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An Enhanced Modular Multilevel Converter for the Mitigation of the Capacitor Voltage Ripple

Ramudu Ganji[1*]

[1] 5Department of Electrical and Electronics Engineering, Aditya University, Surampalem
E-mail: ramudug@adityauniversity.in

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***Abstract*—** Ripple in the module voltage is the common issue in the modular multilevel converter (MMC). To rectify this issue, an enhanced MMC has been implemented in this paper. The proposed converter contains the enhanced auxiliary circuit which is placed in between the arms of the converter and this converter operated at fundamental and below the fundamental frequencies operations of the load. The proposed auxiliary circuit has been designed with reduced number of components with the existing auxiliary circuits. The enhanced converter has been operated at 50 Hz and 10 Hz frequencies under steady state load condition. With these conditions, the proposed enhanced converter has improved performance in terms of voltage ripple reduction in module capacitor voltage, circulating current and arm voltage balancing because of the enhanced circuit is generating additional power which may redistribute from the top arms to lower arms of the converter which may compensate the ripple components in the capacitor voltage. Further the working operation of the proposed converter under steady state condition, mathematical approach, and proposed control strategy have to be explained in detail. The enhanced converter performance has been tested and verified with the MATLAB/SIMULINK and HIL test.

***Keywords*—** Enhanced MMC; Module capacitor voltage ripple reduction; Circulating current; Modified Proportional integral (PI) controller.

1. INTRODUCTION

Multilevel converters are used to transform and convert power from AC to DC and DC to AC with less harmonic distortion of the load voltage and current without filters. Basically, various multilevel converters [1, 2] are cascade H-bridge, flying capacitor and neutral point clamped converters. This type of converter is used in HVDC, AC grid [3, 4] and controls the speed motor drive application. These converters performed well but having some drawbacks such as requirement of dc sources, diodes and capacitors are more and also modularity problem. To overcome these drawbacks, modular multilevel converter was implemented by siemens in 2001. This converter has more advantages compared with the multilevel converter, i.e., modularity, scalability, and low THD. The drawback of MMC is module voltage unbalancing [5]. This issue occurred especially under fundamental and low frequency operation of the load. It causes the circulating current to pass through the phase of the converter. The relation between the branch voltage and circulating current discussed [6]. To reduce this issue, various techniques are implemented in literature review.

The injected harmonic power with the modulation technique has been implemented for the reduction of ripple components in capacitor voltage of each submodule [7, 5]. To rectify the issue, modified MMC topologies like active cross connected MMC [9], flying capacitor MMC [10]. These modified topologies are provided with an additional path to transfer the

* Corresponding author

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power from top arm to lower arm which causes reduced the ripple component in the module capacitor voltage. Although, they have some disadvantages, that is large number of additional submodules are required, and high value of the capacitor is required to create the additional path in between the arms of the phase of the converter. To rectify these disadvantages hybrid MMC [11] are developed which consists of the number of full bridge modules are inserted in the load side of the converter for the mitigation of ripples in each submodule voltage. Although, the size of converter further rises in cost of converter. The harmonic injection power method in each phase of the converter was implemented. This distributed harmonic power which is opposite of that of power transferred through each arm of the converter. Due to that reduced the circuit current further improves the performance of the converter [12]. With that reference, harmonic power is injected in between the branches of the converter through auxiliary circuit. The auxiliary consists of four switching devices and two module capacitors. The auxiliary circuit operated with high modulation frequency. Even though, it raises the complexity and switching losses of the converter.

Various modulation schemes are implemented to the MMC for balancing the module voltage at its base voltage. The modulation schemes are fundamental switching frequency modulation scheme, high switching frequency modulation scheme. The fundamental switching frequency modulation schemes are NLM (nearest level modulation), selective switching harmonic elimination methods, variable level control method [13] . These are implemented to conventional modular multilevel converter [14, 15]. These methods have drawback that is modulation error is generated during the duration of selection of switches. In the case of high frequency modulation technique, switching losses are increased which causes reducing efficiency. To rectify the drawbacks, the improved phase disposition modulation scheme has applied to the conventional MMC [16]. This new approach has given good performance in terms of module voltage and leg current, but it decreases the number of levels in the output voltage. To overcome this issue, hybrid modulation method [17] was applied to MMC with energy storage system. The hybrid modulation consists of fundamental frequency methods and carrier phase shift modulation methods. The fundamental switching frequency modulation was applied to half of the modules and carrier phase shift method was given remaining half of the modules in each arm of the converter. This method has given improved results like number of levels of the load voltage and balancing module voltage at their base value. However, it increased the harmonics in the load voltage.

From the observation of above survey, various hybrid modulation techniques and various modified topologies were implemented. Even though they have some drawbacks like a greater number of components are used for modified topologies, magnitude of the load voltage was distorted or over modulated due to the use of hybrid modulation techniques. To overcome these advantages, this paper proposed an enhanced auxiliary circuit with a smaller number of components which is placed in between the middle of arms of the converter. An enhanced circuit generating power which includes high frequency harmonic power, and it is transferred to each module. An enhanced auxiliary circuit semiconductor devices are operated at particular carrier frequency which is more than that of each module operated carrier frequency. Due to this harmonic power may be cancelled and further reduced the circulating current and also minimize the ripple voltages in each module voltage. The proposed converter operates with steady state load. The phase shift modulation technique is applied to the proposed converter.

The rest of this paper is going as. Section II represents the structure of model of the enhanced MMC. Analysis of proposed converter is discussed in section III. Section IV gives the diagram and explanation of Overall proposed control diagram. The proposed converter's performance is described with/ results of simulation and HIT test in section V and VI. Brings the paper conclusion in section VII.

