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A Modified Sliding Mode Control for Circulating Current Control and Voltage Balancing in Modular Multilevel Converter

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ABSTRACT

The Modular multilevel converter (MMC) is most popular because of its high efficiency, flexibility, less harmonic distortion, usages of less power rating of the devices, high modularity and high scalability. In spite of these advantages, MMC faces many challenges such as voltages balancing and inner or circulating current control. The main goal is balancing the voltages across the capacitor in each submodule without excessive switching of the power electronic devices. So by using a controlled switching frequency technique in voltage balancing in MMC legs, the average switching frequency of the device is reduced. Because of switching actions and fluctuations in capacitor voltages results in even order harmonics in inner currents, in that second harmonic is dominating one. These harmonic components in current introduce large power losses, increase stress on power devices, and also may cause instability of the system. Traditional circulating current suppression methods have some limitations of harmonic rejection capability, complex implementation and computations. A modified sliding mode control is proposed for controlling both voltage balancing and circulating current control in this paper. This controller suppresses the harmonic components, particularly 2nd harmonic in the inner current. For controlling the modular multilevel converter phase disposition PWM is used in this paper.This controller is implemented for single phase MMC which can be extended further for three phase system. The comparison results for conventional PI and SMC controller with modified SMC controller is presented. The results of proposed controller is validated through MATLAB/Simulink environment.

Key words: Phase-Disposition PWM; Sliding Mode control; Voltage balancing algorithm; Modular multilevel converter (MMC);

1. INTRODUCTION

Modular Multilevel Converter (MMC) gaining its importance in popular converters in the present days because of its advantageous features like high voltage stability, higher voltage magnitudes, low harmonic content etc.[1]. The commercial and economic aspects leads to development of Modular multi-level converter in wide spreads in various technical applications like HVDC transmission systems.

The modular multi-level converter consists of half bridge sub modules with capacitors, Inductors, along with various protective devices. Because of the modular structures the unequal voltage distributions among the capacitors will present in the system. This unequal voltage across the capacitor leads to reduction in output voltage profile, escalation in magnitudes of circulating current, decrease the life span of the device, reliability of the converter becomes a major challenge [2]. For grid connected applications [3-4] also MMC will helpful. Recent literature [5-6] has extensively investigated this issue; to attain equal voltage balancing between the arms more voltage and current sensors are required. But in HVDC applications it always comprises hundreds of submodules in each arm or phase. So in those applications always requires hundreds of voltage sensors are normally needed to perfect voltage balancing. This will increase the converters cost, complexity and decrease the reliability of the converter.

In recent years, many attempts have made by researchers to reduce the utilization of number of sensors. In [7] prospects were achieved experimentally with less number of current sensors, but the utilization of voltage sensors were not addressed in these studies. An open-loop solution with fixed pulse pattern [8] was also suggested. However, since this topology is not using any feedback loop, the inconveniences of open-loop control will impact on converter's performance. Recently many observers are proposed for estimation of capacitor voltages [9]. In more recent work, a seven level modular multilevel converter voltage balancing was accomplished with only two voltage sensors, one for every arm. While this approach has made a significant impact on number of required voltage sensors; but the voltage balancing applied to devices will increase the switching losses because of simultaneous activation and deactivation of switching devices.

The SMC approaches were used in various power converters and electric drives for a wide range of applications[10]. Some papers show a method on sliding mode control and it compared with regular PI controller for the MMC. It reduce the circulating current but it is unable to maintain the voltage balancing among arms of MMC. So a modified SMC is proposed in this paper to reduce circulating current along with voltage balancing between the arms. The fundamental model of sliding mode control is used as references of various control parameters to convert state space model into different subspaces and corresponding subspaces has communal control structure. Each of these sub sections, the applied communal control structure forces the controlled parameters to glide along the limits of the sliding surface. The proposed technique is contrasted with the traditional PI controller providing the device with faster dynamic response and equal steady state stability.

2. DYNAMICS OF MMC

The circuit diagram of three phase & single phase circuit MMC is shown in Figure 1. The MMC contains three legs, each leg comprises of two arms for each phase, in which individually arm is embraced by N sub modules connected in series with one of the MMC circuit topology of half-bridge configuration with one current limiting inductor.

