DC motor is used as traction motor [24-25]. The parameters of separately excited DC motor are listed in appendix. To ensure smooth motoring and braking operation, various control algorithms have been proposed [23, 25-32]. However, as the power electronic interface proposed in this work involves capacitors, the existing control algorithms have been suitably modified to control the power flow of the entire system. The complete system schematic is shown in Fig. 3.

Table I. Parameters of circuit components

S.No	Parameters	Value
1	**Capacitor of SCC**	
	Capacitance	1000µf
	Series resistance with capacitor	0.216Ω
2	**Battery Module**	
	Nominal Voltage	250V
	Internal resistance	0.215 Ω
	Rated Capacity	10Ah
	Initial SOC	90%
3	**UC Module**	
	Rated Capacitance	1200F
	Series resistance	0.58m Ω
	Rated voltage	125V
	Initial Voltage	110V

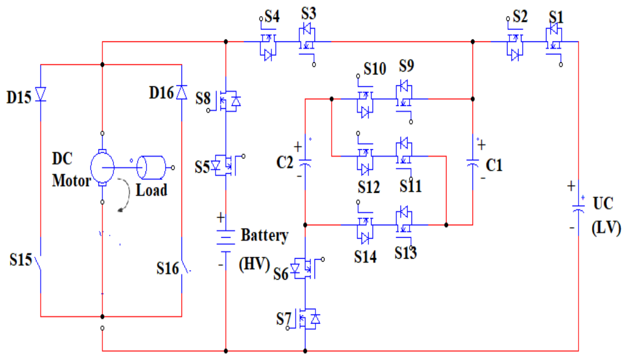


Fig.3. Schematic of 4-Q improved SCC with ESS and traction motor.

3. Operating modes of the system

The improved Switched capacitor Luo converter can operate in all 4 quadrants. In this paper, forward motoring (quadrant I) and forward braking (quadrant II) modes are described. The modes of operation for various conditions are shown in table II and the switching patterns corresponding to various modes are given in table III.

3.1 Forward Motoring Mode

In forward motoring mode (Load torque, TL ≥0), two conditions are considered:

3.1.1 Condition I: Motor Power (Pm) < Load Power (PL)

The Battery (HV) or the UC (LV) delivers power to the motor depending upon their SOC level and the load current requirement. Mode I corresponds to the power flow from battery to motor, which is shown in Fig.4 (a). Power flow from UC to motor is indicated by Mode 2 and Mode 3, shown in Fig.4 (b) and (c). During Mode 2, the capacitors (C1 and C2) are in parallel with UC and voltage across the capacitor increases. During Mode 3, capacitors (C1 and C2) get disconnected from UC and transfers energy to the motor.

3.1.2 Condition II: Motor Power (Pm) ≥ Load Power (PL)

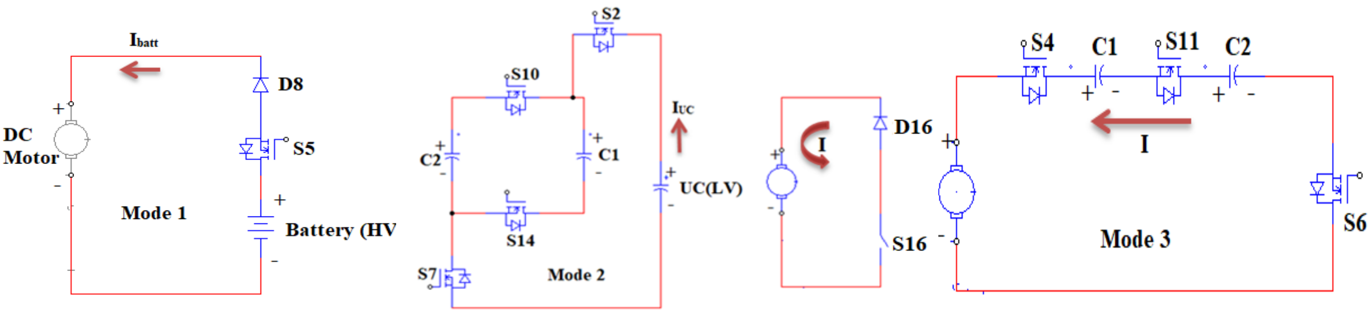
Under this condition, power transfer between the HESS occurs depending on their SOC conditions, which are mentioned in Table II. If battery is partially/fully discharged and UC is fully charged, then UC modules transfer its energy to battery. This operation provides boost mode (voltage lift), which is represented by mode 2 and Mode 4. The mode 4 operation of boost mode is shown in Fig.5. This mode uses voltage lift technique to boost the voltage level form UC to battery.