2. AN ENHANCED MMC STRUCTURE CONFIGURATION

The diagram of three-phase MMC's with modified auxiliary circuit is depicted in Fig. 1 which contains four semiconductor devices and one capacitor. It consists of two branches, i.e., top and bottom branches which are connected in between the supply neutral and load neutral. The supply voltage is divided into Vdc/2 and -Vdc/2. Each branch has N number of modules. These modules are arranged in cascading nature with the branch inductors L1,x and L2,x. The arm inductors are to compensate for the high frequency components of branch current. Each module may be full bridge or half bridge circuit. Half bridge modules are preferred for the reduction switching losses. In half bridge circuit, two IGBTs are S1,x and S2,x connected with one capacitor Cm,x. These switches are operated in complementary manner.

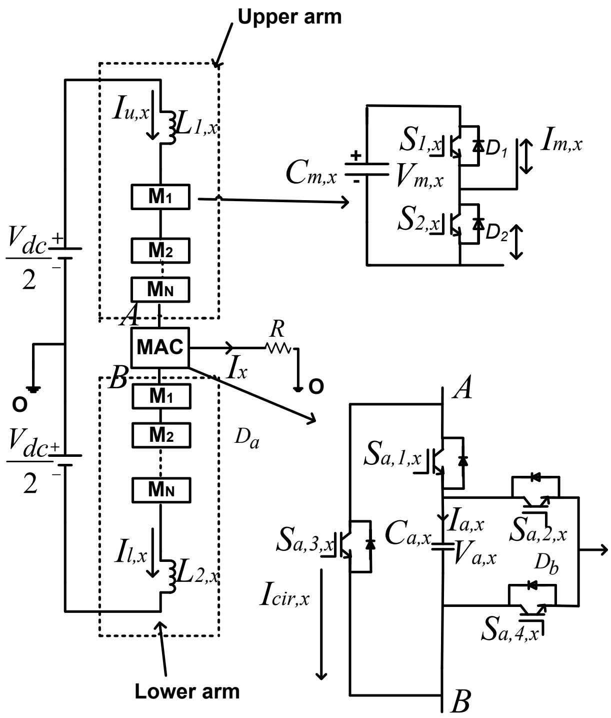


Fig. 1. Circuit structure of modified middleware submodule based MMC.

The module working operation as represented in Fig. 2. Each module is to transfer the power from supply source to load with the help of capacitors Cm,x.. When the dc source applied to branch of each phase, the branch current consists of top and bottom branch currents Iu,x and Il,x which are passing through each module. Due to this, module capacitors start charging and producing electric field voltage as represented as Vm,x. When the branch current is reversely flowing in the module capacitor then start discharging the voltage in it. Due to the continuous charging and discharging voltage in each module capacitor, capacitor does not maintain at its rated voltage i.e., it makes a oscillations. The ripples in each capacitor voltage of module causes losses are increases in the converter that means less power transmitted from source to the load. To reduce the ripples in each module voltage, the enhanced auxiliary circuit is placed in between the top and bottom branches. It helps to transfer the maximum power from source to load by reducing the ripple components in each module voltage and reduce the size of the converter with reference to existing modified MMC. The working operation of modified auxiliary circuits has been explained in section III.

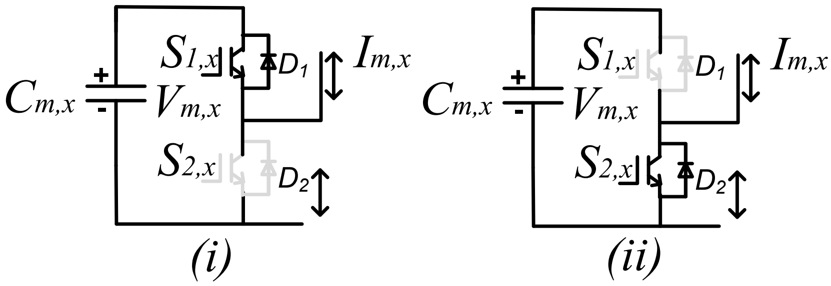


Fig. 2 Working operation of module.

The basic working operation of the module [18].

Conventional MMC upper branch voltage,

$$V_{u,x} = \frac{V_{dc}}{2} - V_p \, Sin\omega t \tag{1}$$

Likewise, down branch voltage,

$$V_{l,x} = \frac{V_{dc}}{2} + V_p \, Sin\omega t \tag{2}$$

Here V_p is the peak voltage of the load, x is the phases of R, Y, and B.

Load Voltage,

$$V_x = V_p \, Sin\omega t \tag{3}$$

Load Current or AC current

$$I_x = I_p \, Sin(\omega t - \theta) \tag{4}$$

Here I_p is the peak current of the load, θ is the angle generated by the R-L load between the load voltage and the load current.

Generally, each branch current includes a DC, AC, and harmonic component. So, upper branch current is denoted by:

$$I_{u,x} = \frac{I_{dc,x}}{2} + I_{nh,x} Sin(nh(\omega t - \theta)) + I_p \, Sin(\omega t - \theta) \tag{5}$$

where nh represents the nth order harmonic, n= 2,4,6 …

Lower branch current,

$$I_{l,x} = \frac{I_{dc,x}}{2} + I_{nh,x} Sin(nh(\omega t - \theta)) - I_p \, Sin(\omega t - \theta) \tag{6}$$

Combining the Eqs. (5) and (6), then get the circulating current:

$$I_{cir,x} = (I_{u,x} + I_{l,x})/2 \tag{7}$$

The upper branch power $P_{u,x}$, $P_{u,x} = V_{u,x} I_{u,x}$ (8)