Dynamic performance of the N-cell MMC is modelled as,

$$\frac{di_p}{dt}=\frac{1}{L_1}\left[E_p-\sum_{i=1}^{N}\left(S_i.v_{ci}\right)-R_1 i_p-v_a\right] \tag{1}$$

$$\frac{di_n}{dt}=\frac{1}{L_1}\left[E_n-\sum_{i=N+1}^{2N}\left(S_i.v_{ci}\right)-R_1 i_n+v_a\right] \tag{2}$$

Where V_a is,

$$V_a=Ri_a+L\frac{di_a}{dt}$$

$$\frac{dV_{ci}}{dt}=\frac{1}{C}\left(i_p.S_i\right)\quad i = 1....N. \tag{3}$$

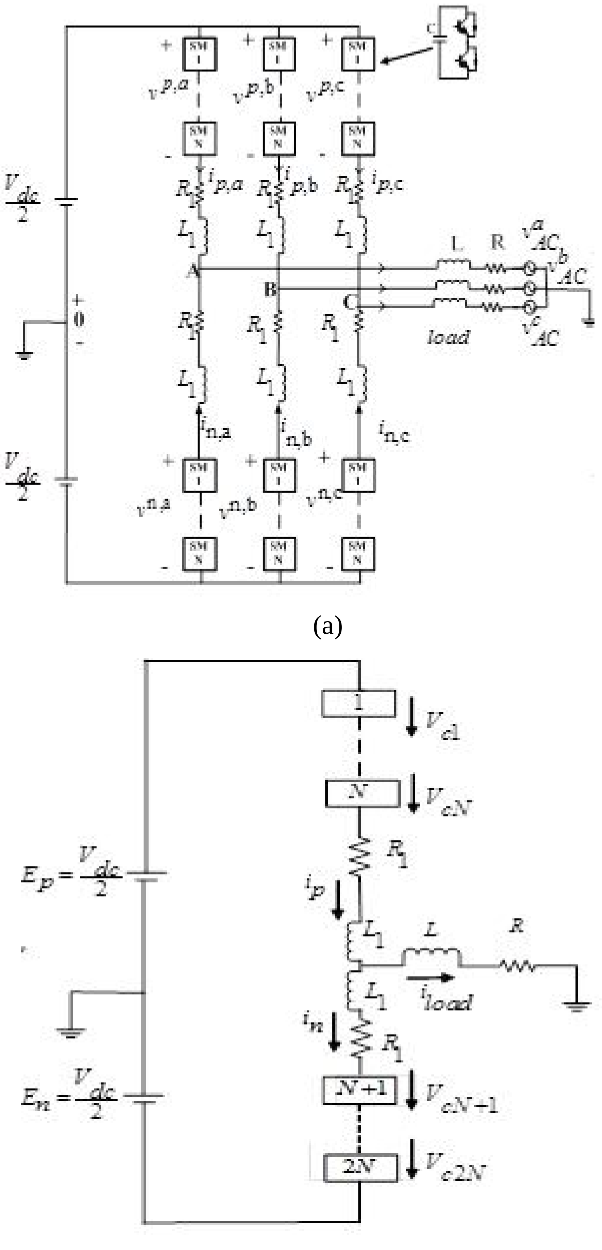
$$\frac{dV_{ci}}{dt}=\frac{1}{C}\left(i_n.S_i\right)\quad i = N+1....2N \tag{4}$$

Where i_p and i_n are currents of upper and lower arm, S_i is switching signal for i^{th} submodule, V_{ci} is capacitor voltage of i^{th} submodule, i_a is phase current v_a is phase voltage. Representing above equations in state matrix form which yields as

$$\overline{x}=Ax+Bu \tag{5}$$

Where,

$$x=\left[i_p i_n v_{c1} v_{c2} v_{c3} v_{c4} v_{c5} v_{c6} v_{c7} v_{c8}\right]^T$$



(a)

(b)

Figure 1: (a) Three phase MMC (b) single phase MMC circuit diagram

$$A = \begin{bmatrix} A_1 & A_2 & A_3 \\ A_4 & 0 & 0 \\ A_5 & 0 & 0 \end{bmatrix}$$