Table II Modes of operation for various conditions

S.No	Quadrant		Condition	Power Transfer	Modes of Operation
1	**Forward Motoring TL≥0**	**P_m<P_L**			
		i)	$I_L \leq I_{batt(max)}$ & $SOC_{batt} > SOC_{batt(min)}$	Battery to Motor	Mode I
		ii)	$I_L > I_{batt(max)}$ & $SOC_{UC} > SOC_{UC(min)}$	UC to Motor	TON - Mode 2 TOFF - Mode 3
		P_m≥P_L			
		i)	$SOC_{UC} >> SOC_{batt}$ & $SOC_{UC} \geq SOC_{UC(max)}$ & $SOC_{batt} < SOC_{bat(max)}$	UC to battery (Boost Mode)	TON - Mode 2 TOFF - Mode 4
		ii)	$SOC_{batt} >> SOC_{UC}$ & $SOC_{batt} \geq SOC_{batt(max)}$ & $SOC_{UC} < SOC_{UC(max)}$	Battery to UC (Buck Mode)	TON - Mode 5 TOFF - Mode 6
		iii)	$SOC_{batt} \leq SOC_{batt(min)}$ & $SOC_{UC} \geq SOC_{UC(min)}$	HESS cut-off	Mode 7
2	**Forward Braking TL<0**	i)	$I_L^* \leq I_{batt(min)}$ & $SOC_{batt} < SOC_{batt(max)}$	Motor to battery	Mode 9
		ii)	$I_L^* > I_{batt(min)}$ & $SOC_{UC} < SOC_{UC(max)}$	Motor to UC	TON - Mode 8 TOFF - Mode 6
		iii)	$SOC_{batt} \geq SOC_{batt(max)}$ $SOC_{UC} \geq SOC_{UC(max)}$	HESS cut-off	Mode 10

Table III Switching patterns corresponding to various modes

Modes Of operation	Status of switches															
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
1					ON											
2		ON					ON			ON				ON		
3				ON		ON					ON					
4				ON		ON		ON			ON					
5			ON		ON		ON					ON				
6	ON					ON			ON				ON			
7																ON
8			ON				ON					ON				
9								ON								
10															ON	



(a) (b) (c)

Fig.4.Forward Motoring (a) Battery delivers power to motor (b) and (c) UC delivers power to motor

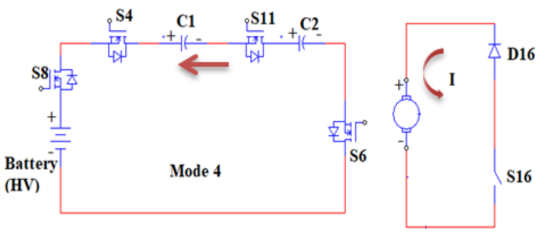
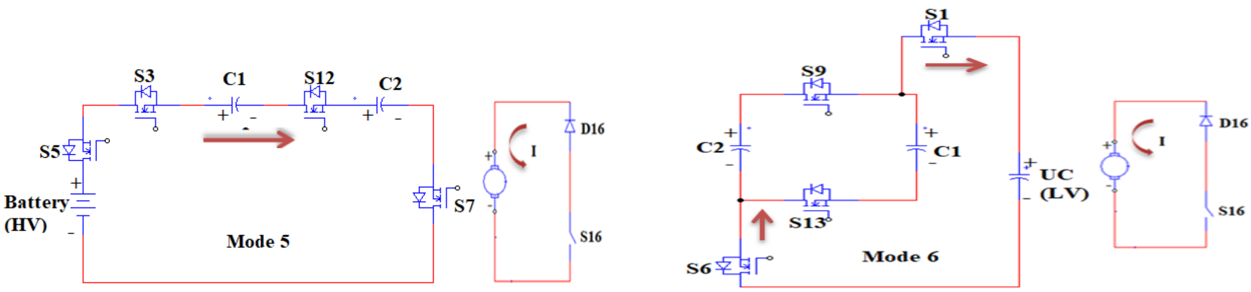