By substituting Eqs. (1) and (3) in Eq. (8),

$$P_{u,x} = \left(\frac{V_{dc,x}}{2} - V_p \, Sin\omega t\right)\left(\frac{I_{dc,x}}{2} + I_{nh,x} Sin(nh(\omega t - \theta)) + I_p \, Sin(\omega t - \theta)\right)$$

$$P_{u,x} = \frac{V_{dc,x}}{2}\frac{I_{dc,x}}{2} + \frac{V_{dc,x}}{2} I_{nh,x} Sin(nh(\omega t - \theta)) + \frac{V_{dc,x}}{2} I_p \, Sin(\omega t - \theta) - V_p \frac{I_{dc,x}}{2} Sin\omega t - V_p \, I_{nh,x} Sin\omega t \, Sin(nh(\omega t - \theta)) - V_p I_p Sin\omega t \, Sin(\omega t - \theta)$$

$$P_{u,x} = \frac{V_{dc,x} I_{dc,x}}{4} + \frac{V_{dc,x}}{2} I_{nh,x} Sin(nh(\omega t - \theta)) + \frac{V_{dc,x}}{2} I_p \, Sin(\omega t - \theta) - V_p \frac{I_{dc,x}}{2} Sin\omega t - \frac{V_p I_{nh,x}}{2} Cos(\omega t - \theta) + \frac{V_m I_{nh,x}}{2} \, Cos((n+1)h(\omega t - \theta)) -$$

$$\frac{V_pI_p}{2}Cos\,\theta + \frac{V_pI_p}{2}\,Cos(nh(\omega t-\theta)) \quad (9)$$

The lower branch power $P_{l,x}$,

$$P_{l.x} = V_{l,x}I_{l,x} \quad (10)$$

By substituting the Eqs. (2) and (4) in Eq. (10),

$$P_{l,x} = \left(\frac{V_{dc,x}}{2} + V_p\,Sin\omega t\right)\left(\frac{I_{dc,x}}{2} + I_{nh,x}Sin(nh(\omega t-\theta)) - I_p\,Sin(\omega t-\theta)\right)$$

$$P_{l,x} = \frac{V_{dc,x}I_{dc,x}}{4} + \frac{V_{dc,x}}{2}I_{nh,x}Sin(nh(\omega t-\theta)) - \frac{V_{dc,x}}{2}I_p\,Sin(\omega t-\theta) + V_p\frac{I_{dc,x}}{2}Sin\omega t + V_pI_{nh,x}\,Sin\omega t\,Sin(nh(\omega t-\theta)) - V_pI_pSin\omega t\,Sin(\omega t-\theta)$$

$$P_{l,x} = \frac{V_{dc,x}I_{dc.x}}{4} + \frac{V_{dc,x}}{2}I_{nh,x}Sin(nh(\omega t-\theta)) - \frac{V_{dc,x}}{2}I_p\,Sin(\omega t-\theta) + V_p\frac{I_{dc,p}}{2}Sin\omega t + V_pI_{nh,x}\,Cos(\omega t-\theta) - V_pI_{nh,x}\,Cos((n+1)h(\omega t-\theta)) - \frac{V_pI_p}{2}Cos\,\theta + \frac{V_pI_p}{2}\,Cos(nh(\omega t-\theta)) \quad (11)$$

From the Eqs. (9) and (10), each branch power contains dc component, fundamental ac component and harmonic ac component powers

By adding Eqs. (9) and (11), then get the phase power

$P_{phase,x}$ $P_{phase,x} = P_{u,x} + P_{l,x}$

$$P_{phase,x} = \frac{V_{dc,x}I_{dc,x}}{2} + V_{dc,x}I_{nh,x}Sin(nh(\omega t-\theta)) - V_pI_p\,Cos\,\theta + \frac{V_pI_p}{2}\,Cos(nh(\omega t-\theta)) \quad (12)$$

The phase power consists of D.C power, A.C power and harmonic power. Branch inductances can be used to remove the higher order harmonics.

The lower order harmonic power causes the harmonic circulating in each phase of the converter. Due to that, high frequency ripples are developed in each module capacitor voltage and also increases the rating of the switching devices which increases the conduction losses and switching losses further reduces the efficiency of the converter.

3. AN ENHANCED AUXILIARY CIRCUIT STRUCTURE AND ITS OPERATION

An enhanced auxiliary circuit is inserted in between point A and B of modular multilevel converter shows in Fig. 1. The enhanced auxiliary circuit is constructed with a smaller number of components compared with the existing auxiliary circuit. The components are represented by $S_{a,1,x}$, $S_{a,2,x}$,$S_{a,3,x}$ and $S_{a,4,x}$ and capacitor $C_{a,x}$.

The working operation of switches of the enhanced auxiliary circuit are explained with the help of diagrams which are depicted in Fig. 3.

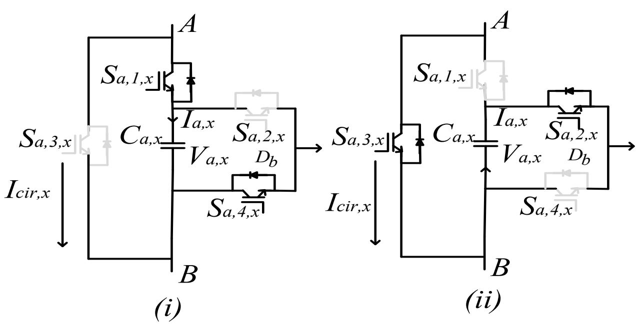


Fig. 3. Working operation of an enhanced auxiliary circuit.

These are operated by high switching frequency modulation techniques compared with the conventional module switching frequency. When the switches $S_{a,1,x}$, $S_{a,3,x}$ are turned on, the capacitor $C_{a,x}$ start charging and producing voltage $V_{a,x}$. This voltage also consists of DC, AC and high frequency component voltage. When the switches $S_{a,2,x}$, $S_{a,4,x}$ are turned on, the $C_{a,x}$ start discharging. In both conditions, the capacitor voltage is opposite that of each branch module voltages. Due to this reason, the ripple components in each module voltages decreased in each phase of the converter and also consistently maintained at its base value.

Analysis of An Enhanced Auxiliary Circuit

To reduce the low order ripple component in each module voltage, an enhanced auxiliary circuit was designed. It created the power which is opposite of the P_{phase}.