Where, $A_1 = \begin{bmatrix} -P_1 - P_2 & -P_1 + P_2 \\ -P_1 + P_2 & -P_1 - P_2 \end{bmatrix}$

$$A_2 = \begin{bmatrix} S_1*(-P3-P_4) & S_2*(-P3-P_4) & S_3*(-P3-P_4) & S_4*(-P3-P_4) \\ S_1*(-P3+P_4) & S_2*(-P3+P_4) & S_3*(-P3+P_4) & S_4*(-P3+P_4) \end{bmatrix}$$

$$A_3 = \begin{bmatrix} S_5*(-P3+P_4) & S_6*(-P3+P_4) & S_7*(-P3+P_4) & S_8*(-P3+P_4) \\ S_5*(-P3-P_4) & S_6*(-P3-P_4) & S_7*(-P3-P_4) & S_8*(-P3-P_4) \end{bmatrix}$$

$$A_4 = \begin{bmatrix} S_1/C & 0 \\ S_2/C & 0 \\ S_3/C & 0 \\ S_4/C & 0 \end{bmatrix} \quad A_5 = \begin{bmatrix} 0 & S_5/C \\ 0 & S_6/C \\ 0 & S_7/C \\ 0 & S_8/C \end{bmatrix}$$

$$B = \begin{bmatrix} (P_3 + P_4) & (P_3 - P_4) \\ (P_3 - P_4) & (P_3 + P_4) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad U = \begin{bmatrix} \frac{V_{dc}}{2} \\ \frac{V_{dc}}{2} \end{bmatrix}$$

$$P_1 = \left(\frac{R_1}{2L_1} \right) \quad P_2 = \left(\frac{R_1 + 2R}{2(2L + L_1)} \right)$$

$$P_3 = \left(\frac{1}{2L_1} \right) \quad P_4 = \left(\frac{1}{2(2L + L_1)} \right)$$

3. CONTROL OF MMC

3.1 Restricted Voltage Balancing Algorithm

The algorithm which has been proposed comprises of two stage sorting arrangement structures along with a basic comparison for choosing the SMs and arm switching state generation.

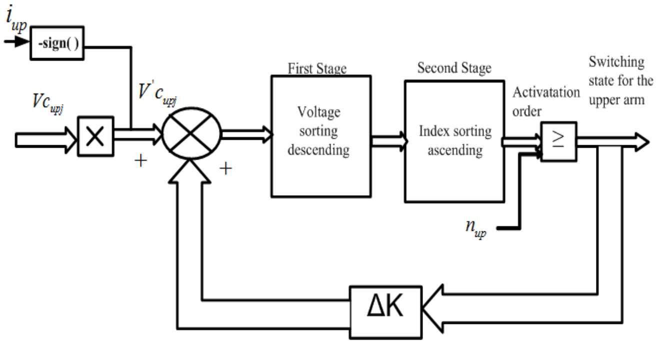


Figure 2: Restricted Voltage balancing algorithm

Figure 2 demonstrates the calculation procedures involved in voltage balancing of upper arm and vice versa for lower arm. In initial stage, the product of negative sign of respective arm current and voltage of capacitors are done. Negative sign of current indicates discharging and positive sign indicates charging of sub module capacitors.

In the first sorting stage voltage measurements (V_{Cupj}) of the modified SM capacitor are used SM indices (j) are sorted out in a descending order that provide sorted recorded list depending on voltages of SM (j') from a greater value to a lesser value as obtained. The next stage of sorting uses the first (j') output as an input, on considering an increasing order. Order activation of an individual SM and the elements list will be demonstrated in the second stage output. The comparison of activation order and required SM's to be connected i.e. n_{up} will gives the switching pattern to the SM of the arms. This voltage balancing algorithm will creates extra switching transitions, hence increase the switching losses of the converter. At a given sampling time, as set of SM's that are connected or bypassed with an objective of reduction in switching frequency of SM. ΔK must be picked such that it is able to distinguish the connected voltage values and the bypassed voltage values of SMs under any working conditions and regardless of the SM ripple voltage of capacitor. Always an equivalent incremental value to V_{dc}/N is recommended as ΔK.

3.2 SLIDING MODE CONTROL FOR SINGLE PHASE MMC

In the Sliding mode control method, two control variables such as circulating current and output current which are precise by designing two control structures. Both control structures acts at a time to dynamism the equivalent control variable to glide on the limits within given range of the two control structures.

