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Three Phase Matrix Converter A Replacement of Rectifier Inverter Frequency Changer

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Abstract: This paper presents a three-phase AC-AC matrix converter as a frequency converter. Due to continuous increase in the use of electronics converters like AC- AC, AC- DC, DC – AC and DC-DC, there is always a thrust to develop a converter, which generates lesser harmonics, minimum switching losses and high quality desired waveforms across output and input. The matrix converter is modeled as a combined operation of Inverter and Rectifier. In this paper, the focus is to design and Implementation of Matrix Converter (MC) for frequency changing applications .A simple PWM mechanism is proposed to design a mathematical model of three phase Matrix Converter. There is no DC link between rectifier and inverter stage which add up some efficient properties like compact design, bi-directional current flow capabilities. A suitable commutation technique is analyzed. Simulation work is done in MATLAB Simulink environment and comparison with mathematical results are presented.

Keywords: Pulse width modulation Matrix Converter, commutation.

I. INTRODUCTION

The Matrix Converter (MC) has several advantages over Rectifier Fed Inverter System (RFIS) like there is an absence of the intermediate Direct Current (DC) in between the input and output of the system but still have very limited industrial applications due to several practical issues like low voltage transfer ratio and increase the number of power electronics devices. The Matrix Converter (MC) is the type of a forced commutated cyclo-converter alternative of the Rectifier Fed Inverter systems technology (RFIS)[18].This converter has the ability to replace RFIS system. MC fed system is more reliable than the conventional RFIS system. It has the capability to provide bi-directional power flow. It can deliver all silicon solution by converting the input frequency to a desired output frequency.But the commutation problem is seviere.The switching algorithm and timing of the switches are quite complicated . Single phase matrix converter has four whereas in three-phase nine bi-directional switches are present [16,17,18].Cyclo converters are appropriate for high power applications. Mostly frequencies in the range 50 to 60 Hz [9]is required in the industrial applications. In three phase to three phase cyclo-converters 36 thyristors are needed, which make the circuit complicated. The two scientists namely “Alesina” and Venturini firstly mentioned MC in the early of 1980’s. They proposed a general model of the MC and its relative Mathematical theory. They got the result that maximum AC to AC voltage transfer ratio is ($\sqrt{3}/2$) which nearly equals to 0.866. In comparison to three phase to three-phasecyclo-converter, they usually have a lesser number of switches but in comparison with the traditional RFIS model, they require more semiconductor power electronics devices. In SPMC consists of four and The TPMC consists of nine bidirectional switches that are arranged in such a way that any of the input phases are connected to any of the output phases at an instant. Generally, the capacitor is so large that it can occupy a total volume of the converter by 30 to 50 % that would withstand for the few kilowatt power level and another complexity is temperature control. The bridge VSI draws generally input current that contains high magnitude of 5th and 7th order harmonics, which becomes a burden for the converter and injected back to the mains supply and can causes severe power losses in the system. To get rid of this problem, the use of PWM based switches to the rectifier, that helps to modulate nearly input sinusoidal current is presented in [18]. [2],Concluded that it is possible to convert frequency from one form to another frequency without having an intermediate DC link in between them or not by traditional method Rectifier Inverter Frequency Changers (RFIS).[10],[11] and [17]presents four quadrant operation of semiconductor switches in power converter devices. Here the possible solution of safe commutation of the switches are discussed. These switches have been constructed from the two-quadrant switches that are separately controllable.[9], describes the method of ‘overlap’ current commutation. Here the incoming switch is turned on before the outgoing switch gets turn off. There is some short circuit has been taken place for the short interval of time between the two phase. In this process, during short circuit there is an extra inductance required to restrict the current rise to the destruction level.[17],[6] the outgoing switch is turned off before the incoming switch is turned on, and proposed method is commonly known as dead time method of current commutation. It requires a snubber circuit that will provide the path to the current. This method has some limitations as snubber design complicates the bidirectional switches, which require more area and method have a poor response.[5] and [8] discussed methods of “semi-soft commutation method”, the method is the most reliable method to commutate the current for bi-directional switches and depends upon the direction of the current. They do not require any snubber or inductance to decrease the losses. [6],discussed the design and realization the direct AC to AC single phase matrix converter. The input is fed from the mains supply at a constant frequency and output frequency is synthesized.

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Only the output frequencies, which are the multiple of the input frequency, are obtained.The papers[14,12,5]investigate the single phase matrix converter fed R-L load and asynchronous motor.In [4] and [7] the analysis and implementation of the novel new space vector modulation technique for the Forced Commutatedcyclo-converter is presented.The modulation strategy adopted helps to attain nearly sinusoidal output voltage waveform. [10],[18]proposes a space vector Modulation control topology to control variable speed drives in AC/DC/AC applications. Here the calculations of time duration on zero states and reference vector for each switching states are analyzed.[13]examines various approaches of SVM technique. The schemes have 512 maximum States but possibly it has 27 switching states that are useful and among them 21 having 18 active vector states and 3 zero vector states and has 6 synchronous configuration states..[6]proposed a novel technique of commutation for the bi-directional switches and improvement in the output voltage errors. The merits of proposed commutation are that they suppressed the input current vibrations in the motor and doesn't require any damping circuit and there is low THD realization in the waveform. The paper [5] concluded that it is possible to convert frequency from one form to another frequency without having an intermediate DC link in between them or not by traditional method Rectifier Inverter Frequency Changers (RFIS), The proposed converter has improved structure and switching scheme of proposed model is the combination of rectifier and inverter. Merits of these papers are to eliminate unwanted DC link components that will help to make the converter less bulky, having bi-directional power flow capability and very less voltage output distortion and also have demerits that it requires high switching frequency this will get this model work only on low and medium power applications.

