Control of a Modular Multilevel DC/DC Converter for Regenerative Applications

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Abstract - *In this paper, different cascaded (buck, boost) and multilevel topologies are compared for regenerative applications to interface super capacitors as energy storage device to dc bus. It shows modular multilevel dc/dc converter (MMC) is best in front of cascaded converters in terms of weight and volume reduction of inductance when phase shifting modulation strategy is used. The proposed control method can balance super capacitor voltage by using specific output current. The converter topologies and control methods are verified by simulation results.*

Keywords: **Modular multilevel dc/dc converetrs (MMCs), supercapacitors(SCs), buck conveter,boost converter phase shifting, control techniques.**

1. INTRODUCTION

In response to the changing global backdrop, scientific group of people and major countries are focusing only on the energy requirements for their development. So, mainly focused on the high energy storage devices which are not present in present world. Hence, super capacitors represent one of the recent innovations in the field of electrical energy storage [1], and will find their position in many applications like electric traction and hybrid electric vehicles (HEV) where high power levels are needed during short period of time, from milliseconds to some hundreds of seconds. Since, super capacitors are used as energy storage devices in regenerative braking applications to store braking energy of HEV [2].

This paper focuses in interfacing super capacitors to a dc bus by cascaded and multilevel converters [3].Through parallelization of batteries and SCs has many drawbacks that there is no control of energy flowing to or from and the voltages across the super capacitors are almost constant. To achieve energy management capabilities, converters are needed to control the energy flow in the SCs.

SCs are low voltage devices. So, to achieve high voltage which is needed in traction applications large numbers of cells have to be connected in series. But it leads voltage imbalance across the SCs due to difference in capacitances of each super capacitors.

To attain high voltage from low voltage devices, or vice versa, cascaded and multilevel converters [4], [5] have been employed in literature. Normally, modular multilevel dc/dc converter (MMC) is used as a traction converter in HEV to achieve charge balance in batteries.

The usage of MMC in traction applications has many advantages which includes the fall of the voltage across the inductor, splitting one inductance into several inductances. Splitting the converter into a number of converters also reduces the voltage rating of the transistors (IGBT's). Low voltage transistors (IGBT's) can attain higher switching frequencies and high current capability. One more important advantage is modularity that can make simpler system design and cooling, and can amplify reliability in N+1 surplus system.

Self-regulating energy management can be achieved for each of the low voltage sources and increases the output frequency which reduces the inductive components size [6]. Multilevel converter topologies are the good swapping solution between performance and cost, as control obscurity increases compared to usual converters.

2. CASCADED AND MMCs

Two quadrant dc/dc converters is needed in regenerative applications with SCs as energy storage devices. When braking, energy flows from load to storage devices and in traction mode, energy flows from energy storage devices to load. All the dc/dc converters are presented in this paper are based on the HB topology.

2.1 HB Converter

Fig. 1(a) shows the HB converter having two transistors with anti-parallel diodes connected in series. This converter has two voltages U_1 and U_2 connected on both sides with one inductor. The HB converter is unidirectional in voltage but bidirectional in current.

When converter working in continuous conduction mode, the transfer function of the two voltages and currents are

$$U_2 = D.U_1 \quad (1)$$

$$I_1 = D.I_2 \quad (2)$$

'D' is the duty cycle and it is in range between $0 \le D \le 1$ and I_1, I_2 are the two currents on both sides of the converter where $I_2 = I_L$. But, the condition $U_1 \ge U_2$ must be always satisfied.

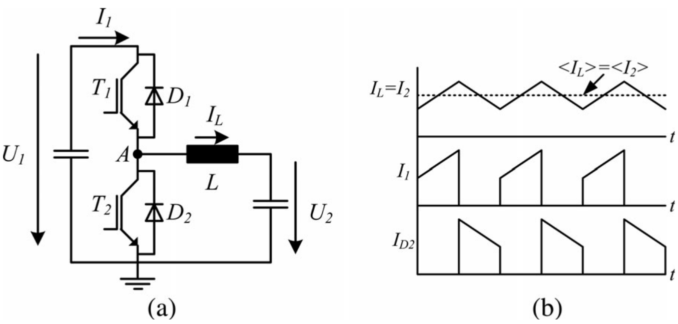


Fig. 1. Topology and waveforms of HB converter.