First we are controlling one phase then it can be extended for other phases of MMC. For single phase MMC, to control i_a and i_{diff}, proposed two control functions f(.) and g(.) in each control structure[11], i.e.,

$$f(.) = F\,\mathrm{sgn}(i_a - i_a^{ref}) = F\,\mathrm{sgn}(e_a) \tag{6}$$

$$g(.) = G\,\mathrm{sgn}(i_{diff} - i_{diff}^{ref}) = G\,\mathrm{sgn}(e_{diff}) \tag{7}$$

Where, $i_{com} = \frac{i_p + i_n}{2}$, $i_{diff} = \frac{i_p - i_n}{2}$

Based on equations (6),(7) the two control parameters adjusts itself based on their actively controlled current value and its reference value. The reference of the inner current is acquired from load power (P_{out}) requirement and extra DC component required is obtained from average of capacitor volatges V_{Cang} as shown in Figure 3. The output power consists of fundamental & second harmonic component, hence mean value can be obtained from MAF (Moving average filter) filter [12]. The mean value obtained is then divided with DC link voltage to achieve i_{diff1}. An extra DC component i_{diff2} required to maintain capacitor voltage balanced, is obtained from the average capacitor volatges V_{Cang} when compared with input DC voltage passed through a PI controller. Hence a control signal was attained from the controller to normalize the circulating currents is v_{diff}.

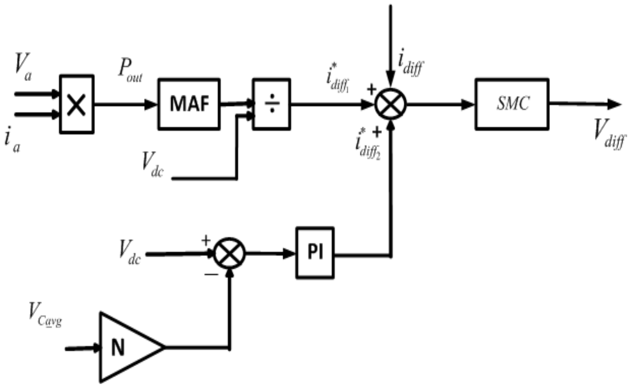


Figure 3: Sliding mode control

3.3 Modulation Technique

In MMC the modulation process will describes which submodule is to be triggered intern number of submodules that to be inserted or bypassed in each arm which is shown in Figure 4. There are two different techniques in PWM i.e. phase shift and Level shift pulse width modulation. Again in Level Shift PWM, three different configuration are available, they are phase disposition, phase opposition disposition and alternate phase opposition disposition pulse width modulation. Out of these three configurations phase disposition (PD) pulse width modulation technique will gives less THD when compared to other techniques for MMC. So the proposed paper employs PD-PWM with four submodules for each arm to attain five level MMC.

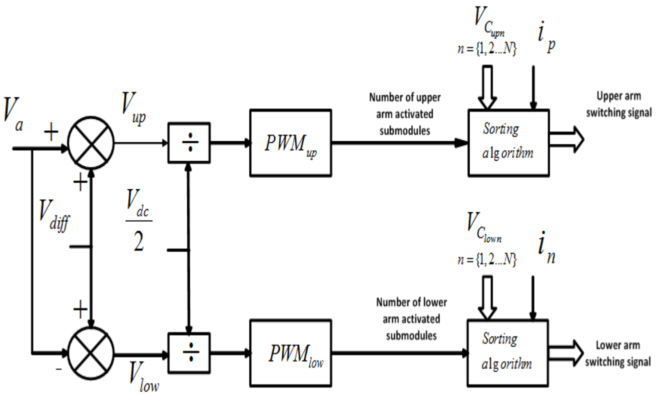


Figure 4: Modulation process applied to phase leg of MMC

To implement PD-PWM it utilizes N carrier waveforms and compared with reference waveform, so that it produce N+1 level voltage waveform. If we are using interleaving nature of carriers in upper and lower arm of PD-PWM, it can develops 2N+1 voltage levels but in this paper we are not reflected.

3.4 Modified sliding mode control

The modified SMC control is also works same as SMC control expect the second reference current generation i.e. i_{diff_2} . The average capacitor voltages V_{Cang} when compared with input DC voltage mainly contains second harmonic component. Hence to reduce this second harmonic component a MAF is introduced and it passes through another SMC control, so we will get a perfect DC component required to maintain the voltage balancing between the two arms. So the proposed control structure is shown in Figure 5.[13] This controller will perfectly balance the voltage between the arms along with control of inner current of each leg.