Fig.5. Boost Mode: Capacitors discharges to HV side



(a) (b)

Fig.6. Buck Mode (a) Capacitors are charged by HV side (b) Capacitors discharges to LV side

If the battery is fully charged and UC is partially/fully discharged, then the energy transfer takes place from battery to UC.This provides buck mode of operation (current amplification), represented by mode 5 and mode 6

The buck mode of operation is shown in Fig.6 (a) and 6(b). During the buck and boost mode of operation, S16 is ON to provide continous current flow to armature. If the battery and UC modules are fully discharged, then switch S16 is switched ON to provide path for the flow of armature current and HESS are cut-off from the motor terminal. This mode of operation is represented by mode 7, which is depicted in Fig.7.

3.2 Forward regeneration Mode

In forward braking mode (Load Torque, TL<0), the UC or battery receives the regenerated power based on the regenerated current and the SOC level. Mode 9 represents the regenerated power flow from motor to battery and the power flow from motor to UC is represented by mode 8 and mode 6. S15 conducts both during mode 8 and mode 6 to provide continous flow of armature current.

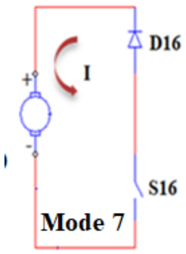


Fig.7. Motor continues to run due to the flow of armature current

Fig.8.(a) depicts the mode 9 operation and the mode 8 and mode 6 is shown in Fig.8(b) & (c). However, if both the battery modules and UC modules are fully charged, then switch S15 is switched ON and armature current continues to flow through the armature, which is represented by mode 10 and sources are cut-off, as shown in Fig.8(d).

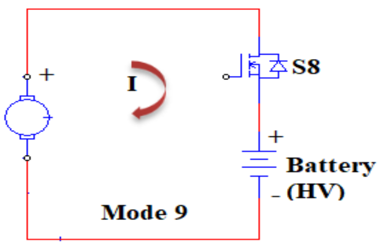
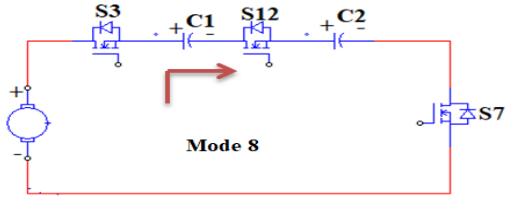
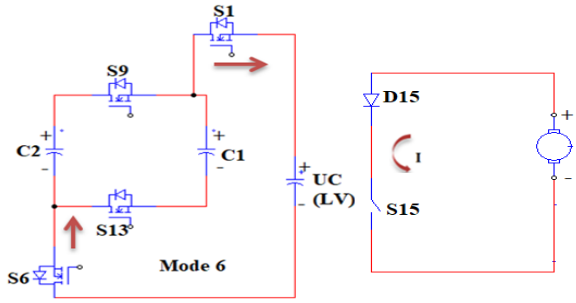


Fig.8. Forward regeneration (a) Transfer of motor power to battery

For reverse motoring (III Quadrant) and reverse braking (IV Quadrant) operation, the armature terminal of the motor has to be reversed.