(a) HB converter with two voltage sources. (b) Current waveforms of HB converter

For a given input voltage U_1 and switching frequency F_S and maximum current ripple ΔI_L at D = 0.5.Then, the value of the inductor is

$$L_{HB} = \frac{U_1}{4\Delta I_L F_S} \quad (3)$$

The SCs and DC bus can be connected on either side of $U_1 or U_2$.In regenerative braking applications, SCs are releases or absorbs the energy but the DC bus is supposed to be constant.

In this paper, when SCs are connected on high voltage side U_1 of the HB converter then that converter is said to be work in buck mode, because it reduces the SCs voltage to the DC bus voltage. When SCs are connected on high voltage side U_2 of the HB converter then that converter is said to be work in buck mode, because it elevate the SCs voltage to the DC bus voltage.

Cascaded and modular multilevel converters split the converter into several modules. Each module can work independently and allows multiple inputs and outputs for different current and voltage levels and switching frequencies.

In the paper, cascaded and multilevel converters are series connected HB converters. Depending on where the SCs are connected, three converters are classified and compared in terms of magnetic energy stored in the inductor. Cascaded buck (CBk), cascaded boost (CBt), modular multilevel dc/dc converter (MMC).

2.2 Cascaded Buck Converter (CBk)

Fig. 2(a) shows cascaded buck converter having SCs on high voltage side U_1 and series connection of HB converters on low voltage side U_2.Due to buck mode, SCs are fully charged $U_{SCN} = 2U_{DC}/N$, where N is the number of series connected sub modules. The inductance of each sub module can be computed as

$$L_{CBkN} = \frac{U_{DC}}{2\Delta I_L F_S N} \quad (4)$$

As seen in equ(4),the inductor split into several inductors, but the total energy of the sub modules inductance is equal to the total magnetic energy of the unique converter at same switching frequency and inductor ripple.

2.3 Cascaded Boost Converter (CBt)

Fig. 2(b) shows cascaded buck converter having SCs on low voltage side U_2 and series connection of HB converters on high voltage side U_1.Due to boost mode, SCs are half charged $U_{SCN} = U_{DC}/(2N)$, where N is the number of series connected sub modules. The inductance of each sub module can be computed as

$$L_{CBkN} = \frac{U_{DC}}{4\Delta I_L F_S N} \quad (5)$$

2.4 Modular Multilevel DC/DC converter (MMC)

Fig. 2(c) shows modular multilevel converter having SCs on high voltage side U_1 and inductor on low voltage side U_2.It has only inductor for the whole converter. So, this converter called as a unique converter not as cascaded converters having series connection of HB converters. Normally, MMCs are used where high voltage applications are needed due to modularity structure. Each HB has a $U_{SCN} = U_{SC}/N$ voltage level.

Phase shifting strategies are more preferable for this type of converters which offers several advantages over others. Hence, each carrier wave is shifted by $360^0/N$ with respect to next HB.

When SCs are fully charged, $U_{SCN} = 2U_{DC}/N$, then the inductance can be computed as

$$L_{MBkN} = \frac{U_{DC}}{2\Delta I_L F_S N^2} \quad (6)$$

Here inductance value depends on the square of the series connected sub modules.