The papers [6] [7] [8] presents 4 quadrant operation of semiconductor switches in power converter devices. The paper described the possible solution of safe commutation of the switches. These switches have been constructed from the two-quadrat switches that are separately controllable. The merits of this paper is to provide 4 quadrant switches from the MC with safe commutation strategy. Along with that it had some demerits also that the load current flows and switching sequence all are dependent on each other, like if one switch gets turn off before turning off of another switch cause open circuit in output give rise to voltage spikes and if one switch will turn on before turning off of another switch cause short-circuited in the input side give rise to current spikes.[9], it describes the method of 'overlap' current commutation. In this method, the incoming switch is just turned on before the outgoing switch gets turn off. There is some short circuit has been taken place for the short interval of time between the two phase. In this process, during short circuit there is an extra inductance is required just to stop the current rise to the destruction level. This proposed technique is barely used as the inductor is too costly and make the system bulky.

In the papers[10],[9] the outgoing switch is turned off before the incoming switch is turned on, and proposed method is commonly known as dead time method of current commutation. In this method there is a requirement of the Snubber circuit, that will provide the path to the current. This method has some limitations as Snubber design complicates the bidirectional switches, require more area and method have a poor response.

[10],[11] proposed a method as "semi-soft commutation method", this method is the most reliable method to commutate the current for bi-directional switches and depends upon the direction of the current. As they have merits that they don't require any Snubber or inductance to decrease the losses. For the TPMC topology, this commutation technique has been used. In the proposed commutation method, as this commutation process does not require any Snubber circuit and energy storing device for the necessity of the dead time. This proposed method requires an optimal sequence of the switches so that it is possible to achieved optimal operation, the only demerit of this it's difficult to achieve optimal operation. For the direction of the load current in this proposed model, it depends upon the input and output voltages.

The paper [12] is the inherent limitation of AC-AC MC. In MC there is the unavailability of the natural freewheeling path, the paper is more concerned about providing freewheeling path to the SPMC through simple commutation strategy. This strategy provides the path to the current to dissipate in the dead time and helps in reducing the voltage spikes. The merits of this proposed model are to provide a free-wheeling path through the bidirectional switches that provide switching sequences carefully.

This paper [13] is all about design and realization the direct AC to AC SPMC topology, having four bi-directional switches. The input is fed from the mains supply at a constant frequency and output frequency is synthesized as per our demand. The operation has been done on the RL circuit. The merits of this topology is to provide variable frequency and voltage at the output end and the only demerit of this topology is to get the output frequencies which are the multiple of the input frequency, not any frequency i.e. if input frequency is 50 Hz the Output must be natural number multiplication or division of 50Hz i.e. 12.5, 25,100 etc.

The papers [14]–[16] help to investigate SPMC fed R-L load and asynchronous motor. It presents analysis of Single phase AC-AC converter drive characteristics on square wave modulation and sinusoidal wave modulation. It also analyses harmonics effects on output voltages. As PWM shows poor response towards output voltage as it generates distorted voltage output and doesn't reduce the harmonics content. So, in place of PWM generator, the authors have used sinusoidal PWM. This paper investigated that it shows good results in low output synthesized output but there is an increase in the lower order harmonics as we increase the frequency. The merits of the proposed model is to provide an alternative to indirect DC link for low output frequencies and demerits of this model is that there is an increase in the lower order harmonics in the converter when there is decrease in the output synthesized frequency. The main purposes of the papers [18] and [19] is the analysis and implementation of the novel new space vector modulation technique for the Forced Commutated cyclo-converter, which is Indirect SVM. This modulation helps to attain nearly sinusoidal output voltage waveform and help to cover up the harmonics. The merits of this proposed modulation are THD of this model is independent of output and switching frequency, there is notably decrement in THD by using a filter at the output side.

The demerits of this proposed modulation are the value of THD for FCC is slightly higher and changes with the change in voltage transfer ratio of input and output.

[20],[21] proposes a space vector Modulation control topology to control variable speed drives in AC/DC/AC applications. These papers proposed the calculations of time duration on zero states and reference vector for each switching states. The current and voltage regulation are done on rectifier and inverter respectively. This proposed scheme shows low harmonics because of symmetrical distribution of the switches, especially on high Modulating Index. The merits of this topology are these will provide us nearly sinusoidal waveform and having lesser harmonics whereas disadvantages were requiring separately SVM for each Rectifier and Inverter that will add up the cost along with the intermediate DC link. The paper [22] examines various approaches of SVM technique. The schemes have 512 maximum States but possibly it has 27 switching states that are useful and among them 21 having 18 active vector states and 3 zero vector states and has 6 synchronous configuration states due to their variable direction of output voltage and input current they are not synthesized reference vectors, that are usefully implemented in SVM strategy. This strategy has reference voltage and current at any instant of time. This important feature of this strategy is to select four active states having suitable time during the cycle interval T_s.[23] proposed a novel technique of commutation for the bi-directional switches and improvement in the output voltage errors, the proposed method is based on the duty cycle of the converter. The merits of proposed commutation are that they suppressed the input current vibrations in the motor and doesn’t require any damping circuit and there is low THD realization in the waveform. The paper [24] explains the calculation for the optimum output filter design for single-phase. To demonstrate the validity of the simulated results, experimental results are presented.