(b)



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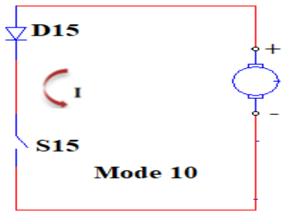


(d)

Fig.8. Forward regeneration (b) & (c) Transfer of motor power to UC (d) Motor continues to run due to the reverse flow of armature current

4. Controller Design

It is very important to manage the power flow properly from and into the system to maximize the benefits of the hybrid energy storage system. The proposed control strategy aims for the energy management of entire system, which is based on the load power requirement, motor power and the SOC levels of hybrid energy storage system. The parameters PL,Pm,TL, speed and SOC status of battery and UC are used to calculate the load current (I_L),Regenerated current(I_L*), allowable current limit of battery and the allowable SOC levels of HESS. It is assumed that the motoring or braking quadrant is chosen based on the load torque (TL). When the load torque, TL≥0, the converter operates in motoring mode, else operates in braking mode. The measurement of load power and motor power is considered for the selection of various modes of operation. If the Motor Power (Pm) < Load Power (PL), battery modules supply their energy to the motor side or UC modules supply their power to motor side depending on the load current requirement and SOC level of battery and UC. Under this condition, three modes of operation are possible (mode 1, mode 2 and mode3). Mode 1 represents the power transfer from battery to motor terminal. Mode 2 and mode 3 contributes for the power transfer from UC (LV) to motor.In case, if the Motor Power (Pm) ≥ Load Power (PL), the transfer of energy takes place between the energy storage systems.

Fig.9. shows the flowchart of the proposed energy management controller. Thus, buck or boost mode of operation is possible depending on the SOC and voltage level of energy storage systems. The buck mode of operation (transfer of energy from HV to LV side) is represented by mode 5 and mode 6. Mode 2 and Mode 4 present the boost mode of operation (transfer of energy from LV to HV). Mode 7 indicates no power transfer between energy sources and conduction of S16 to provide continous motor current. When the load torque, TL<0, the converter operates in generating mode which implies that the transfer of power is from motor to the energy storage systems. Depending upon the SOC level and regenerated current, the motor transfers its braking energy to the battery or UC modules. Mode 9 shows the transfer of regenerated power from motor to battery and the mode 8 and 6 represents the flow of braking power from motor terminal to UC. In mode 10, transfer of braking energy to HESS does not occur. In order to track the desired speed profile (drive cycle) for EV application, a speed controller is designed and used to control the speed of the motor both during forward motoring and forward regeneration mode, which in turn controls the armature voltage of the motor.