From the Enhanced auxiliary circuit MMC topology,

$$V_{u,x}^{1} = V_{u,x} + V_{nr,x}^{*}$$

$$V_{nr,x}^{*} = V_{u,x} - V_{u,x}^{1} \quad (13)$$

$$V_{l,x}^{1} = V_{l,x} - V_{nr,x}^{*}$$

$$V_{nr,x}^{*} = V_{l,x} + V_{l,x}^{1} \quad (14)$$

Here v_{nr}^{*} is developed by an enhanced circuit.

$$V_{nr,x}^{*} = V_{a,x}\, Sin\omega_{nr}t = -V_{b,x} Sin\omega_{nr}t \quad (15)$$

Due to v_{nr}^{*} is produced in $V_{a,x}$, the ripple current I_{nr}^{*} opposite to ripple current I_{nr} in each module of normal MMC.

Likewise, from an enhanced auxiliary circuit MMC,

$$I_{u,x} = I_{cir,x} + \frac{I_p}{2}\, Sin(\omega t - \theta) - I_{nh,x}^{*}$$

$$I_{l,x} = I_{cir,x} - \frac{I_p}{2}\, Sin(\omega t - \theta) - I_{nh,x}^{*} \quad (17)$$

where $I_{nh,x}^{*} = I_{a,x} = -I_{a,x}$

For a lossless converter, the active power formula is:

$$V_{dc,x}\, I_{cir,x} = \frac{V_p I_p}{2} Cos\ \theta$$

$$I_{cir,x} = I_{dc,x} = \frac{p}{4}\, I_p\, Cos\ \theta \quad (18)$$

From the Eqs. (3) and (4), the leg current is passing in each phase of the converter, it includes DC and harmonic component current and is given by

$$I_{cir,x} = I_{dc,x} + I_{nh,x} = (I_{u,x} + I_{l,x})/2 \quad (19)$$

Now the Eqs. (5) and (6) can be written as [19],

$$I_{u,x} = \frac{I_p}{2}\, Sin(\omega t - \theta)(1 + pSin(\omega t) \quad (20)$$

$$I_{l,x} = \frac{I_p}{2}\, Sin(\omega t - \theta)(1 - pSin(\omega t) \quad (21)$$

Now substitute Eqs. (18), (20) in Eq. (16), then

$$I_{nh,x}^{*} = I_{cir,x} + \frac{I_p}{2}\, Sin(\omega t - \theta) - I_{u,x} \quad (22)$$

$$I_{nh,x}^{*} = \frac{p}{4}\, I_p\, Cos\ \theta + \frac{I_p}{2}\, Sin(\omega t - \theta) - \frac{I_p}{2}\, Sin(\omega t - \theta)(1 + pSin(\omega t) \quad (23)$$

$$I_{nh,x}^{*} = \frac{p}{4}\, I_p\, Cos\ \theta - \frac{I_p}{2}\, pSin(\omega t - \theta) Sin(\omega t) \quad (24)$$

$$I_{nh,x}^{*} = -p\frac{I_p}{4}\, Cos(nh(\omega t - \theta)) \quad (25)$$

Here nh= 2,4,6 …

Now the ripple voltage developed from the enhanced circuit,

$$V_{nr,x}^{*} = \int I_{nh,x}^{*}\, d\,t \quad (26)$$

Substitute Eq. (25) in Eq. (26),

$$V_{nr,x}^{*} = \frac{1}{C_{a,x}} \int -p\frac{I_p}{4}\, Cos(nh(\omega t - \theta))\ d\,t \quad (27)$$

$$V_{nr,x}^{*} = -p\,\frac{I_p}{4\omega C_{a,x}} Sin\ (nh(\omega t - \theta)) + \partial \quad (28)$$

Here ∂ is constant parameter

At initial value of t,

$$V_{nr,x}^{*} = -p\frac{I_p}{4\omega C_{a,x}} Sin(nh(\omega t - \theta)) + p\frac{I_p}{4\omega C_{a,x}} Sin\,\theta \quad (29)$$

It is produced when the module voltage makes a high order ripple. This indicates that a enhanced circuit is used to balance each module voltage at its rated value. In addition to maintaining a rated capacitor voltage, the enhanced circuit's capacitor voltages add up to zero. The objective of this circuit is part of the converter to transfer power from supply source to load in addition to lowering the ripple component in capacitor voltage.

4. CONTROL SCHEMES FOR AN ENHANCED MMC

To operate the switches of enhanced auxiliary circuit MMC, various modulations are there, but phase shift modulation techniques are implemented. Each module in modular multilevel converter is running with the low modulation frequency which is mentioned in Table 1. The modified circuit operates with high frequency phase shift modulation technique. The control schematic of modified auxiliary circuit MMC is represented in Figure. Basically, three types of controllers are used in MMC such as module voltage control, branch voltage control, and average branch voltage control. These controllers are required to balance the module capacitor voltage further, improving converter steady state performance. In module voltage control, each module capacitor voltage is compared with the base voltage. In branch voltage control, upper branch voltage is compared with lower branch voltage of each phase of the converter. In average branch voltage control, average of each branch voltage is compared with the reference module voltage.

To maintain stability of the proposed system and reduction of module voltage ripples in the converter, a proposed controller is designed to an enhanced MMC system. The proposed controller diagram is depicted in Fig. 4. Mean control diagram is indicated in Fig. 4(i). In that means module voltage control, calculated the meaning of branch module voltages and compared these voltages.

To mitigate error PI controller is used and after getting signal is added with reference current signal. This reference current signal again compared with actual current in each branch. After comparing the resultant signal is multiplied with proportional controller then get adjusted mean voltage of each module of the converter. Similarly, the phase controller, individual controller and modified controller for the enhanced circuit are depicted in Figs. 4(ii), 4 (iii) and 4(vii). From these all controller, adjusted signals are getting which are given to the carrier shift modulation method.