II. METHODOLOGY USED FOR THREE PHASE MATRIX CONVERTER (TPMC)

Fig.1 represents the circuit configuration of three phase matrix converter. At any instant of time, power flow from the input does not equal to the power output. This difference in power losses that must be absorbed or delivered by the source. The MC succeed to replace the multiple stage conversions and get rid of the intermediate DC energy storage devices or element through a single stage power converter.It e uses bidirectional switches in matrix form by connecting input terminals and output terminals as shown in Figure 1. Assuming ideal switches of the MC, the typical arrangement in the bidirectional switches, the power can flow through the converter and can be in reversed direction. Due to the absence of any intermediate DC link in between them, the input power flow must be equal to output power flow. However practically, due to the presence of reactive filter and switching losses in the MC , the input power is not equal to the output power.The TPMC consists of nine bidirectional switches that are arranged in such a way that they are divided into three groups of three switches. In each group of the TPMC, each output phase can be connected to any input phase. In TPMC there are maximum possible 512 (2^n where n=9) switching states. But among all of them, there are only 27 possible switching states that are permitted and to operate for this converter For the TPMC safety, the switching state should follow these given following rules:

The two different input lines are never being short-circuited.

There should not be any discontinuity of inductor load output line i.e. they should not be open circuited.

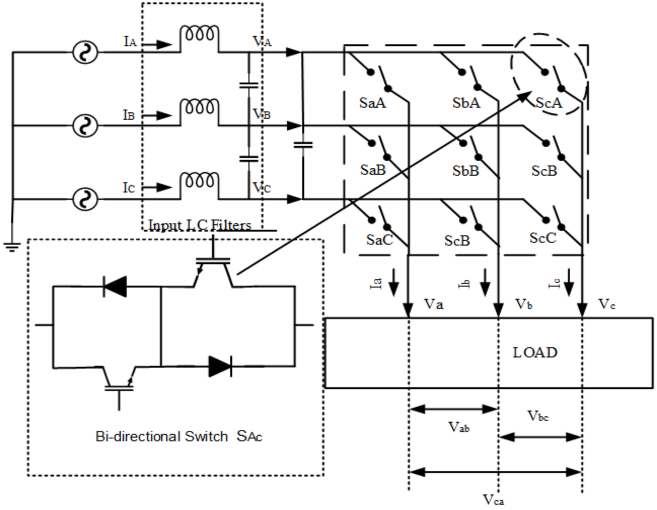
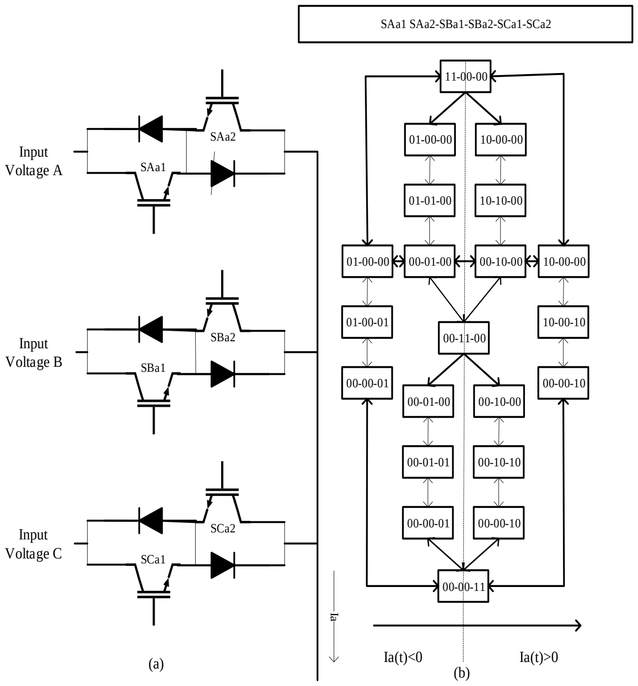


Figure.1.Circuit Configuration of TPMC

In TPMC, this process is known as Semi-Soft Commutation process and is illustrated in Figure 2. The working principle of this process is to disconnect one input phase and connect another input-phase without violating the rules of commutation, e.g. disconnection of input phase A and connection of input phase B with the output phase A. This process of commutation has been done in several steps and the steps are shown in Fig.2.



(a)

(b)

Fig. 2. Three Phase MC Semi-soft commutation process

The representation of three phase MC is 3X3 matrix form. since there is no energy storing element and all nine bi-directional switches are connected in the sequence that every input is connected to every output phase is shown in Figure.1.

Output Voltage of the MC ,In Matrix Form;

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{aB} & S_{aC} \\ S_{bA} & S_{bB} & S_{bC} \\ S_{cA} & S_{cB} & S_{cC} \end{bmatrix} \cdot \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}; \qquad (1)$$

Similarly, for the input current

$I_I = T^T * I_0;$

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{bA} & S_{cA} \\ S_{aB} & S_{bB} & S_{cB} \\ S_{aC} & S_{bC} & S_{cC} \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (2)$$

where V_A, V_B and V_C are input voltages phase, I_A, I_B and I_C are input currents V_a, V_b and V_c are output voltages phase, I_a, I_b and I_c are output currents and. All these elements of transfer matrix T_{ij} represented the instantaneous input voltage to the instantaneous voltage output of the switch function.

Considered the AC to AC power frequency conversion system and having virtual DC link in between the Input and output side. This converter has two AC to AC conversion stages, stage 1 is the rectification stage and stage 2 is inversion stage as shown. In rectification stage, the process of conversion of DC from AC takes place and Energy stored in the virtual DC link. In the another stage, the energy stored in the virtual DC link becomes the input for Inverter stage and hence here DC to AC conversion takes place as shown in Fig.3.