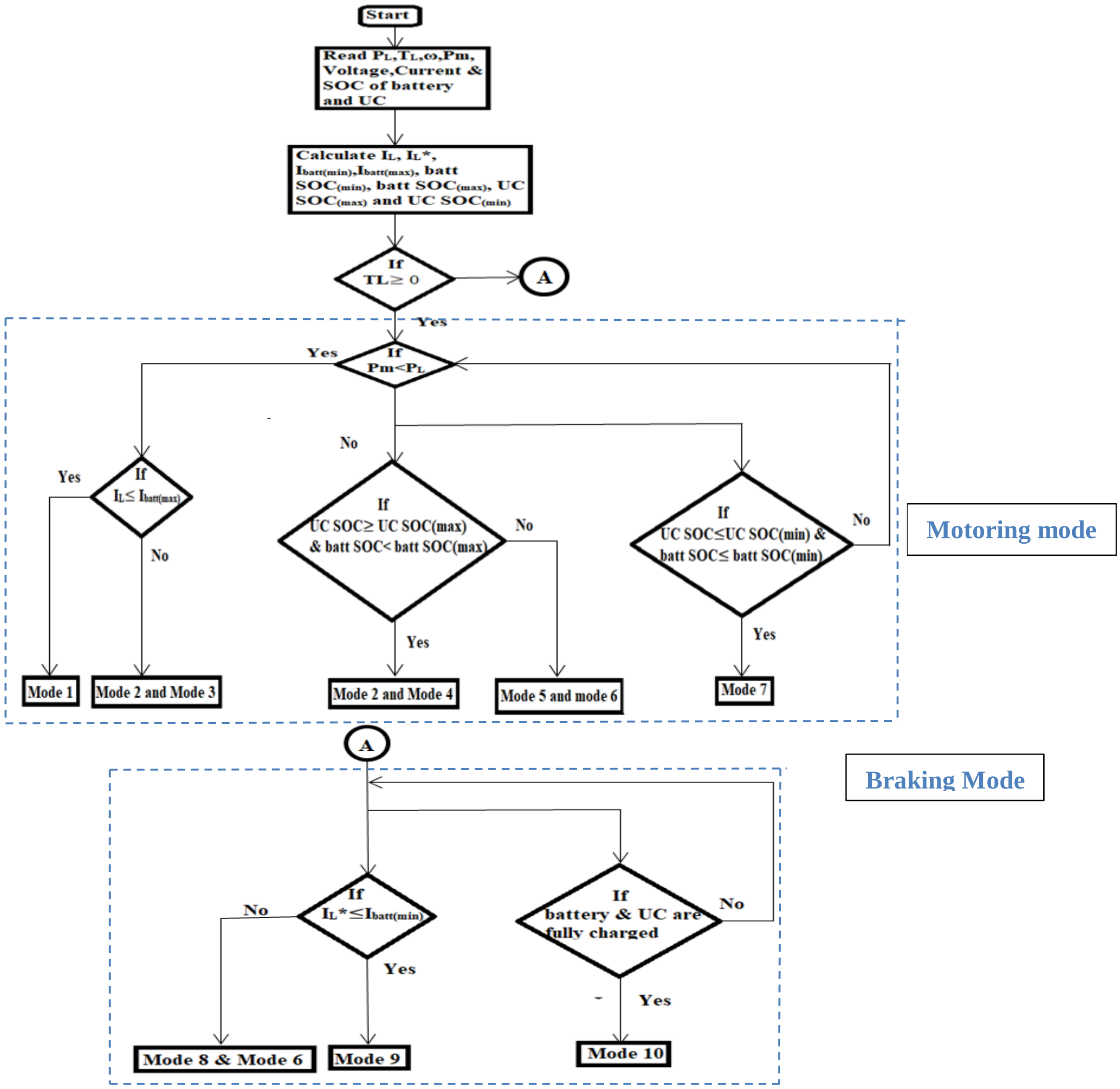
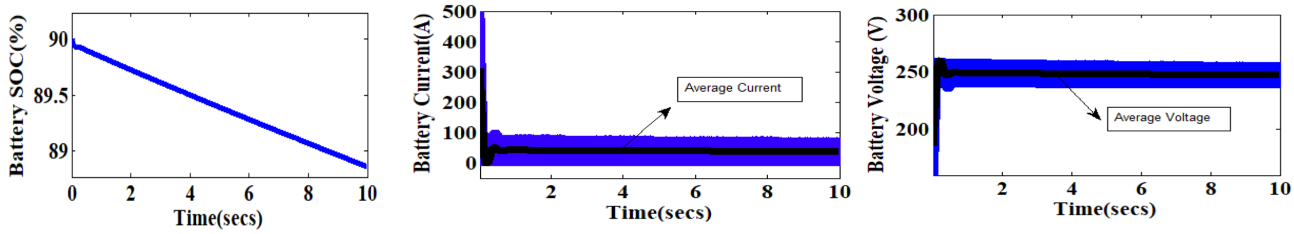


