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AC Circulating Current Control in Modular Multilevel Converter based on Estimation of Capacitor Voltages through Kalman Observer

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ABSTRACT

The modular multi-level converter (MMC) is a recently the most popular converter for high and medium voltage and power applications especially for Facts and HVDC transmission systems. But there are some technical problems in controlling the MMC in which one is balancing the voltages across the capacitor in each submodule without excessive switching of the power electronic devices. By using a reduced switching frequency technique (RSF) in voltage balancing in MMC legs, the average device switching frequency is reduced. This requires knowledge about an instantaneous capacitor voltage, so a Kalman observer is introduced for measuring instantaneous voltages across capacitors in each submodule. The proposed method needs only one current sensor per arm means two sensors for one leg. By using this method number of voltage sensors requisite will be reduced compared with the traditional voltage sensors method. So the sensor noise, system complexity, and cost will be minimized, consequently increasing the efficiency of the overall converter system. The Kalman observer estimates the capacitor voltages of each submodule by using arm currents and switching patterns. In addition to sensor cost problems, the paper also examines the effect of flowing current on the voltages of arm capacitors. This paper also deals with a controller that will control the circulating current in MMC. The efficiency of the proposed method is proved by simulating a single phase MMC using MAT LAB/ SIMULINK.

Key words: Sensors requirement; Phase-Disposition PWM; Kalman observer; Voltage balancing algorithm, Modular multilevel converter;

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.

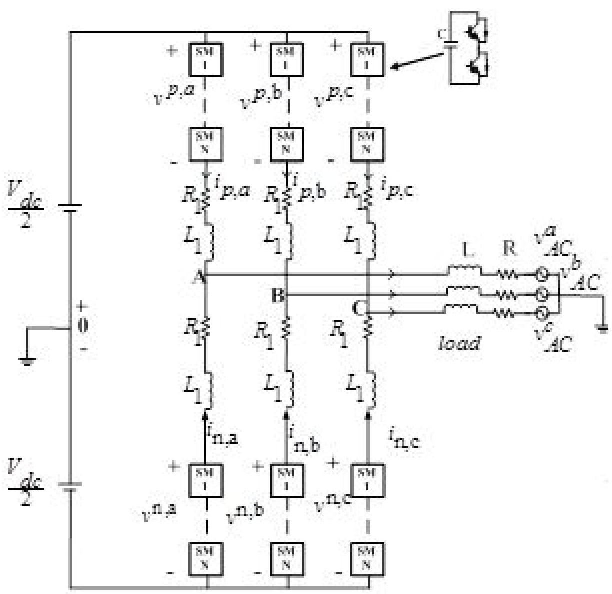
The modular multi-level converter consists of half bridge sub modules with capacitors, Inductors, along with various protective devices. Because of the modular structures the unequal voltage distributions among the capacitors will present in the system. This unequal voltage across the capacitor leads 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 [2]. Recent literature [3-4] 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. It also have an applications in solar energy storage systems and transformer less systems [5-6].

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. Some online observers are proposed recently for estimation of capacitor voltages [9]. In more recent work, for 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.

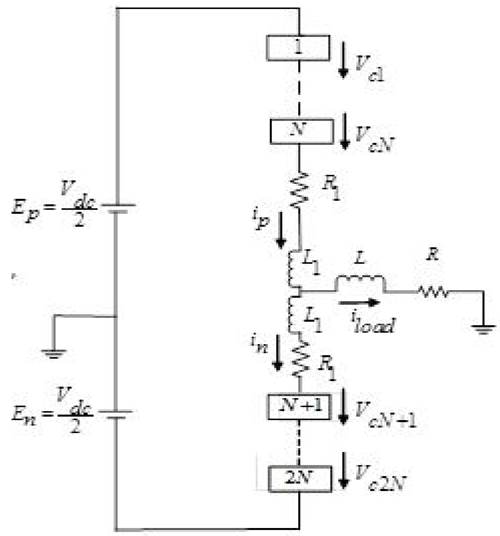
An efficient voltage estimation method was proposed in this paper which aims to reduce the sensors burden in the MMC to attain perfect voltage balancing. This method requires only one current sensor per arm then total of two current sensors per leg. The method of voltage estimation used is Kalman observer, which will consider noise effect also [10-11]. This approach minimizes the complexity of the system and overall cost of the system. To validate the proposed strategy, it is simulated on 5-level single phase MMC system. The simulation results shows the ability of Kalman observer to estimate the capacitor voltages. A restricted voltage balancing algorithm is used to control the switching losses in the power devices. Then a resonant controller is used as circulating harmonic current removal technique for controlling the harmonics in circulating current.