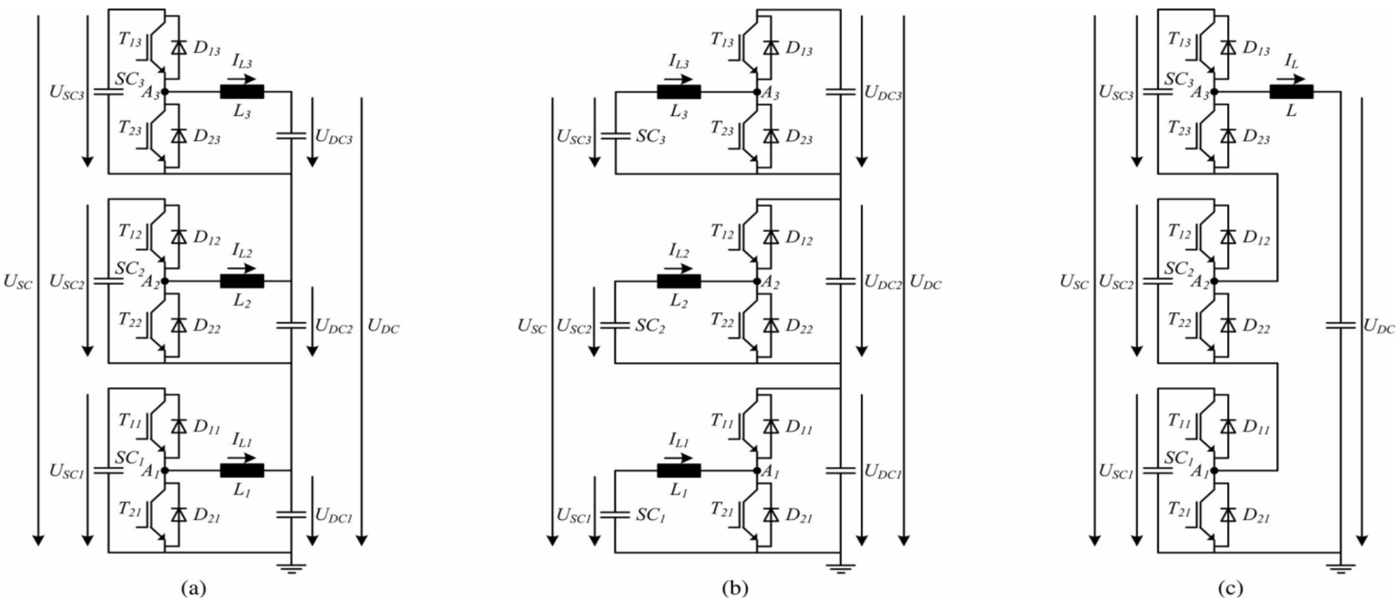


Fig.-2: Four-Level converters compared (a) Buck converter (b) Boost Converter (c) MMC

2.5 Comparison of Different Topologies

SCs can be connected either in high voltage side U_1 or low voltage side U_2.But, as shown in Fig. 3, when connected to low voltage side U_2, the inductor and SC current ripples are smaller compare with SCs connected in low voltage side U_2.Hence, filters are needed for converters having SCs on high voltage side to reduce ripples. But, it leads to raise the inductance of the converter.

However, the reduction of inductor size and volume needed by modular multilevel dc/dc converter compared to other HB converters. With the maximum current ripple of 15% of nominal current of 5A, parameters of converter for calculation of inductance can be taken for Table I, the calculated output inductance is $0.18mH$ for four-level modular multilevel dc/dc converter and output inductance for HB converter is $1.62mH$, which reduces energy stored in the inductor of 9 times by using four-level compared to HB converter and has common Dc bus.

Table-1: Converter parameters

Parameter	Name	Unit
U_1	Input voltage	97.2 V
U_2	Output voltage	12 V
C_{sc}	SC capacity	58.3 F
ESR_{sc}	SC ESR	8.8 mΩ

Table-2: Comparison of inductance in different topologies

CONVERTER TYPE (4-LEVEL)	SC VOLTAGE (VOLTS)	DC BUS VOLTAGE (VOLTS)	INDUCTANCE (mH)
BUCK	97.2	48.6	0.54
BOOST	97.2	194.4	1.08
MMC	97.2	48.6	0.18

Table-2 summarizes that boost converter requires more inductance compare with the buck converter. But, buck converter has more ripples which require filters compare to boost converter. So, inductive components increases which are not desire to the traction applications.

Modular multilevel dc/dc converter has low inductance value compare with HB converter, even though having filters for MMC.As the number of levels increases their inductance value reduces for MMC as in equation (6).

3. CONVERTER CONTROL

The converters are designed to store the regenerative energy in storage elements as SCs and releases in traction mode. The power flow from SCs to load and from load to SCs can be controlled easily by controlling the output current I_L .Another control objective is equalize the SCs voltages to same value.

