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ANALYSIS AND SIMULATION OF CURRENT CONTROL TECHNIQUES FOR CIRCULATING CONTROL OF MODULAR MULTI-LEVEL CONVERTER

M. VENKATESH[1] AND K. CHANDRA SEKHAR

ABSTRACT. The modular multilevel converter (MMC) is most popular because of its high efficiency, flexibility, low harmonic distortion, usages of low power rating devices, high modularity and 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 reduced switching frequency technique (RSF) in voltage balancing in MMC legs, the average device switching frequency 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. In this paper different circulating current control techniques are compared such conventional PI, resonant control, sliding mode control. In that sliding mode controller suppresses the harmonic components, particularly 2nd harmonic in the inner current better than remaining controllers. This controller is implemented for single phase MMC which can be extended further for three phase system. The results of these controllers are validated through MATLAB/Simulink environment.

[1]*corresponding author*

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1. INTRODUCTION

Modular Multilevel Converter (MMC) has grown into more popular converter 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. Recently renewable energy sources are also depends on multilevel converter systems [2].

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, Increase in magnitudes of circulating current, decrease the life span of the device, reliability of the converter becomes a major challenge [3]. Recent literature [4-5] 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 [6] prospects were achieved experimentally with less number of current sensors, but the utilization of voltage sensors were not addressed in these studies. Recently online observers have been proposed for estimation of capacitor voltages. In more recent work, a seven-level MMC voltage balancing was achieved with only two voltage sensors, one for each 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-based approaches have been applied to a wide range in various power converters and electrical drives [7]. A sliding mode control (SMC)-based method is presented and compared with regular PI and Resonant controller [8] for the MMC. The fundamental model of the SMC is to use references of various controlled parameters to model the state space into different subspaces corresponds to a common control structure. In each sub module, the applied common control structure forces the controlled parameters to glide along the limits of the sliding surface. The proposed technique is compared with the conventional PI and Resonant controller which provides a faster dynamic response and equivalent steady state stability of the system.

2. Dynamics of the MMC

The three-phase circuit diagram of an MMC is shown in Fig.1. The MMC contains three legs and each leg is made up of two arms per phase, in which each arm is embraced of N half-bridge sub modules connected series with an inductor. Dynamic performance of the N-cell MMC is modelled and is given follows

$$\begin{aligned} \frac{di_p}{dt} &= \frac{1}{L_1}\left[E_p - \sum_{i=1}^{N}(S_i \times V_{ci}) - R_1 i_p - V_a\right], \\ \frac{di_n}{dt} &= \frac{1}{L_1}\left[E_n - \sum_{i=1+N}^{2N}(S_i \times V_{ci}) - R_1 i_n + V_a\right], \end{aligned}$$

where, $V_a = Ri_a + L\frac{di_a}{dt}$, $\frac{dV_{ci}}{dt} = \frac{1}{C}(i_p \times S_i), i = 1, ..., N$, and $\frac{dV_{ci}}{dt} = \frac{1}{C}(i_n \times S_i), i = N+1, ..., 2N$, in which i_p is upper arm current and in is lower arm current, 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 follows.

$$\overrightarrow{x} = Ax + Bu,$$

where, $x = [i_p i_n V_{c1} V_{c2} V_{c3} V_{c4} V_{c5} V_{c6} V_{c7} V_{c8}]^T$.

3. Control of MMC

3.1. **Resonant based Circulating Current Control.** The reference value of circulating current is obtained from the output power required and the average and differential voltages of submodule capacitors as shown in Fig.2. The output power consists of fundamental & second harmonic component, hence mean value can be obtained from MAF (Moving average filter) filter. The mean value