2. DYNAMICS OF MMC

The three-phase and single-phase circuit diagram of a MMC is shown in Figure 1. The three-phase MMC contains three legs and each leg is made up of two arms per phase, in which each 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.



(a)



(b)

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

Dynamic performance of the N-cell MMC is modelled as follows:

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

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

Where V_a is,

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

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

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

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

$$\overline{x} = Ax + Bu \quad (5)$$

Where,

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

$$A = \begin{bmatrix} A_1 & A_2 & A_3 \\ A_4 & 0 & 0 \\ A_5 & 0 & 0 \end{bmatrix} \quad (6)$$

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

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

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

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

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

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

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

3. KALMAN FILTER ESTIMATION METHOD

In the proposed estimation method, the state variables such as voltage across individual capacitors and arm currents are estimated by Kalman observer approach. This estimation methods requires the data of available input and output such as arm currents of the converter. Which means by using the two state variable information & input we can estimate the remaining states such as voltage across the capacitors. The Figure 2 shows the block diagram of MMC with Kalman observer in state space form.

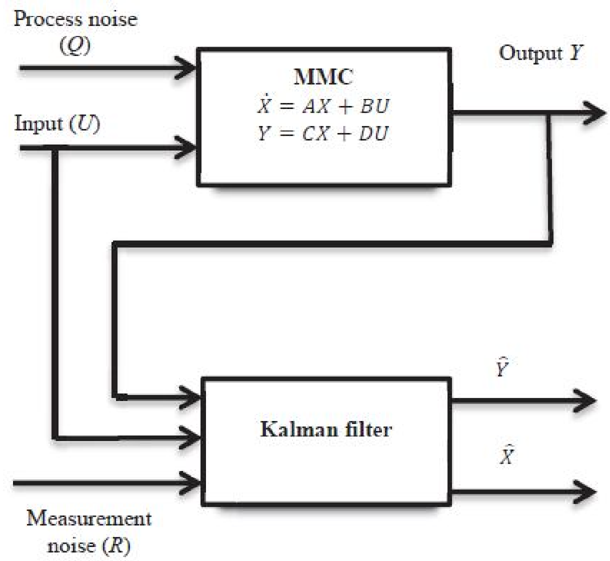


Figure 2: Block diagram of MMC with Kalman filter

Where Q is process noise and R is measured noise of sensors.

The data required for proposed Kalman observer is obtained from two current sensors each for one arm and a voltage sensor for measuring the input DC voltage for single-phase five-level MMC. The Kalman observer algorithm implements the following stages:

(i)Prediction stage:

Evaluate the predicted state and covariance using the following equations:

$$\hat{x}_{(k|k-1)} = A_{(k-1)}\hat{x}_{(k-1|k-1)} + B_{(k-1)}U_{(k-1)} \qquad (7)$$

$$P_{(k|k-1)} = A_{(k-1)}P_{(k-1|k-1)}A^T_{(k-1)} + Q_{(k-1)} \qquad (8)$$

Where P is the covariance matrix. In this stage we are injecting the initial values to state variables and covariance matrix.