In Inverter stage,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \cdot \begin{bmatrix} V_{DC}+ \\ V_{DC}- \end{bmatrix} \qquad (3)$$

For Rectification stage,

$$\begin{bmatrix} V_{DC}+ \\ V_{DC}- \end{bmatrix} = \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \qquad (4)$$

On Comparing , (3) and (4), one has

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \cdot \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \cdot \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \qquad (5)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_7.S_1 & S_8.S_2 & S_7.S_3 & S_8.S_4 & S_7.S_5 & S_8.S_6 \\ S_9.S_1 & S_{10}.S_2 & S_9.S_3 & S_{10}.S_6 & S_9.S_5 & S_{10}.S_6 \\ S_{11}.S_1 & S_{12}.S_2 & S_{11}.S_3 & S_{12}.S_8 & S_{11}.S_5 & S_{12}.S_6 \end{bmatrix} \cdot \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \qquad (6)$$

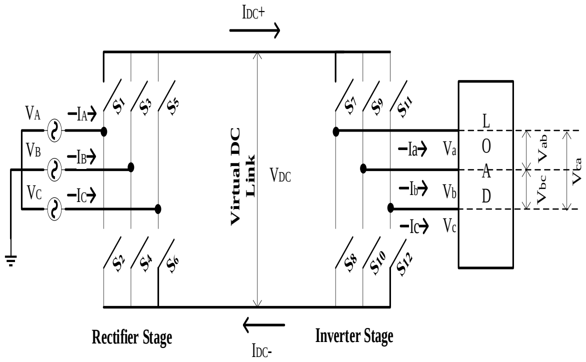


Figure. 3 Indirect PWM Equivalent model

2.1 SPACE VECTOR MODULATION FOR INVERTER RECTIFIER STAGE

In this section, the introduction of SVM in the Inverter and Rectifier stage is presented. The final output voltages are represented by multiplying inverter transfer function **I** to virtual DC-link voltage V_{DC}. On the same time, I_{DC} which is the DC link current has been represented by $\mathbf{I}^T$.

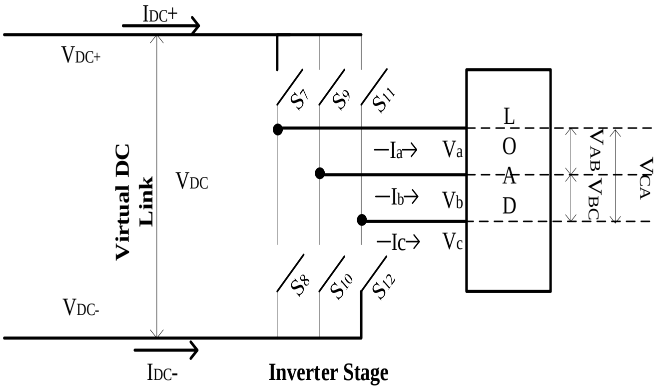


Figure.4. Inverter stage from the equivalent model

To know the values of the output voltage and output voltage angle, there are 6 switches in inverter stage that is represented in order S_7, S_8, S_9, S_{10}, $S_{11,}$ and S_{12} and when a switch is off by it is denoted by '0' and when a switch is on it is denoted by "1" . Consider that inverter stage of the active vector V_1 [1 0 0]. In this active stage, switch number 7 has been switched on from the upper part and switch number 10 and 12 from the lower part shown in Figure.4.

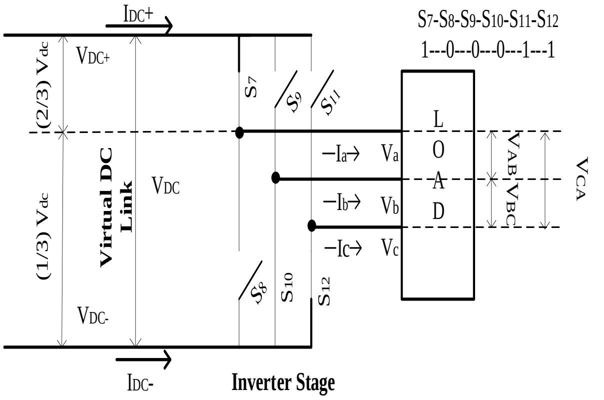


Figure.5 Inverter Stage when switches S_7, S_{10} ,S_{12} are on in the Equivalent model of the Inverter Stage

Hence the output voltage phase angle of the Inverter stage is start at 0^0 and magnitude of voltage output is.

In Table .1, it displays the output voltage magnitudes and output voltage angles of all the six active and 2 zero states of the Inverter stage. Table.2 presents the period of the Vectors active V_1, V_2 and Zero vector V_{0v} having a time interval of T_1, T_2 and T_0 respectively. Table.3 represents the switching durations of all the six switches.

2.2 SVM FOR THE RECTIFIER STAGE

This section introduces SVM for the Rectifier stage. In the previous section, the analysis has been done for the inverter stage. The equivalent circuit is shown in Figure.6. (7) and (8) represents corresponding matrix equations.