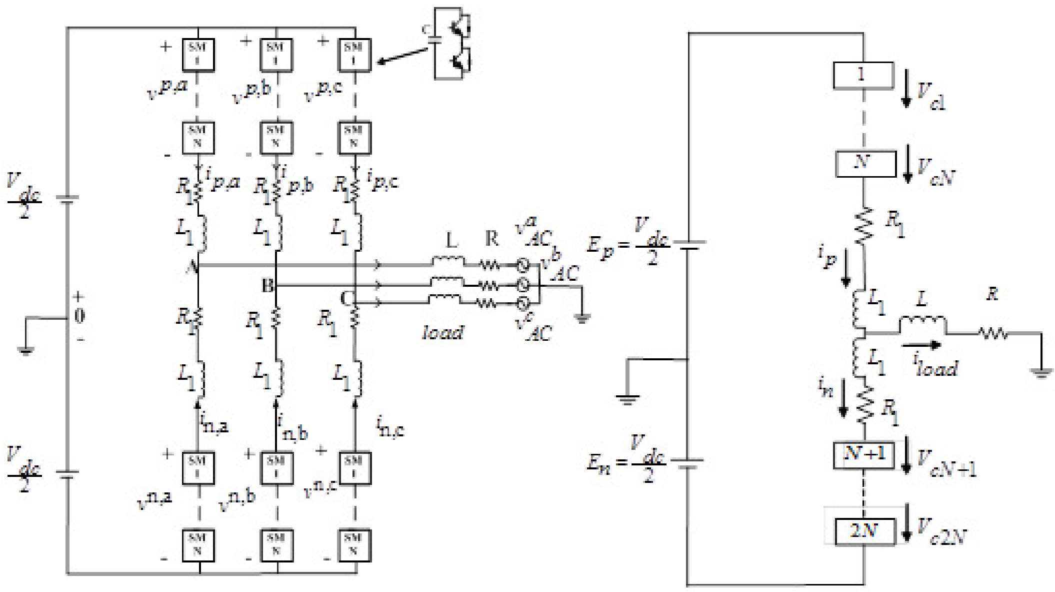

FIGURE 1. Three phase and single phase MMC circuit diagram

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 voltages. An extra fundamental component of AC current is required to maintain capacitor voltage balance between upper and lower arm. This reference circulating current is compared with actual circulating current and passes through proportional resonant controller, hence a control signal was attained from the controller to normalize the circulating currents is V_{diff} [9].

3.2. **Sliding Mode Control for Single Phase MMC.** In the sliding mode control method, two control variables such as load current and circulating currents are controlled by designing two control structures. Both control structures acts at a time to dynamism the corresponding control variable to glide along the boundary of inside a given range of the two control structures. First we are controlling one phase then it can be extended for three phase MMC which is shown in Fig. 3. In a single phase MMC, to control i_a and i_{diff}, proposed two control functions $f(.)$ and $g(.)$ in each control structure [10] is given as follows

$$f(.) = F.sgn(i_a - i_a^{ref}) = F.sgn(e_a), \tag{3.1}$$

$$g(.) = G.sgn(i_{diff} - i_{diff}^{ref}) = F.sgn(e_{diff}), \tag{3.2}$$

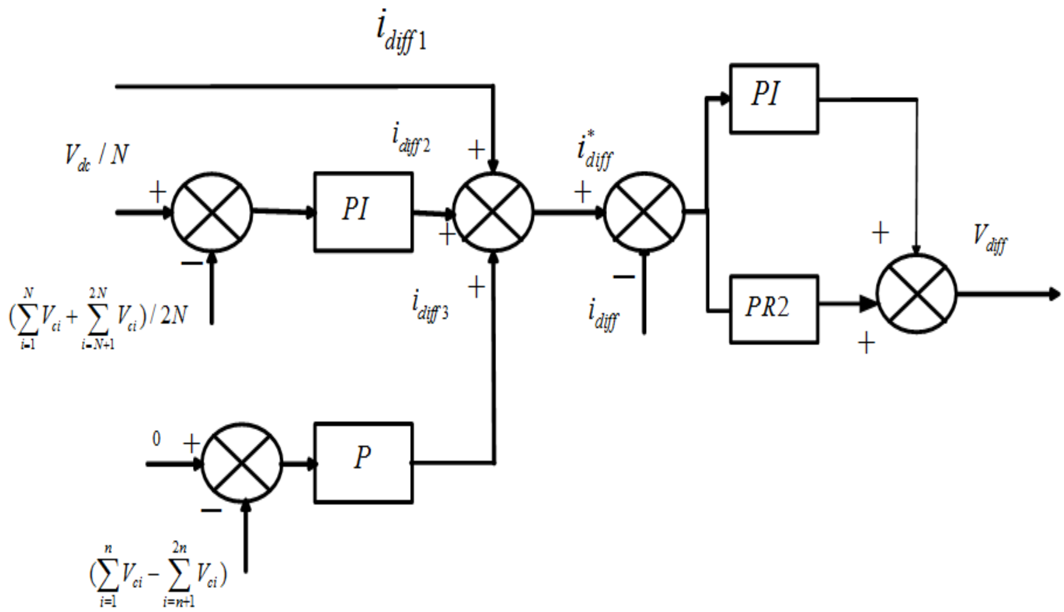

FIGURE 2. Resonant Circulating current control

where, $i_{com} = \frac{i_p+i_n}{2}$ and $i_{diff} = \frac{i_p-i_n}{2}$. Based on Eq. 3.1-3.2, the two control parameters adjusts itself based on their actively controlled current value and its reference value.