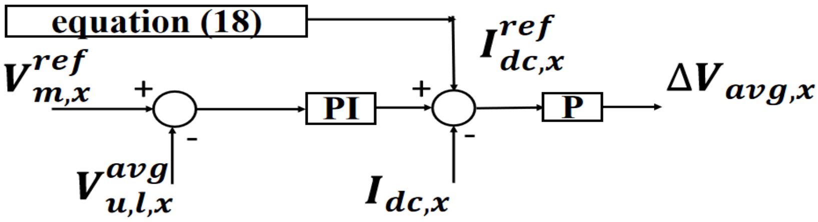
From the modulation techniques various pulses are generated which are applied to the switches of each module of the converter. These controllers are helpful for increasing the system's performance.

From various controller methods, reference voltages for the top branch, bottom branch and enhanced auxiliary circuits are as:

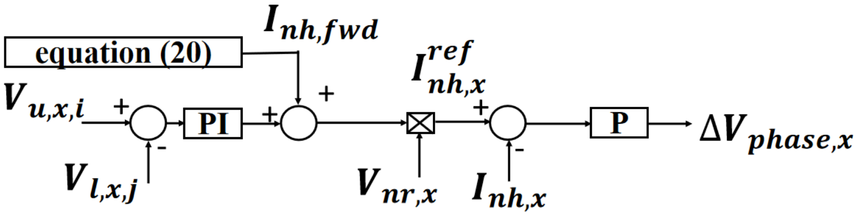
$$V_{u,x}^{ref} = V_{u,x}^{measured} - V_{nr,x}^{*} - V_x + \Delta V_{avg} + \Delta V_{phase} + \Delta V_{ind} \quad (27)$$

$$V_{l,x}^{ref} = V_{l,x}^{measured} + V_{nr,x}^{*} + V_x + \Delta V_{avg} + \Delta V_{phase} + \Delta V_{ind} \quad (28)$$

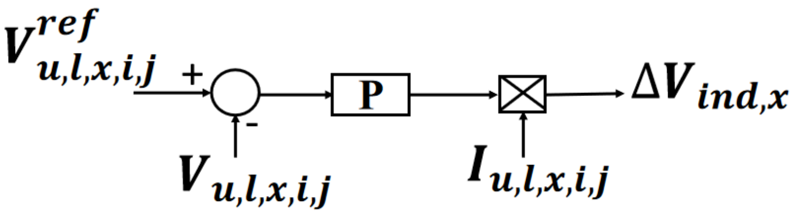
$$V_{nr,x}^{ref} = V_{nr,x}^{*} + \Delta V_{a,x} \quad (29)$$


equation (18)
$V_{m,x}^{ref}$
$V_{u,l,x}^{avg}$
PI
$I_{dc,x}^{ref}$
$I_{dc,x}$
P
$\Delta V_{avg,x}$

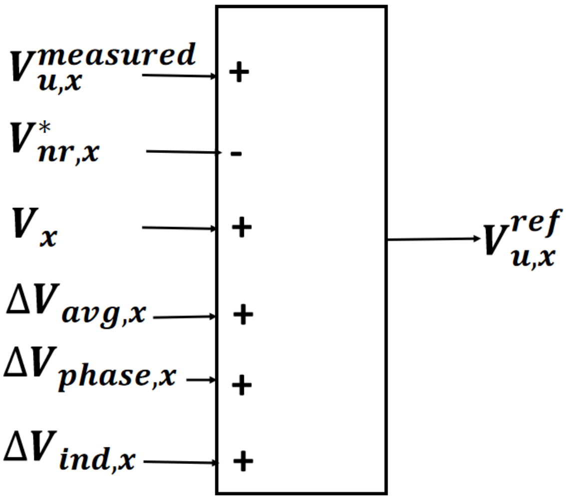
(i)


equation (20)
$I_{nh,fwd}$
$V_{u,x,i}$
$V_{l,x,j}$
PI
$I_{nh,x}^{ref}$
$V_{nr,x}$
$I_{nh,x}$
P
$\Delta V_{phase,x}$

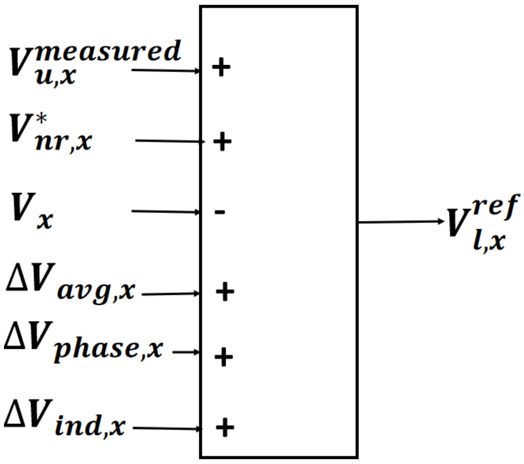
(ii)


$V_{u,l,x,i,j}^{ref}$
$V_{u,l,x,i,j}$
P
$I_{u,l,x,i,j}$
$\Delta V_{ind,x}$

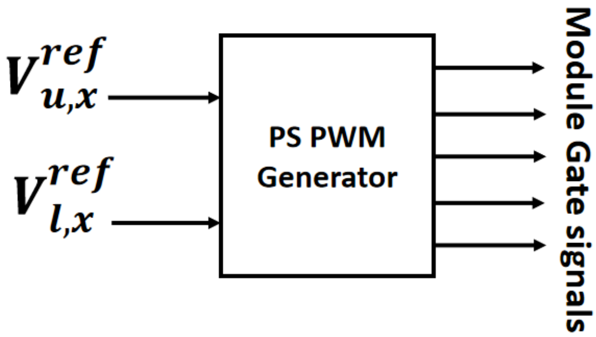
(iii)


$V_{u,x}^{measured}$
$V_{nr,x}^{*}$
V_x
$\Delta V_{avg,x}$
$\Delta V_{phase,x}$
$\Delta V_{ind,x}$
$V_{u,x}^{ref}$