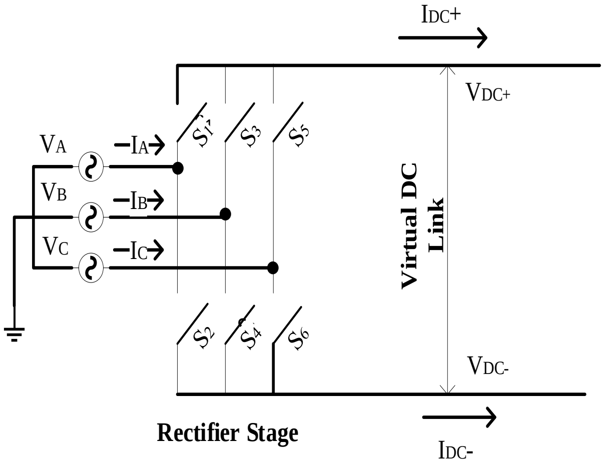


Figure.6 Rectifier stage equivalent circuit

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} S_1 & S_2 \\ S_3 & S_4 \\ S_5 & S_6 \end{bmatrix} . \begin{bmatrix} I_{DC}+ \\ I_{DC}- \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} V_{DC}+ \\ V_{DC}- \end{bmatrix} = \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \tag{8}$$

To know the values of the Input Current and Input Current phase angle. In Rectifier we have two output DC values. Consider that inverter stage of the active vector I_1 [AB]. In this active stage, switche number 1 has been switched on from the upper part and switch number 4 from the lower part shown in Figure .7.

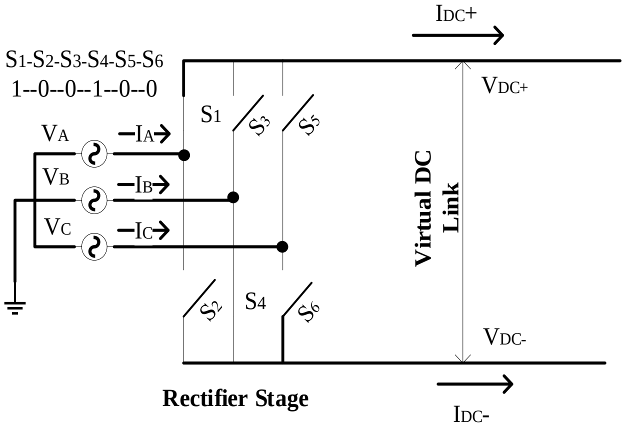


Figure.7 Equivalent circuits for Rectifier Stage when Switches S_1 and S_4 are closed

There are 6 switches in rectifier stage and the respective vectors are presented in Table.4.Tables are presented in section 5 as appendix. **Error! Reference source not found.** time interval of the Vectors active I_3, I_4 and Zero vector I_{0c} and V_7 having a time interval of T_3, T_4 and T_{0c} respectively.**Error! Reference source not found.**. This explains the switching states of all the switches S_1 to S_6 in all six sectors of the Rectifier stage.

Table .7 and Table.8 represents the combined switching states of Inverter and rectifier to generate sinusoidal output at desired frequency.

III. SIMULATION RESULTS AND DISCUSSION

The complete system is simulated in simulink environment and results are presented.Figure.8 represents the phase A output voltage and current without filter. shows the output current and voltage of the phase a for resistive inductive load without filter.Figure.9 represents the three phase output voltage and current without filter.

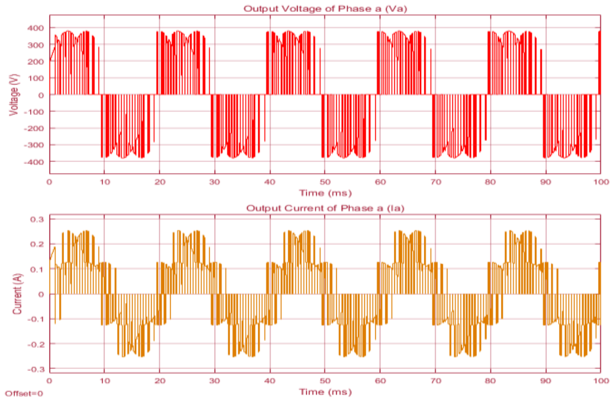


Figure.8. TPMC output voltage and current of phase a without Filter

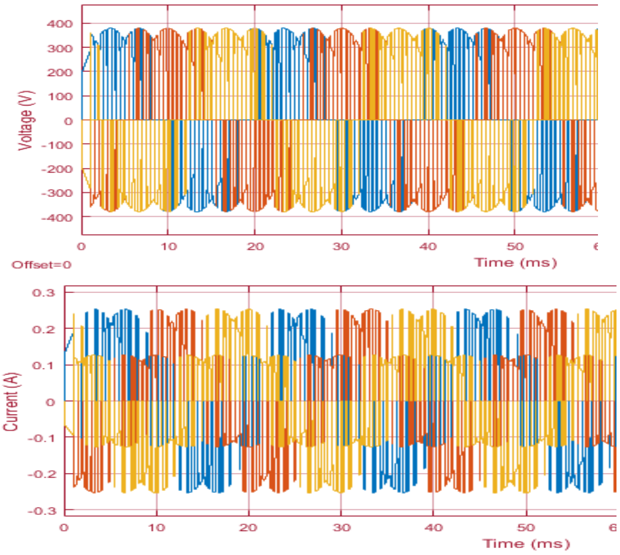


Figure.9.TPMC Output Voltage and current without Filters

Figure 9. shows the output current and voltage of the phase a for resistive inductive load with filter.