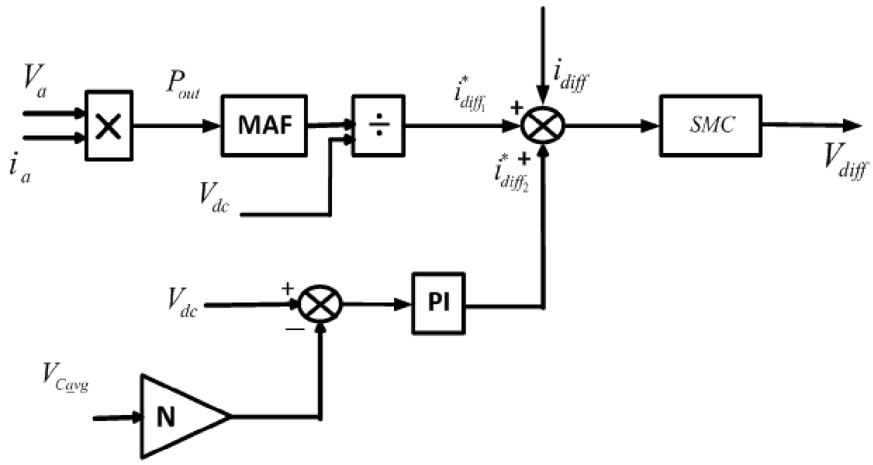

FIGURE 3. Sliding mode circulating current control

4. Simulation Results

To demonstrate the proposed control method effectiveness and performance, a single phase MMC with 4 submodules per 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, sliding mode control and proposed modified sliding mode control with PD-PWM. The phase voltage and current wave

TABLE 1. Simulation parameters using for MMC

Parameters	**Values**
No. of submodules per arm	4
DC link voltage	10 kV
Submodule reference voltage	2500 V
Submodule capacitor	2.7 mF
R_1 and L_1	0.02 Ω and 3 mH
Load, (R and L)	30 Ω and 2.3 mH

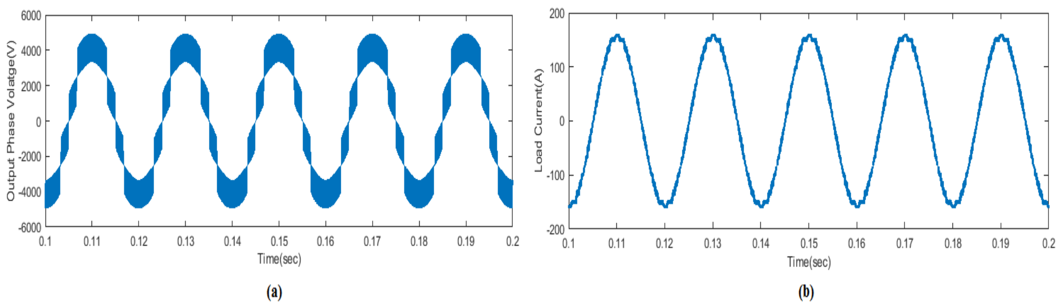

FIGURE 4. (a) Phase voltage; (b) Phase current

forms for single leg MMC are presented in Fig. 4(a)-(b). 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-leg control is independent for the remaining phases of the converter, hence the results shown are for single phase and then it can be prolonged for multi-phase systems.