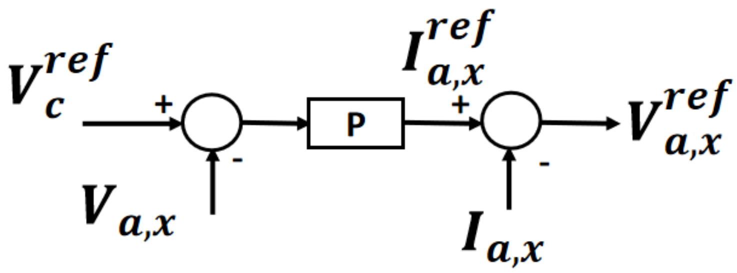
(iv)


$V_{u,x}^{measured}$
$V_{nr,x}^{*}$
V_x
$\Delta V_{avg,x}$
$\Delta V_{phase,x}$
$\Delta V_{ind,x}$
$V_{l,x}^{ref}$

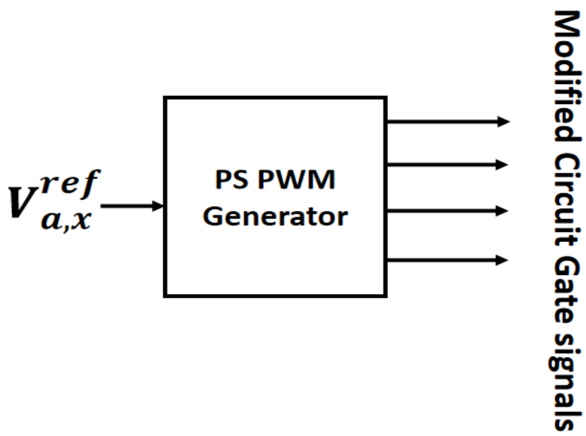
(v)



(vi)



(vii)



(viii)

Fig. 4. Proposed control diagrams of an enhanced MMC topology.

5. SIMULATION RESULTS

The enhanced auxiliary circuit of modular multilevel converters have been implemented using MATLB/Simulation and the converter parameters as indicated in Table-1.

Fig. 5 gives the proposed model simulation results at steady-state conditions and running at fundamental frequency. Fig. 5(i) represents the proposed model output voltage, and it varies -Vdc/2 to Vdc/2. Due to the placing of two modules in each branch, the output voltage contains five levels. According to the load parameters, the output current varies from -8.4 A to 8.4 A and it is depicted in Fig. 5(ii). The top branch and bottom branches are operating in complementary manner due to the supply voltage. Each branch current contains DC, AC and harmonic components which are shown in Fig. 5 (iii). These vary from -3.8 A to 6.1 A. According to the working operation of the proposed converter, each module should maintain at 100 V. But the harmonic current is passing through each module capacitor, it is maintained at its base value with oscillations, and these are called ripples. Each module voltage is represented in Fig. 5 (iv) and these are also peak to peak ripple component with respect to its rated value of 2.5 % of base value. The upper branch and lower branch voltages are not equal which results in the circulating current passing through each phase of the enhanced converter and it is indicated in Fig. 5 (v).

Table 1. Converter Parameters of Enhanced MMC for simulation and RT-LAB.

Symbol	Variable name	Base value
V_x	Load voltage	100 V
I_x	Load current	8.6 A
R_x,L_x	Load resistor and inductor	2.86 ohm, 28.6 mH
V_{dc}	DC source voltage	200 V
N	Number of modules per branch	2
f	Fundamental load frequency	50 Hz
f_C	switching frequency	1000 Hz
f_h	Square wave frequency	100 Hz
$L_{1,x}$ and $L_{2,x}$	Arm inductance	4.7 m H
Cm, x	Module Capacitance	600 μF
Vm, x	Module capacitance-voltage	100 V

6. HARDWARE IN-LOOP TEST RESULTS

The proposed system has been implemented in hardware in-loop test to verify the simulation results at the same load condition. The hardware in-loop test results are determined using a Tektronix MDO403, 100MHz, GS/s oscilloscope. When it is activated, send a signal in order to accurately record the transients, see Fig. 6.

In order to balance the module voltage at its base value, proposed converter has been tested in the HIL test which interacts with MATLAB/SIMULINK by Hardware in-loop (HIL) test. In this, each signal is reduced by 100 multiplication factors.

Fig. 7 represents the load voltage, load current and branch currents of the proposed system at the RL load and running at fundamental load frequency. The load voltage varies -100 V to 100 V according to the supply voltage and it contains five levels due to the use of two modules in each branch of the proposed system.

Likewise, the load current is also varying from -8.4 A to 8.4 A according to the load resistor and inductance value. The top and bottom branch currents are opposite manner.