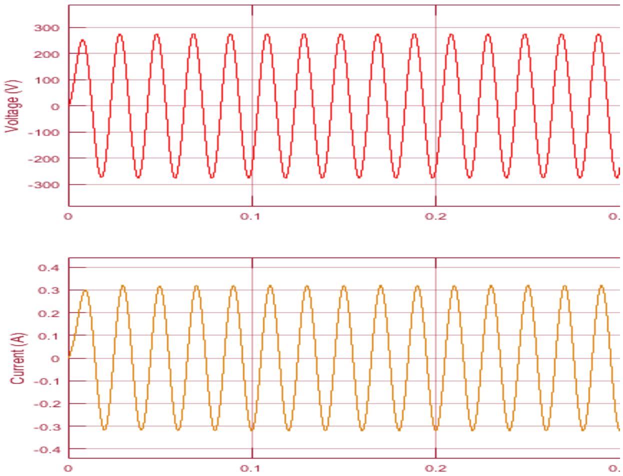


Figure.10. TPMC output voltage and current of Ia phase without Filter

Figure .10 represents the phase A output voltage and current after filtering.Fig.11 represents the three phase output voltage and current after filter.

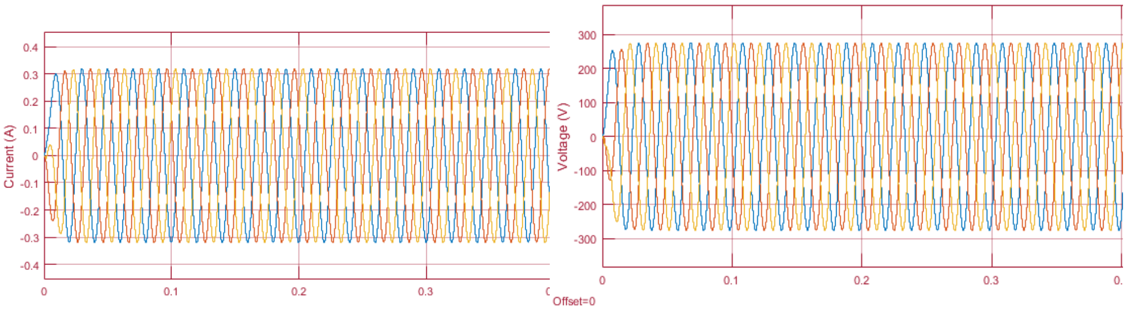


Figure.11. TPMC Output Voltage and current with Filters

IV. CONCLUSIONS

The paper presented a comprehensive analysis of different modes of three phase Matrix converter. Commutation issues are addressed and suitable PWM technique is proposed. Two different models have been proposed both having different topologies. It is concluded from this work that the switches of the MC is in the array of MXN, where M is number of input lines and N is number of output lines. In MC the input mains fed up with the constant frequency and supply. The amplitude of this MC can step up or down the frequency by synthesizing the output voltage equals to the multipliers of the input fundaments. For the safe commutation technique, by providing carefully arrangements of the switching sequence, the bi-directional switches used for free-wheeling path. The TPMC SVM is the combination of the Product of the Sum of the modulation of Inverter and Rectifier stage. Simulation results are presented in support of that.

5.APPENDIX

Table.1 Switching Vectors and Switching States for the Inverter side

Type	*Vector*	$\begin{bmatrix} S_7 & S_9 & S_1 \\ S_8 & S_{10} & S_1 \end{bmatrix}$	$\begin{bmatrix} V_A & V_B & V_C \\ V_{AB} & V_{BC} & V_{AC} \end{bmatrix}$	$\lvert V_{out} \rvert$	$\angle \alpha_0$	I_{dc+}
Active	V_1[1 0 0]	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \end{bmatrix}^T$	$\begin{bmatrix} \frac{2}{3}V_{DC} & -\frac{1}{3}V_{DC} & -\frac{1}{3}V_{DC} \\ V_{DC} & 0 & -V_{DC} \end{bmatrix}$	$\frac{2}{3}V_D$	0	I_A

Active	***$V_2[1\ 1\ 0]$***	$\begin{bmatrix}1&1&0\\0&0&1\end{bmatrix}^T$	$\begin{bmatrix}\frac{1}{3}V_{DC}&\frac{1}{3}V_{DC}&-\frac{2}{3}V_{DC}\\0&V_{DC}&-V_{DC}\end{bmatrix}$	$\frac{2}{3}V_{D}$	$\frac{\pi}{3}$	***$-I_C$***
Active	***$V_3[0\ 1\ 0]$***	$\begin{bmatrix}0&1&0\\1&0&1\end{bmatrix}^T$	$\begin{bmatrix}-\frac{1}{3}V_{DC}&\frac{2}{3}V_{DC}&-\frac{1}{3}V_{DC}\\-V_{DC}&V_{DC}&0\end{bmatrix}$	$\frac{2}{3}V_{D}$	$\frac{2\pi}{3}$	***I_B***
Active	***$V_4[0\ 1\ 1]$***	$\begin{bmatrix}0&1&1\\1&0&0\end{bmatrix}^T$	$\begin{bmatrix}\frac{2}{3}V_{DC}&-\frac{1}{3}V_{DC}&-\frac{1}{3}V_{DC}\\V_{DC}&0&-V_{DC}\end{bmatrix}$	$\frac{2}{3}V$	π	***$-I_A$***
Active	***$V_5[0\ 0\ 1]$***	$\begin{bmatrix}0&0&1\\1&1&0\end{bmatrix}^T$	$\begin{bmatrix}-\frac{1}{3}V_{DC}&\frac{2}{3}V_{DC}&-\frac{1}{3}V_{DC}\\0&-V_{DC}&V_{DC}\end{bmatrix}$	$\frac{2}{3}V_{D}$	$\frac{-2}{3}$	***I_C***
Active	***$V_6[1\ 0\ 1]$***	$\begin{bmatrix}1&0&1\\0&1&0\end{bmatrix}^T$	$\begin{bmatrix}\frac{1}{3}V_{DC}&-\frac{2}{3}V_{DC}&\frac{1}{3}V_{DC}\\V_{DC}&-V_{DC}&0\end{bmatrix}$	$\frac{2}{3}V_{D}$	$-$	***$-I_B$***
Zero	***$V_0[0\ 0\ 0]$*** ***$V_7[1\ 1\ 1]$***	$\begin{bmatrix}0&0&0\\1&1&1\end{bmatrix}^T \begin{bmatrix}1&1&1\\0&0&0\end{bmatrix}^T$		***0***		***0***