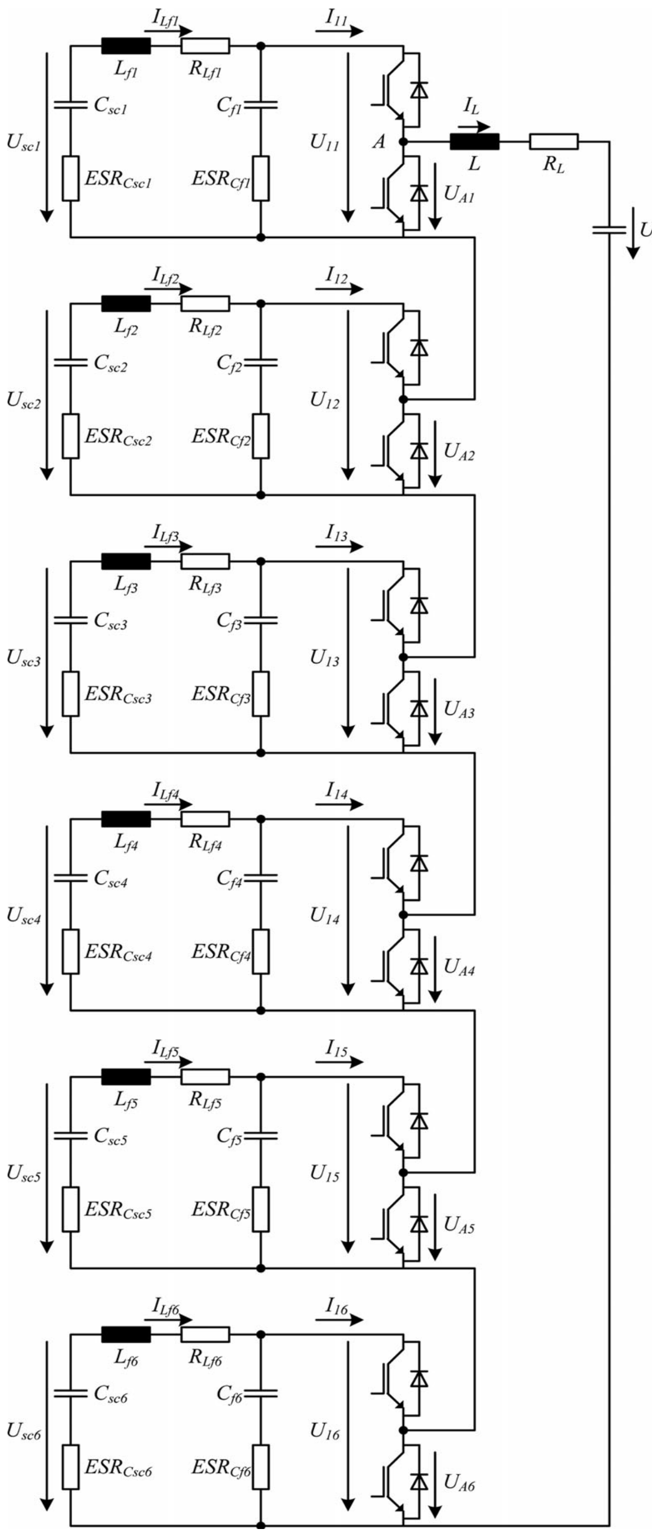


Fig-3: Seven-level Modular multilevel dc/dc converter

Two-level MMC is designed for the controlling purpose is as shown in Fig-4. Normal methods are used to design the controller G_c.

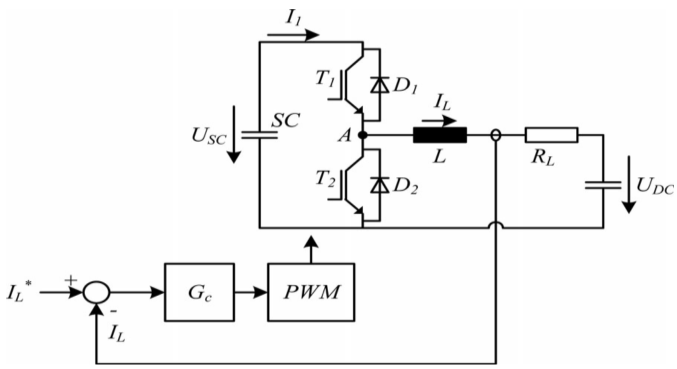


Fig- 4: Two-level MMC for control purpose

3.1 Current Control Loop

The system to be controlled is an first-order RL system can be defined as

$$G_s(s) = \frac{\frac{1}{R_L}}{1 + S\frac{L}{R_L}} \qquad (7)$$

First-order RL systems can be controlled with zero steady-state error by using a proportional-integral (PI) controller. Here, K_P and K_I are chosen as

$$K_P = \alpha . L \qquad (8)$$

$$K_I = \alpha . R_L \qquad (9)$$

Where α is chosen to fix 10-90% rise time t_r as

$$t_r = \frac{\ln 9}{\alpha} \qquad (10)$$

In proposed seven-level MMC have six converters having their individual filters shown in Fig.3.The control scheme of the seven-level modular multilevel dc/dc converter is shown in Fig-5.