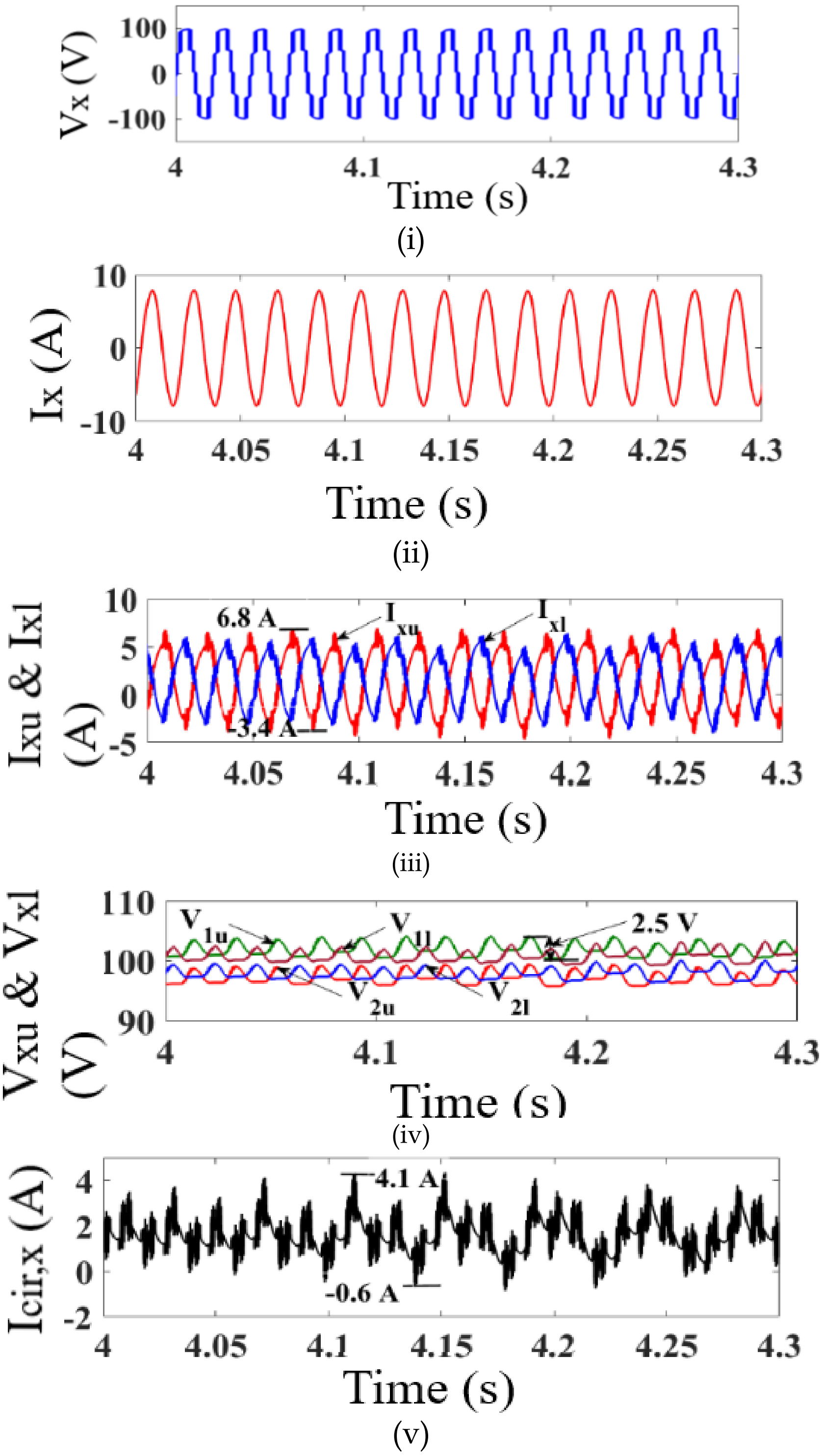


Fig. 5. Proposed system simulation results at 50 Hz of i) Load voltage; ii) Load current; iii) top and bottom branch currents; iv) top and bottom branch module voltages; v) circulating current.

Fig. 7 (ii) depicts each module voltage with reduced ripple components i.e., 2.5% of the base value at the fundamental frequency of 50 Hz. Fig. 7 (iii) denoted the modified circuit capacitor voltage, and it is also balanced at its rated value. Suppose the converter load operates below the fundamental frequency i.e. 10 Hz. Because the module voltage is inversely related to the load frequency in this case, the module capacitor voltage oscillates more which is more than 20% according to IEEE 519 standards. With the added of the modified auxiliary circuit between arms of the converter, there are fewer oscillations in the module capacitor voltage, indicating a lower ripple component i.e., 9% and it is acceptable which is observed by showing the Fig. 7 (iv).

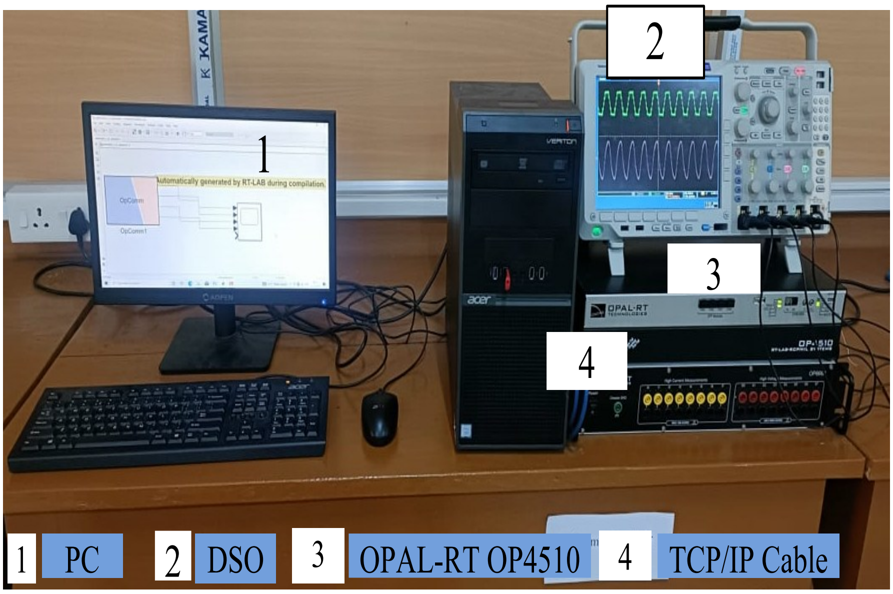
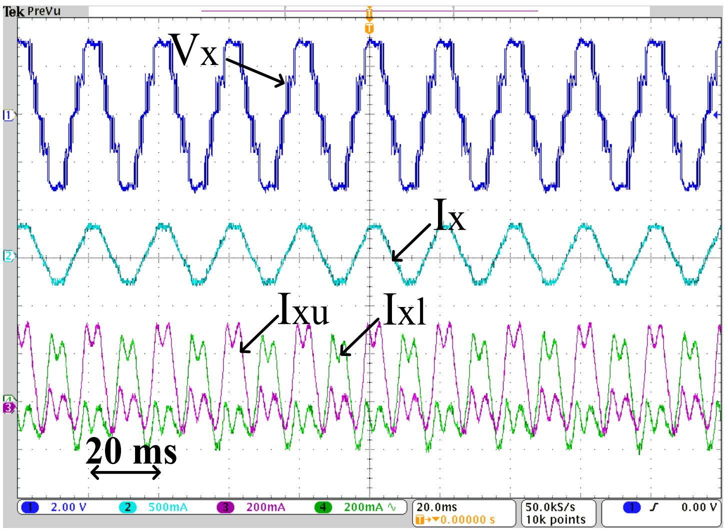
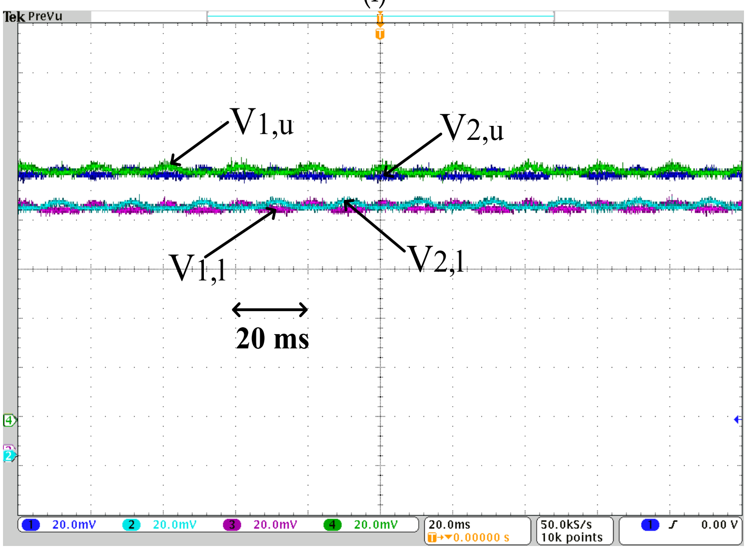