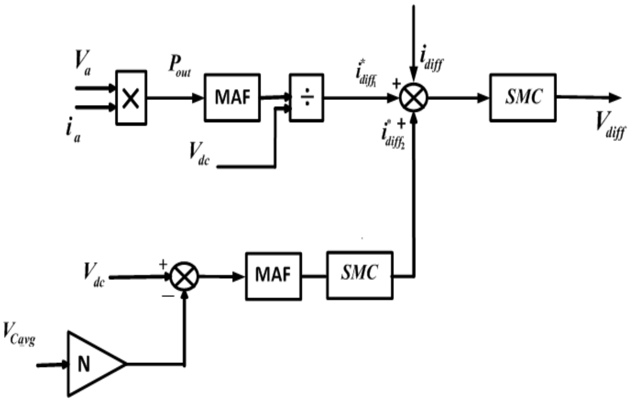


Figure 5: Modified Sliding mode control

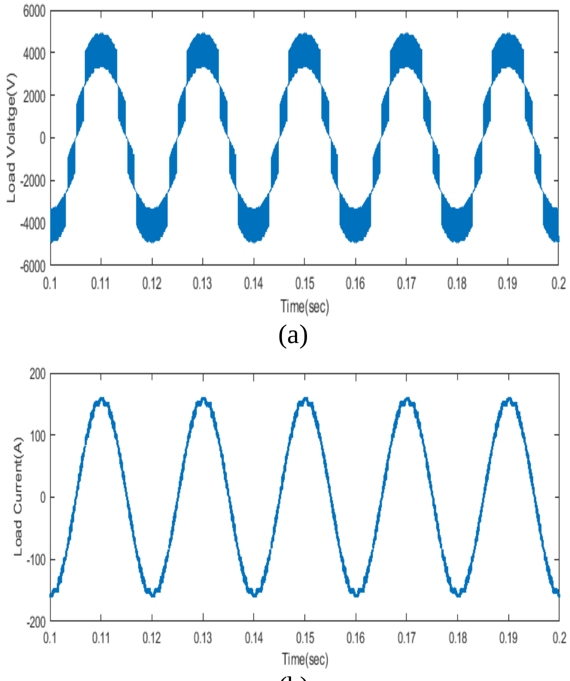
4. SIMULATION RESULTS

To demonstrate the proposed control method effectiveness and performance, MMC with 4 submodules per each arm is considered and the parameters of the circuit are tabulated in Table 1. The simulation is carried out in MATLAB for conventional PI control, SMC and proposed modified SMC with PD-PWM.

Table 1: Simulation parameters using for MMC

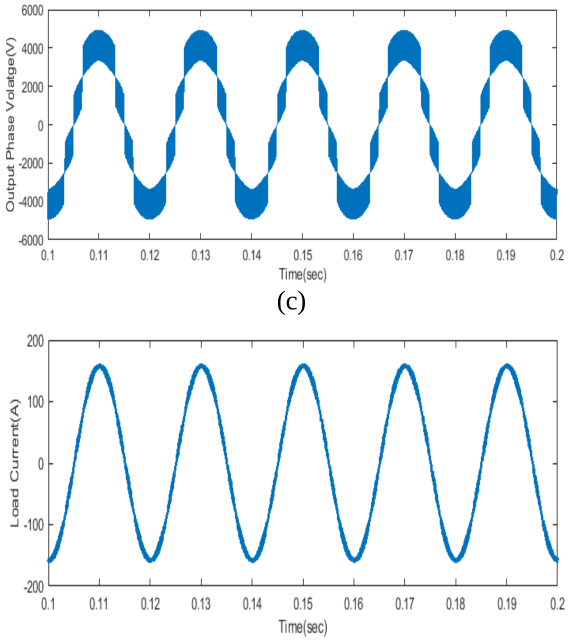
Parameter	Value
Submodules in each arm	4
DC voltage	10kV
Submodule blocking voltage	2500V
Submodule capacitor	2.7mF
Submodule Resistance,inductor-R1,L1	0.02 Ω, 3mH
Load R , L	30Ω, 2.3mH
Switching frequency	2500Hz
Sampling frequency	1000kHz

The phase voltage and current wave forms for single leg MMC are presented in Figure 6. From the figure one can identify quality of output waveforms that the MMC can generate. The results depicted in the figure are considered only for single phase of the MMC since each phase control is free from the remaining phases, hence the results shown are for single phase and then it can be prolonged for multi-phase systems. From the results it clearly shows that the ripples in output voltage and currents further reduced by the proposed control.