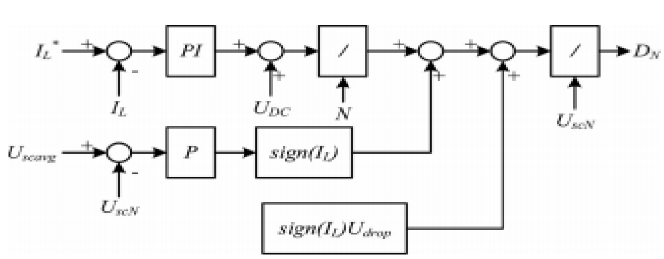


Fig-5: Control scheme of seven-level MMC

As shown in Fig-5, PI controller values can be taken from equations (8), (9) and (10).SCs voltage balancing can be controlled by voltage balancing loop.

3.2 SC voltage balancing loop

SCs voltage balancing is very crucial and it can be controlled by controlling the output inductor current.

From Fig-3, the six converters can perform independently. So, the SCs voltages are need not be equal. The control objective can be done by comparing the average SCs voltage with the individual voltages.

$$G_{SC}(s) = \frac{1}{sC_{SC}} \qquad (11)$$

In SCs voltage balancing loop only P controller is used and the K_{PSC} can be selected as

$$K_{PSC} = 10^{\frac{-3}{20}} \frac{\omega_C}{\frac{1}{C_{SC}}} \qquad (12)$$

Where, ω_C is the desired bandwidth of closed loop converter

3.3 Compensation of semiconductor voltage drop

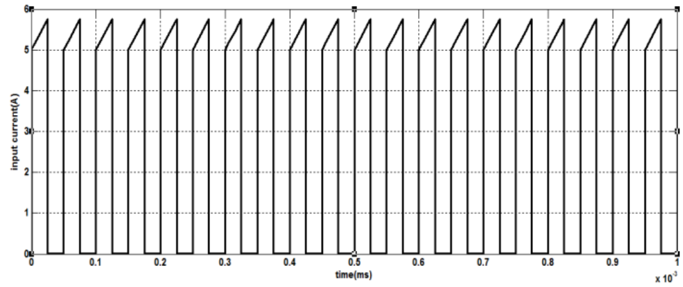
To get current response good, semiconductor voltage drop must be compensated as in equation (13)

$$D_{drop} = sign(I_2)\frac{U_{drop}}{U_{SC}} \qquad (13)$$

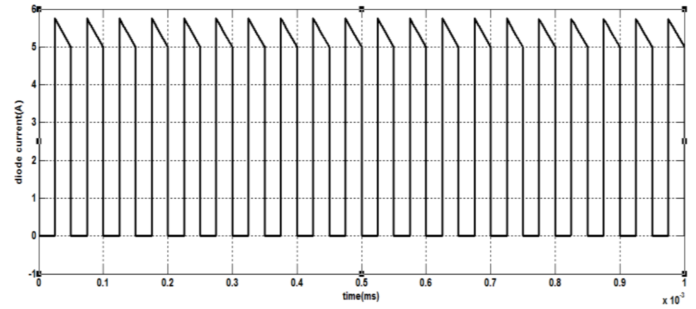
The converter parameters for seven-level MMC can be taken from Table-3.