Fig.9 Proposed Power management controller

5. Simulation Results

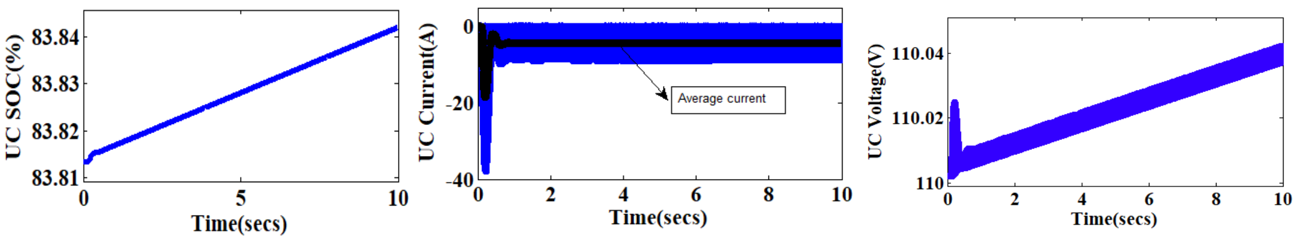
The proposed system is simulated in MATLAB/ SIMULINK environment. The proposed energy management controller provides excitation to the BDC to control the power flow. Fig.10 and Fig.11 shows the buck mode operation.The SOC, current and voltage waveforms of the battery (HV side) are illustrated in Fig10.

The SOC, current and voltage waveforms of the UC are shown in Fig11. The current and voltage waveforms in the figures illustrate the fact that the SOC of the UC increases while SOC of battery decreases. The boost mode of operation assuming UC voltage of 125V(100% SOC) and battery voltage of 175V(50% SOC) is depicted in Fig.12 and Fig.13 respectively. From the Fig, it is observed that the energy from UC is transferred to the battery.



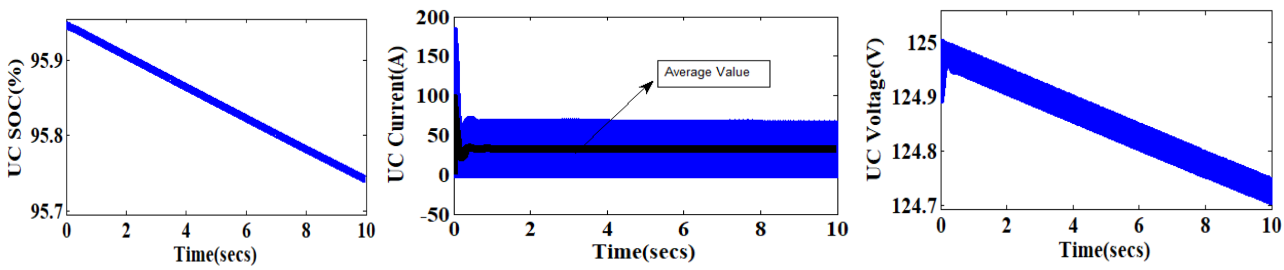
(a) (b) (c)

Fig.10.Buck Mode (a) SOC (b) current and (c) voltage waveforms of discharging battery (HV side)



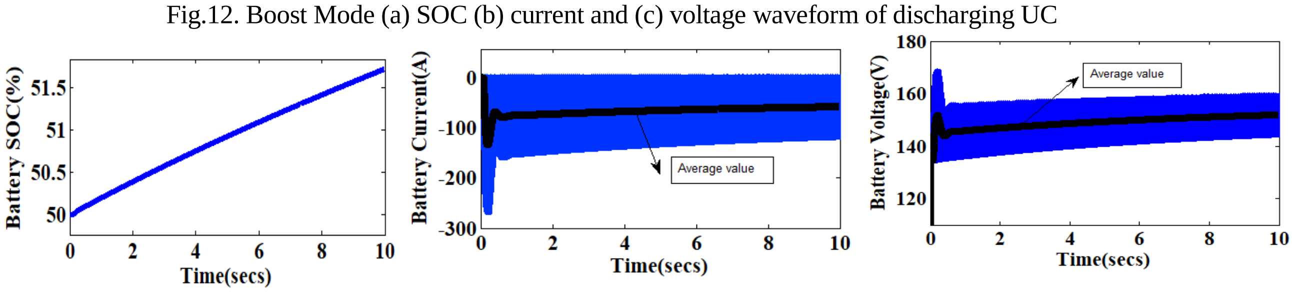
(a) (b) (c)

Fig.11. Buck Mode (a) SOC (b) current and (c) voltage waveform of charging UC module (LV side)



(a) (b) (c)