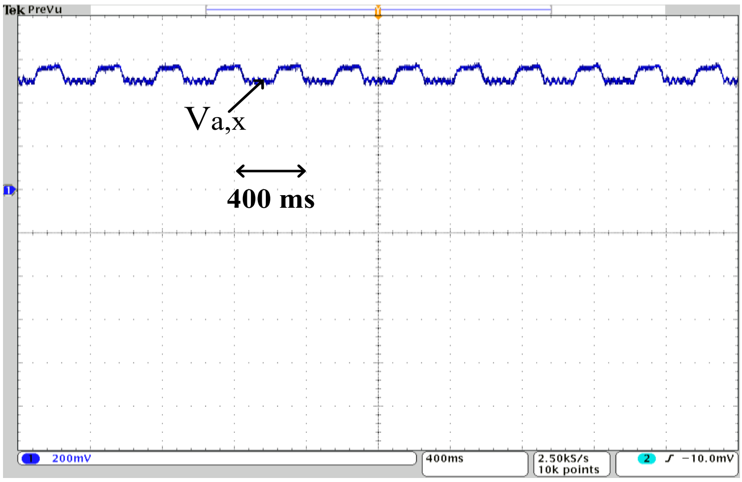
Fig. 6. HIL Test setup.



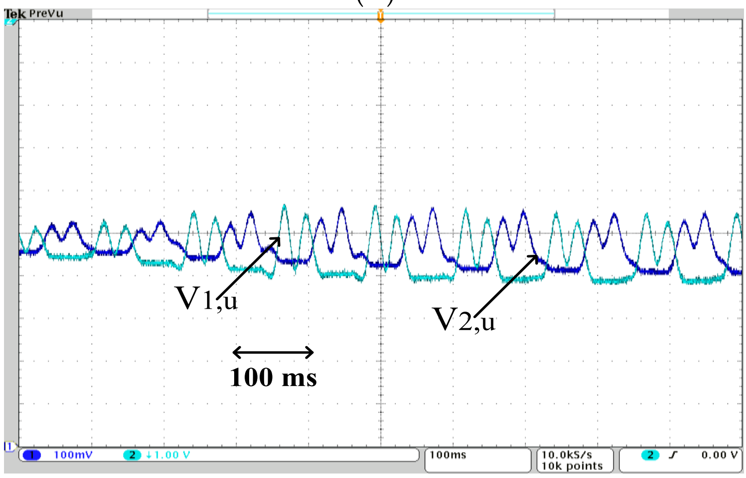
(i)



(ii)



(iii)



(iv)

Fig. 7. HIL test results of the proposed converter at 50 Hz i) output voltage; ii) top and bottom branch currents; iii) enhanced circuit voltage; iv) top and bottom arm voltages of proposed converter at 10 Hz.

7. CONCLUSIONS

This paper focused on a proposed MMC in which modified auxiliary circuit was designed with a smaller number of components which is placed in between the branches of each leg of the MMC, and it is operated with the RL load. Due to the inversely proportional nature of the module voltage and load frequency, the proposed system was implemented under the fundamental frequency i.e., 50 Hz and below fundamental frequency i.e., 10 Hz. At these conditions the modified MMC was performed well in terms of magnitude of ripples in the module voltage, circulating current and arm currents because of the modified auxiliary circuit generated the high frequency ripple component which is opposite that of the module voltage. The allowable ripple voltages obtain 2.5 % of the rated module voltage at 50 Hz and 9 % of the rated module voltage at 10 Hz according to IEEE 519 standards which causes magnitude of circulating current also decreased further reduced the size of the switching devices. For getting these results, modified controllers were implemented to the module switches and proposed auxiliary circuit with the help of carrier shift modulation method. This proposed converter has been implemented at the RL load using by MATLAB/Simulation and tested in the real-time simulator.

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