(ii) Measurement Update stage:

The updated state and covariance can be obtained as:

$$\hat{x}_{(t|t)} = \hat{x}_{(t|t-1)} + K_t(Y_t - C_t\hat{x}_{(t|t-1)}) \qquad (9)$$

$$P_{(t|t)} = (I - K_tC_t)P_{(t|t-1)} \qquad (10)$$

Where, $K_t = P_{(t|t-1)}C_t^T(C_tP_{(t|t-1)}C_t^T + R_t)^{-1}$

In this stage first, we need to calculate the Kalman gain (K). By using the calculated gain and output state variable information, the state estimates values and covariance matrix are updated, then only it is again going back to stage one.

4. CONTROL OF MODULAR MULTI LEVEL CONVERTER

(a) 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 3 demonstrates the calculation procedures involves in voltage balancing of upper arm and vice versa for lower arm. In initial stage, the voltage of capacitors are multiplied by the negative sign of respective arm current. The positive sign of the current indicate charging and negative sign indicates discharging of sub-module capacitors.

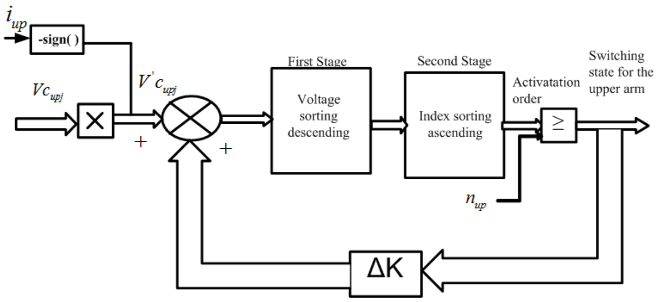


Figure 3: Restricted Voltage balancing algorithm

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 which is shown in Fig.3. 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.[12]. 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.

(b) Resonant based Circulating current control

In this control the reference values for circulating current is obtained from the output power requirement and the average and differential voltages of submodule capacitors as shown in Figure 4. The output power consists of fundamental & second harmonic component, hence mean value can be obtained from MAF (Moving average filter) filter. The mean value obtained is then divided with DC link voltage to achieve $i_{diff\,1}$. An extra DC component $i_{diff\,2}$ required to maintain capacitor voltage balanced, is obtained from the average capacitor voltages. An extra fundamental component of AC current is required to maintain the capacitor voltage balancing between upper and lower arms. 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} .[13].

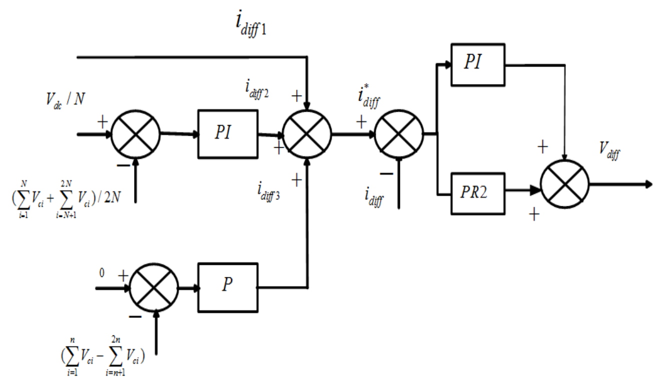


Figure 4: Resonant Circulating current control

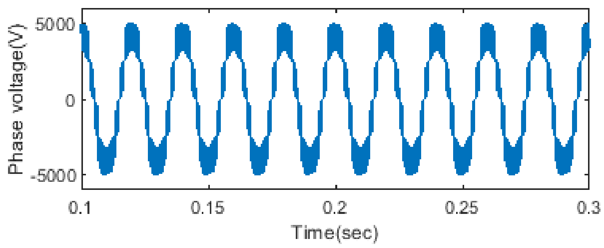
5. SIMULATION RESULTS

To prove the proposed control method effectiveness and performance, a single phase MMC with 4 submodules per arm is considered and the parameters considered for the circuit are tabulated in Table-1. The simulation in mat lab is carried out with two cases which are considered for both conventional PI control and sliding mode control with PD-PWM.