Fig.12. Boost Mode (a) SOC (b) current and (c) voltage waveform of discharging UC



(a) (b) (c)

Fig.13. Boost Mode (a) SOC (b) current and (c) voltage waveform of charging battery (HV side)

Under boost mode of operation, it is perceived that the conversion efficiency depends on the nominal voltage of battery. The relationship between nominal voltage of battery and conversion efficiency is depicted in Fig.14, which demonstrates the fact that the incorporation of UC improves the conversion efficiency thereby extending the life of the battery. Obtained efficiency of the proposed system during forward motoring is shown below in Table II. From the results, it is evident that the proposed power management controller ensures energy transfer between battery and UC. If the load torque (TL) is negative, then the converter operates in regeneration mode due to the reverse flow of armature current. It is assumed that the depth of discharge of UC SOC is 20% and battery SOC is 30%. Then the transfer of regenerated power takes place from motor to battery (HV side)/ UC(LV side) by considering the SOC state of energy storage systems and the regenerated current range.

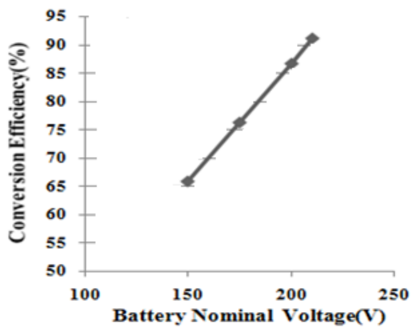


Fig.14. Relationship between nominal voltage of battery and conversion efficiency during boost mode.

Table II Efficiency of the proposed system

Condition	Forward Motoring	Efficiency (%)
$P_m < P_L$	Battery delivers power to motor	95.2
	UC delivers power to motor	71.8
$P_m > P_L$	Buck Mode	80
	Boost Mode	77

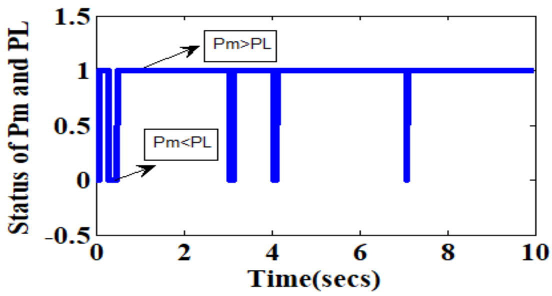


Fig.15 (a) Effect of variation in motor and load power levels

In addition, the power management controller is designed to control the speed of the traction motor. Fig.15 (a) presents the effect of variation in levels of motor and load powers. This can be possibly achieved by varying the load torque over a period of time as shown in Fig.15(b). When Pm>PL, the control operation is either in buck or boost mode (denoted by value=1). However when Pm<PL, depending on the SOC level of energy sources and load current requirement, power is fed to the motor by either UC or battery (status indicated by value=0). It is observed that the SOC of battery is found to be higher than UC SOC. Under this condition, the battery delivers power only to the motor to maintain the reference speed of the motor and the UC is not charging. The changes obtained in the SOC level of both energy sources during this condition are shown in Fig.15(c) and (d).