Table.2 Duty period of the Switching Vectors of Inverter Stage

Sector	T_1	T_2	T_{0v}
1	$M_vT_s\sin\left(\frac{\pi}{3}-\theta_0\right)$	$M_vT_s\sin\theta_0$	$T_S-T_1-T_2$
2	$M_vT_s\sin\left(\frac{2\pi}{3}-\theta_0\right)$	$M_vT_s\sin\left(\theta_0-\frac{\pi}{3}\right)$	
3	$M_vT_s\sin\left(\pi-\theta_0\right)$	$M_vT_s\sin\left(\theta_0-\frac{2\pi}{3}\right)$	
4	$M_vT_s\sin\left(\frac{4\pi}{3}-\theta_0\right)$	$M_vT_s\sin\left(\theta_0-\pi\right)$	
5	$M_vT_s\sin\left(\frac{5\pi}{3}-\theta_0\right)$	$M_vT_s\sin\left(\theta_0-\frac{4\pi}{3}\right)$	
6	$M_vT_s\sin\left(2\pi-\theta_0\right)$	$M_vT_s\sin\left(\theta_0-\frac{5\pi}{3}\right)$	

Table. 3. Switching Timing of the switches

Sector	Switching timing for upper switch	Switching timing for lower switch
1	$S_7(t)=T_1+T_2+\frac{T_{0v}}{2};S_9(t)=T_2+\frac{T_{0v}}{2};S_{11}(t)=\frac{T_{0v}}{2}$	$S_8(t)=\frac{T_{0v}}{2};S_{10}(t)=T_1+\frac{T_{0v}}{2};S_{12}(t)=T_1+T_2+\frac{T_{0v}}{2}$
2	$S_7(t)=T_2+\frac{T_{0v}}{2};S_9(t)=T_1+T_2+\frac{T_{0v}}{2};S_{11}(t)=\frac{T_{0v}}{2}$	$S_8(t)=T_1+\frac{T_{0v}}{2};S_{10}(t)=\frac{T_{0v}}{2};S_{12}(t)=T_1+T_2+\frac{T_{0v}}{2}$
3	$S_7(t)=\frac{T_{0v}}{2};S_9(t)=T_1+T_2+\frac{T_{0v}}{2};S_{11}(t)=T_2+\frac{T_{0v}}{2}$	$S_8(t)=T_1+T_2+\frac{T_{0v}}{2};S_{10}(t)=\frac{T_{0v}}{2};S_{12}(t)=T_1+\frac{T_{0v}}{2}$
4	$S_7(t)=\frac{T_{0v}}{2};S_9(t)=T_1+T_2+\frac{T_{0v}}{2};S_{11}(t)=T_2+\frac{T_{0v}}{2}$	$S_8(t)=T_1+T_2+\frac{T_{0v}}{2};S_{10}(t)=T_1+\frac{T_{0v}}{2};S_{12}(t)=\frac{T_{0v}}{2}$
5	$S_7(t)=T_2+\frac{T_{0v}}{2};S_9(t)=\frac{T_{0v}}{2};S_{11}(t)=T_1+T_2+\frac{T_{0v}}{2}$	$S_8(t)=T_1+\frac{T_{0v}}{2};S_{10}(t)=T_1+T_2+\frac{T_{0v}}{2};S_{12}(t)=\frac{T_{0v}}{2}$
6	$S_7(t)=T_1+T_2+\frac{T_{0v}}{2};S_9(t)=\frac{T_{0v}}{2};S_{11}(t)=T_2+\frac{T_{0v}}{2}$	$S_8(t)=\frac{T_{0v}}{2};S_{10}(t)=T_1+T_2+\frac{T_{0v}}{2};S_{12}(t)=T_2+\frac{T_{0v}}{2}$