Table-3: Converter parameters of seven-level mmc

Parameter	Name	Value
F_s	Switching frequency	20 kHz
F_{ctrl}	Control execution frequency	120 kHz
U_1	Input voltage	900 V
U_2	Output voltage	400 V
C_{sc}	SC capacity	18.75 F
ESR_{sc}	SC Equivalent Series Resistance	60 mΩ
L	Output inductor inductance	41.67 μH
R_L	Output inductor resistance	14 mΩ
L_f	Filter inductor inductance	15 μH
R_{Lf}	Filter inductor resistance	5.7 mΩ
C_f	Filter capacitor capacity	150 μF
ESR_{Cf}	Filter capacitor ESR	1.9 mΩ
r_{on}	IGBT On resistance	1 mΩ
U_{drop}	IGBT voltage drop	1.5 V
t_r	Rise time (controller)	0.4 ms



(a)



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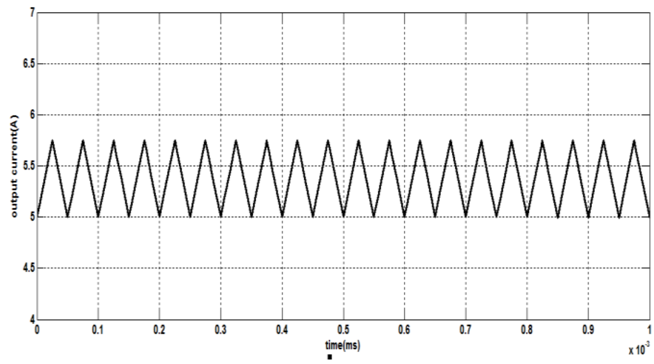


(c)

Fig-6: Simulation results of HB converter

a) Input current (b) Diode current (c) Output current

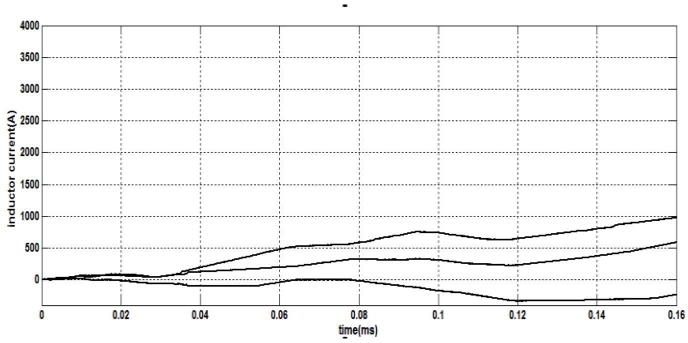


Fig-7: Inductor current of four-level buck converter

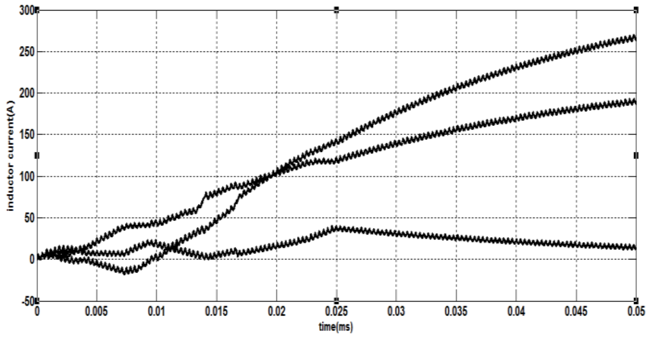


Fig-8: Inductor current of four-level boost converter

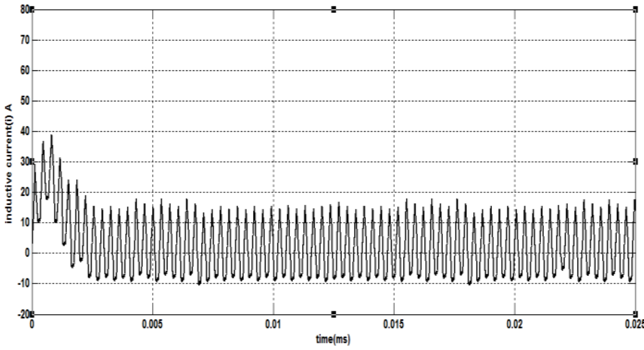
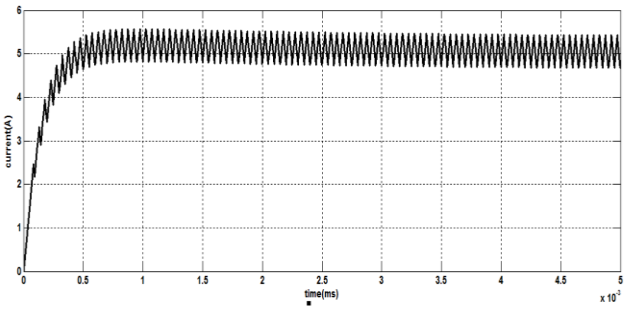
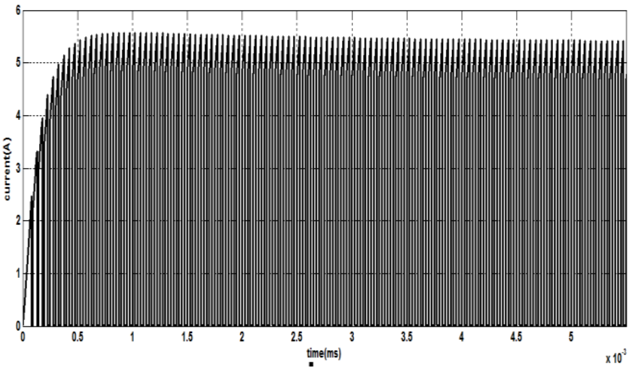