Fig. 5(a) shows the arm current waveforms for the three control techniques. From the Fig. 5(b), 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. The SMC controller will considerably reduce the harmonic compo-

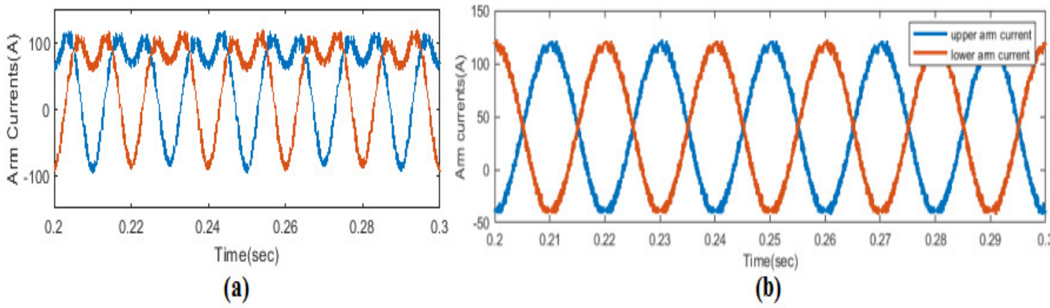

FIGURE 5. Arm current waveforms with, (a) PI; (b) PR and SMC control

nents in the arms currents of the converter when compared with remaining two controllers. However, it is allows the required dc current component to establish naturally charging and discharging process of the capacitors. The conventional PI control is unable to eliminate the second harmonic component in the circulating current which is shown in Fig. 6(a). The proposed SMC controller will further reduce the harmonics in the circulating current shown in Fig. 6(b). Fig.6(c) shows that Proportional Resonant controller will reduce the circulating harmonic currents when compared to conventional PI controller.

5. CONCLUSION

This paper presents sliding mode controller (SMC) for the MMC that diminishes the differential currents in the arms of each phase-leg of the MMC by removing the harmonic components and accounts the performance of the MMC. The root means square value of the arm currents 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 PR Controller will reduce the harmonic component when compared with PI controller but the proposed control method is proficient in reducing the harmonic components with faster dynamic response with less computational efforts which is required for the system. The results which obtained by Simulation are presented to illustrate the significant features of the strategic control method as contrasting to the conventional PI and PR control method.

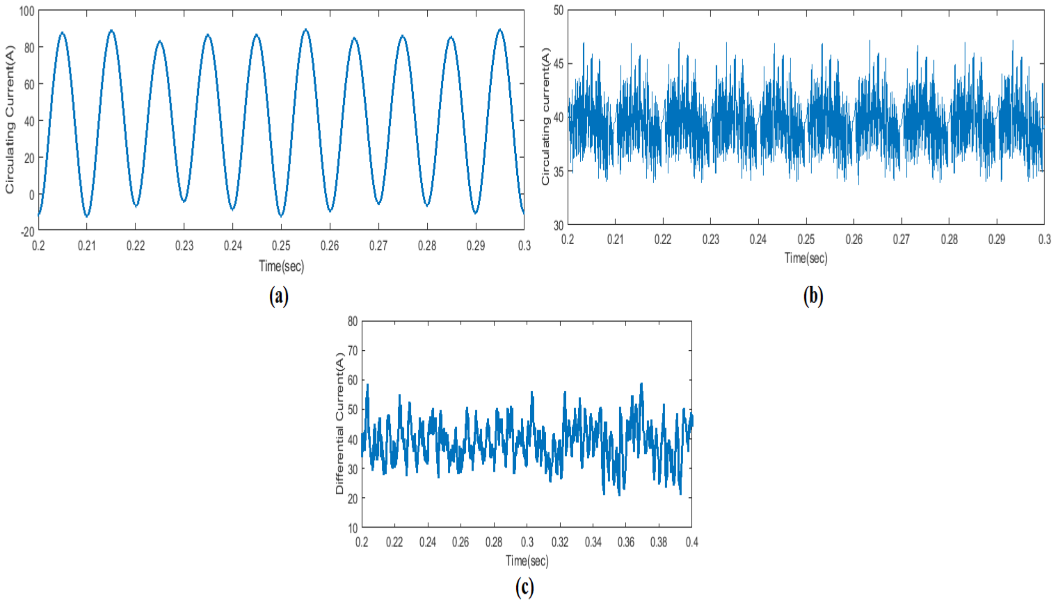

FIGURE 6. Circulating current with, (a) PI; (b) SMC control; (c) PR

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
GMR INSTITUTE OF TECHNOLOGY
RAJAM, ANDHRA PRADESH, INDIA
Email address: venkateshmudadla@gmail.com

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
RVR & JC COLLEGE OF ENGINEERING
GUNTUR, ANDHRA PRADESH, INDIA
Email address: cskoritala@gmail.com