(a)

(b)

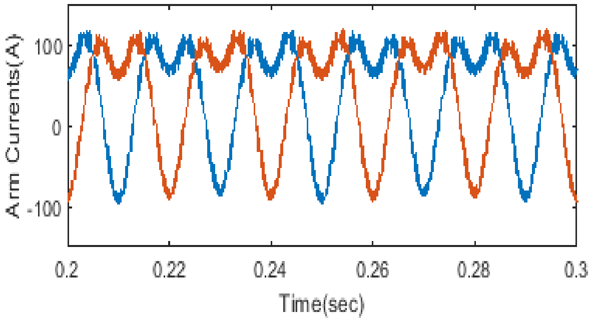


(c)

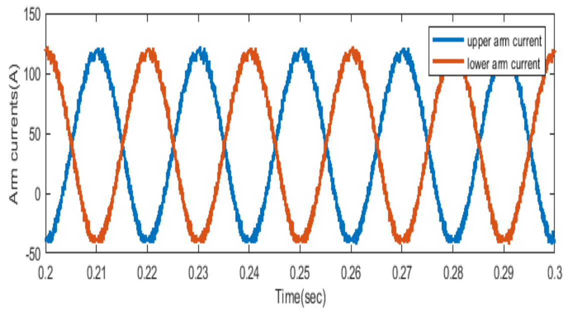
(d)

Figure 6: (a), (b) Voltage and Current with SMC (c), (d) Voltage and Current with Modified SMC

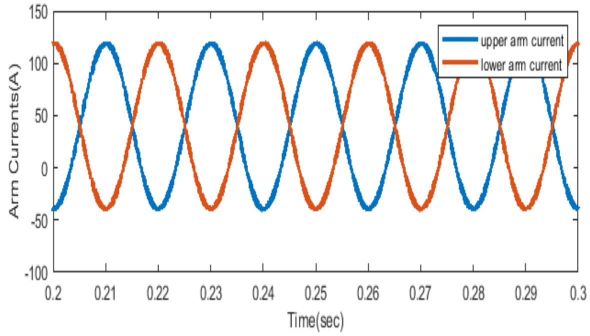
The Figure 7 shows the arm current waveforms for the three control techniques. From the waveform's we can justify that the arm currents are more ripple free in the proposed controller than normal SMC. The Figure 8 shows that the sum of arm capacitor voltage waveforms for three Controllers. By using the proposed controller the arm capacitor voltages are stable and reached its reference value when compared with other two controllers. From the Figure 7(c), one can observe that the reduction in RMS values of the arm currents and it further leads to reduction of internal losses with in arms of the converter. Similarly Figure 8(c) shows that capacitor voltage ripples are reduced by using the voltage balancing control.



(a)



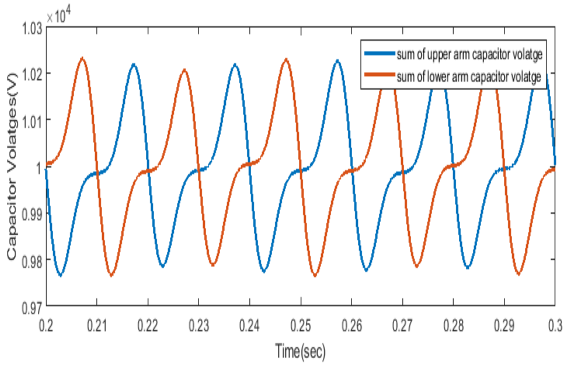
(b)



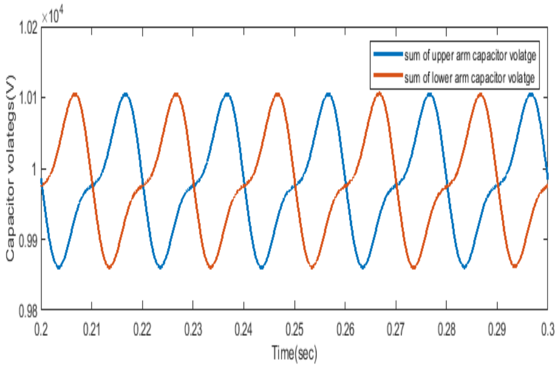
(c)