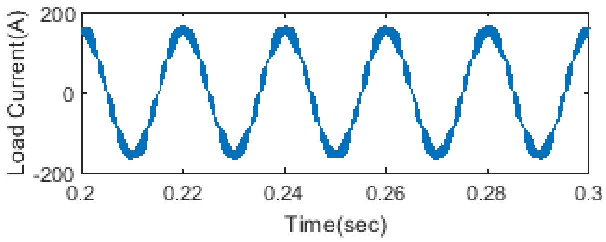
Table 1 Simulation parameters using for MMC

Parameter	Value
No. of submodules per arm	4
Dc link voltage	10kV
Submodule reference voltage	2500V
Submodule capacitor	2.7mF
Submodule inductor	3mH
Load R, L	30Ω, 2.3mH

The phase voltage and current wave forms for single leg MMC are presented in Figure 5 (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.



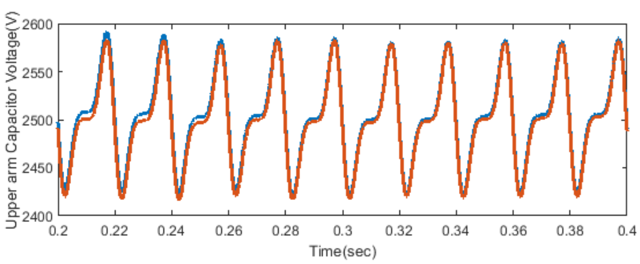
(a)



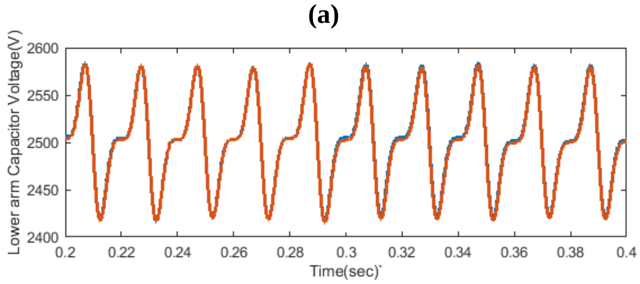
(b)

Figure 5: (a) Phase voltage (b) Phase current

Figure 6 shows the voltage across the upper arm capacitors C1 and lower arm capacitor C5, both estimated and measured values by considering the process and measurement noise. This shows the ability of KF to estimate the submodule capacitor voltage with adequate error.



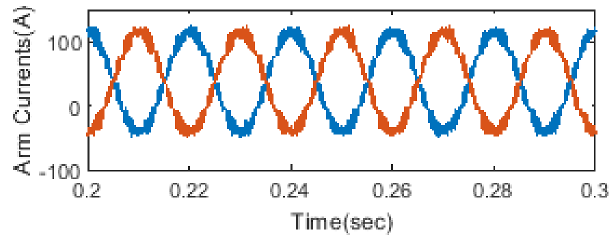
(a)



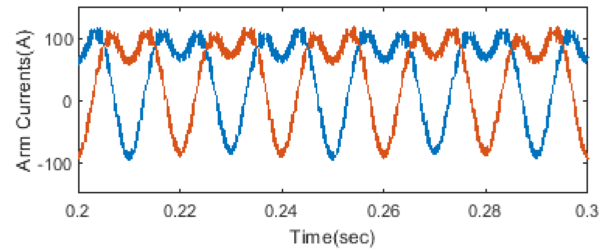
(b)

Figure 6: Measured and estimated (a) Capacitor voltage (C1) of Upper arm, (b) Capacitor voltage (C5) of Lower arm

Single phase arm currents and sum of upper and lower submodule capacitor voltage waveforms are shown in Figure 7 with conventional PI control and PR control. From the output waveforms Figure 7 (a),(b), one can observe 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 7 (c), (d) shows the reduction in capacitor voltage fluctuations by using PR controller when compared with conventional PI controller.