Fig-9: Inductor current of four-level MMC



(a)



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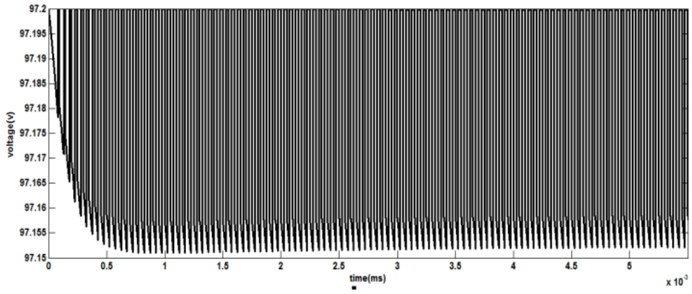
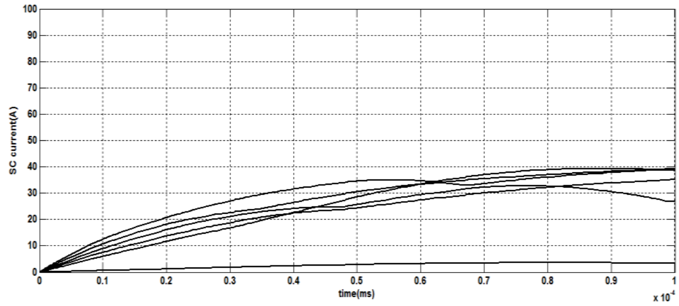
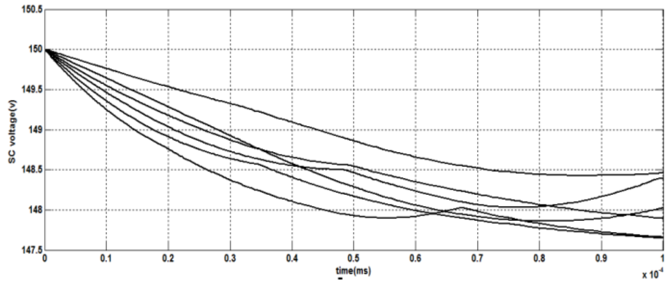


(c)

Fig-10: Simulation results of two-level MMC for control purpose. (a) Output current (b) SC current (c) SC voltage



(a)



(b)

Fig-11: Simulation results of seven-level MMC (a) SC current (b) SC voltage

3.4 Simulation result analysis

Fig-6. Shows the input current and SC current of HB converter have more ripples. Simulation results of the buck converter shown in Fig-7 has more ripples and settling time compare to the four-level boost converter shown in Fig-8.MMC currents shown in Fig-9, has less ripples and less rise time and settling time compare to the cascaded converters. When number of levels increases, the inductance value reduces from equations (3), (4), (5) and (6).So, the proposed results shown in Fig. 10 of two-level MMC for the controlling of SC voltage and load current shows that rise time only 0.4ms and settles very quickly than the four-level MMC. Fig-

11 shows that seven level MMC has SC voltage and current balancing.

3. CONCLUSION

The paper presents a modular multilevel dc/dc converter (MMC) used in regenerative applications to interface energy storage devices to the DC bus. The main objective is to reduce magnetic components size and volume which is most suitable for electric hybrid vehicles (EHV) along with voltage balancing in SCs is accomplished.

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