Figure 7: Arm current waveforms with (a) PI (b) SMC (c) Modified SMC controller

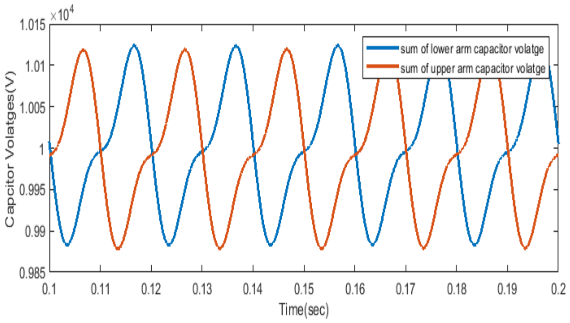
The SMC controller will considerably reduce the even order harmonics in the arm currents. However, it permits the required DC current to establish naturally charging and discharging process of the capacitors. However conventional PI controller is unable to reduce the even order harmonics in the inner current of the converter which is shown in Figure 9(a). In the Figure 9(b) it clearly shows that SMC control will reduce the circulating harmonic currents when compared to conventional PI controller. But SMC will not balance the capacitor voltages perfectly. The proposed controller will further reduce the harmonics in the circulating current with perfect balancing among the arm capacitor voltages shown in Figure 9(c) and Figure 8(c).



(a)



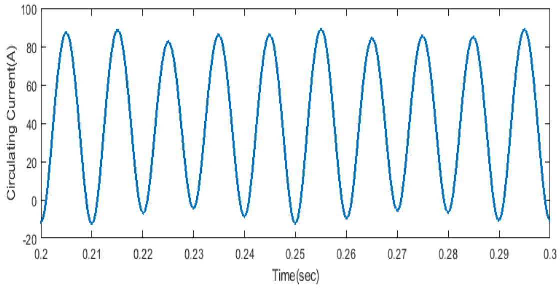
(b)



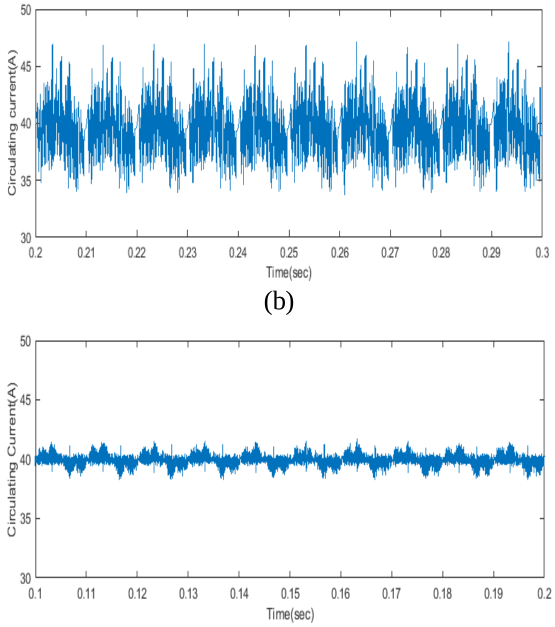
(c)

Figure 8: Capacitor voltage waveforms with (a) PI (b) SMC (c) Modified SMC controller

The harmonic analysis of circulating current with proposed controller when compared with SMC evidently shows that second harmonic component is reduced significantly. When there is no differential current control there is no addition of V_{diff} component into the reference generated signal and the number of submodules activated at any time in each phase leg of MMC is maintained constant i.e. N as defines by PWM. In contrast, the inner current controller generates V_{diff} signal and then added to the reference signal to eradicate the harmonics in inner current with different number of submodule selection but its average is N only.



(a)



(b)

(c)

Figure 9: Circulating currents with (a) PI (b) SMC (c) Modified SMC

5. CONCLUSION

This paper presents a modified SMC for MMC that diminishes the inner currents in the arms of each phase by removing the harmonic components and accounts the performance of the MMC. The proposed modified SMC controller will removes the circulating current can also improves the system performance. The arm currents Root Means Square value is controlled which leads to the reduction of converter losses. The conventional PI control will reduce the steady state error but it does not affect the harmonic components and SMC will reduce the harmonic component when related with PI controller but the proposed controller proficient in reducing the harmonic components with faster dynamic response with less computational efforts which is required for the system. The results obtained through simulation are presented to demonstrate the important characteristics of the strategic current controller as contrasting with the conventional control method of PI and SMC.

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