(a)



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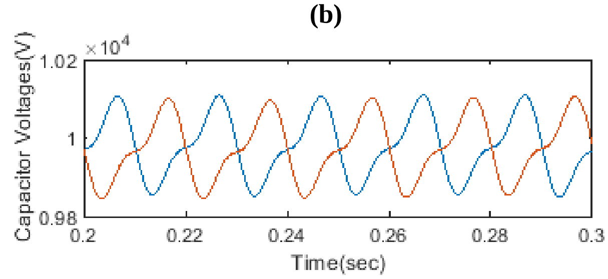
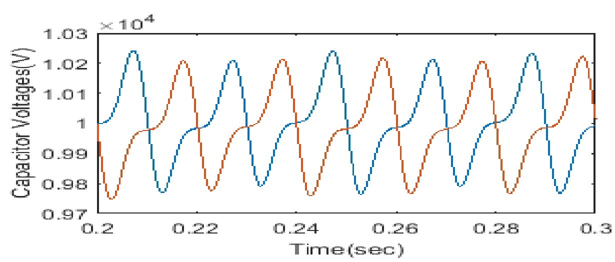


(c)



(d)

Figure 7: Upper and Lower arm currents and sum of Upper and Lower arm Capacitor Voltages of single phase MMC for (a), (c) PR controller, (b), (d) Conventional PI controller

The controller which is proposed in present paper can considerably diminish the harmonic components in arm currents of single–phase MMC, particularly second harmonic component. However, the controller will allows the required DC current component in the circulating current, which will helpful for charging and discharging of capacitors. The conventional PI control was incapable to eliminate the circulating harmonic currents which is shown in Figure 8. In the Figure 8 it clearly shows that Proportional plus Resonant control will reduce the circulating harmonic currents when compared to conventional PI controller.

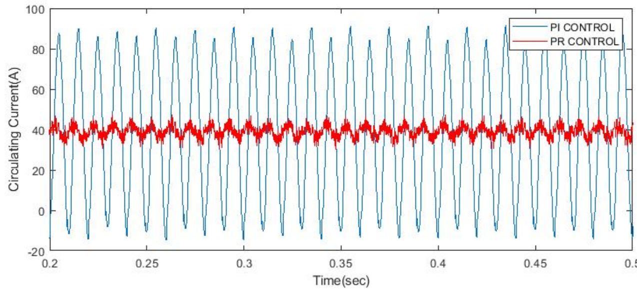


Figure 8: Circulating currents with PR and PI control

When there is no differential current control there is no addition of V_{diff} component into the reference generated signal. Hence the number of submodules activated in each phase leg of MMC at any time is maintained constant and it is equal to number of submodules in that arm i.e. N as defined by PWM. In contrast, when the differential current controller is permitted, it generates V_{diff} signal and then added to the reference signal which eradicates the harmonic components particularly second harmonic component of circulating current. This will try to changes the number of submodules connected in each phase leg fluctuates between (N-1) to (N+1), but its average is always equal to N only.

6. CONCLUSION

In this paper, an adaptive Kalman observer has proposed in MMC for estimation of capacitor voltages. The Kalman observer will effectively estimates the capacitor voltages by considering the noise effects that are process and measuring noise of sensors. By the results we can prove the ability of Kalman observer for estimation of capacitor voltage with reduced number of voltage sensors, hence cost of the converter will reduce and increase the reliability which is suitable for HVDC applications. The proportional plus resonant controller used in MMC will diminishes the differential current in arms of each phase-leg, by removing the harmonic components particularly second harmonic 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, but the proposed control method is proficient in reducing the harmonic components with faster dynamic response which is required for the system. The results which obtained by simulation are presented to prove significant features of PR controller as contrasting with conventional PI controller.

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