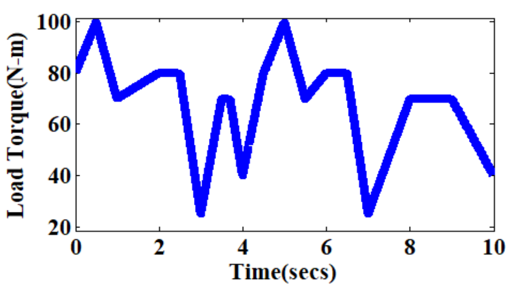


Fig.15 (b) Variation of Load torque over a period of time

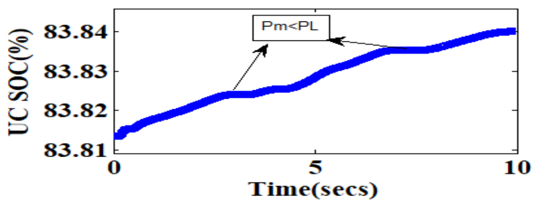


Fig.15 (c) Variation in SOC level of UC

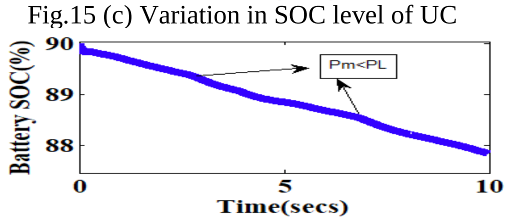
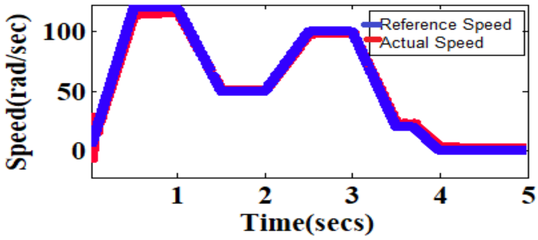
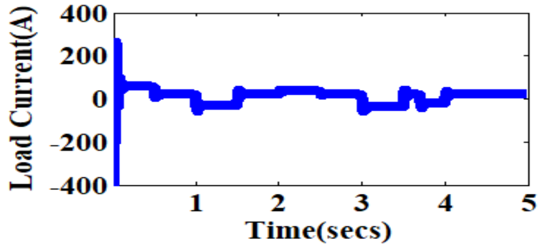


Fig.15 (d) Variation in SOC level of battery

Speed control of traction motor is a vital part of HEV as the speed variations need to track the desired drive cycle. The robustness of the proposed controller is tested for a drive cycle and the speed profile and load current profile is presented in Fig.16. The corresponding SOC level of battery and UC are depicted in Fig.17.



(a)



(b)

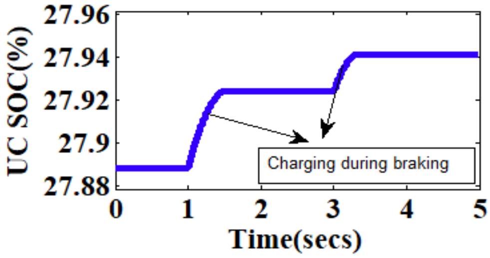
Fig.16 (a) Reference and actual speed profile (b) Load current for the desired speed profile

From the fig.16, it is clear that the proposed energy management controller ensures the comparison of actual speed profile with the ideal speed profile, which illustrates the effectiveness of the proposed energy management and the converter configuration for hybrid electric vehicle application.

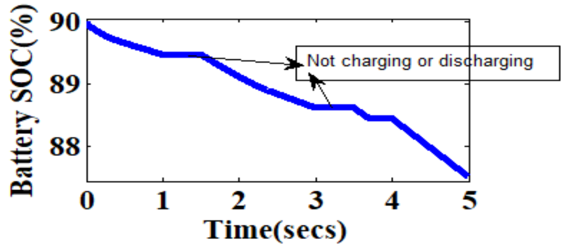
APPENDIX

Motor Data:

Parameters	Values
Armature voltage, V_a	250V
Armature Resistance, R_a	0.4822Ω
Armature inductance, L_a	0.006763 H
Motor Torque Constant, K	1.8 N-m/A
Moment of inertia, J	0.2053 Kg-m^2
Viscous Friction co-efficient, B_m	0.007032 N-m-s



(a)



(b)

Fig.17 (a) SOC level of UC (b) SOC level of battery

6. Conclusion

This paper presents the design and control of a 4-Quadrant switched capacitor Luo converter with dual energy storage systems. A power management controller is designed to ensure proper power flow of the entire system. The proposed controller design improves the conversion efficiency and ensures efficient power conversion in all operating modes with reduced current ripple. In addition the proposed controller regulates the traction motor drive in accordance with the driving cycle. Simulation is carried out in MATLAB/SIMULINK and the results indicate the suitability of the controller and converter configuration for hybrid electric vehicle applications.

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