Table.4 Switching vectors of Rectifier stage

Type	***Vector I [P N]***	$\begin{bmatrix}S_1&S_3&S_5\\S_2&S_4&S_6\end{bmatrix}^T$	***[I_a, I_b, I_C]***	$\lvert I_{in}\rvert$	$\lvert\angle I_{in}\rvert$	***V_{dc}***
ACTIVE	$I_1[AB]$	$\begin{bmatrix}1&0&0\\0&1&0\end{bmatrix}^T$	***[I_{dc+} I_{dc-} 0]***	$\frac{2}{\sqrt{3}}I_{DC}$	$-\frac{\pi}{6}$	***V_{ab}***
	$I_2[AC]$	$\begin{bmatrix}1&0&0\\0&0&1\end{bmatrix}^T$	***[I_{dc+} 0 I_{dc-}]***	$\frac{2}{\sqrt{3}}I_{DC}$	$\frac{\pi}{6}$	***-V_{ca}***
	$I_3[BC]$	$\begin{bmatrix}0&1&0\\0&0&1\end{bmatrix}^T$	***[I_{dc+} 0 I_{dc-}]***	$\frac{2}{\sqrt{3}}I_{DC}$	$\frac{\pi}{2}$	***V_{bc}***
	$I_4[BA]$	$\begin{bmatrix}0&1&0\\1&0&0\end{bmatrix}^T$	***[I_{dc-} I_{dc+} 0]***	$\frac{2}{\sqrt{3}}I_{DC}$	$\frac{5\pi}{6}$	***-V_{ab}***
	$I_5[ca]$	$\begin{bmatrix}0&0&1\\1&0&0\end{bmatrix}^T$	***[I_{dc-} 0 I_{dc+}]***	$\frac{2}{\sqrt{3}}I_{DC}$	$\frac{-5\pi}{6}$	***V_{ca}***
	$I_6[cb]$	$\begin{bmatrix}0&0&1\\0&1&0\end{bmatrix}^T$	***[0 I_{dc-} I_{dc+}]***	$\frac{2}{\sqrt{3}}I_{DC}$	$\frac{-\pi}{2}$	***-V_{bc}***
ZERO	$I_0[aa]$ $I_0[bb]$ $I_0[cc]$	$\begin{bmatrix}1&0&0\\1&0&0\end{bmatrix}^T$ $\begin{bmatrix}0&1&0\\0&1&0\end{bmatrix}^T$ $\begin{bmatrix}0&0&1\\0&0&1\end{bmatrix}^T$		***0***		***0***

Table.5 Duration of the Switching Vectors (Rectifier Stage)

Sector	T3	T4	T0c
1	$M_c T_s \sin\left(\frac{\pi}{3}-\theta_c\right)$	$M_c T_s \sin\theta_c$	$T_S - T_1 - T_2$
2	$M_c T_s \sin\left(\frac{2\pi}{3}-\theta_c\right)$	$M_c T_s \sin\left(\theta_c-\frac{\pi}{3}\right)$	
3	$M_c T_s \sin\left(\pi-\theta_c\right)$	$M_c T_s \sin\left(\theta_c-\frac{2\pi}{3}\right)$	
4	$M_c T_s \sin\left(\frac{4\pi}{3}-\theta_c\right)$	$M_c T_s \sin\left(\theta_c-\pi\right)$	
5	$M_c T_s \sin\left(\frac{5\pi}{3}-\theta_c\right)$	$M_c T_s \sin\left(\theta_c-\frac{4\pi}{3}\right)$	
6	$M_s T_s \sin\left(2\pi-\theta_c\right)$	$M_c T_s \sin\left(\theta_c-\frac{5\pi}{3}\right)$	

Table.6 switching timing of switches in Rectifier stage

Sector	*Switching timing for upper switch*	*Switching timing for lower switch*
1	$S_1 = T_3 + T_4 + \frac{T_{0c}}{2}; S_3 = \frac{T_{0c}}{2}; S_5 = \frac{T_{0c}}{2}$	$S_2 = \frac{T_{0c}}{2}; S_4 = T_3 + \frac{T_{0c}}{2}; S_6 = T_4 + \frac{T_{0c}}{2}$
2	$S_1 = T_3 + \frac{T_{0c}}{2}; S_3 = T_4 + \frac{T_{0c}}{2}; S_5 = \frac{T_{0c}}{2}$	$S_2 = \frac{T_{0c}}{2}; S_4 = \frac{T_{0c}}{2}; S_6 = T_3 + T_4 + \frac{T_{0c}}{2}$
3	$S_1 = \frac{T_{0c}}{2}; S_3 = T_3 + T_4 \frac{T_{0c}}{2}; S_5 = \frac{T_{0c}}{2}$	$S_2 = T_4 + \frac{T_{0c}}{2}; S_4 = \frac{T_{0c}}{2}; S_6 = T_3 + \frac{T_{0c}}{2}$
4	$S_1 = T_3 + T_4 + \frac{T_{0c}}{2}; S_3 = \frac{T_{0c}}{2}; S_5 = \frac{T_{0c}}{2}$	$S_2 = \frac{T_{0c}}{2}; S_4 = T_3 + \frac{T_{0c}}{2}; S_6 = T_4 + \frac{T_{0c}}{2}$
5	$S_1 = T_3 + \frac{T_{0c}}{2}; S_3 = T_4 + \frac{T_{0c}}{2}; S_5 = \frac{T_{0c}}{2}$	$S_2 = \frac{T_{0c}}{2}; S_4 = \frac{T_{0c}}{2}; S_6 = T_3 + T_4 + \frac{T_{0c}}{2}$
6	$S_1 = T_4 + \frac{T_{0c}}{2}; S_3 = \frac{T_{0c}}{2}; S_6 = T_5 + \frac{T_{0c}}{2}$	$S_2 = \frac{T_{0c}}{2}; S_4 = T_3 + T_4 \frac{T_{0c}}{2}; S_6 = \frac{T_{0c}}{2}$

Table.7 Switching configuration selection for a combination of Inverter and Rectifier stage

S_r		S_i											
	Sector	***1***				***2***				***3***			
	1	***+1***	***-3***	***-7***	***+9***	***-7***	***+9***	***+4***	***-6***	***+4***	***-6***	***-1***	***+3***
	2	***-3***	***+2***	***+9***	***-8***	***+9***	***-8***	***-6***	***+5***	***-6***	***+5***	***+3***	***-2***
	3	***+2***	***-1***	***-8***	***+7***	***-8***	***+7***	***+5***	***-4***	***+5***	***-4***	***-2***	***+1***
	4	***-1***	***+3***	***+7***	***-9***	***+7***	***-9***	***-4***	***+6***	***-4***	***+6***	***+1***	***-3***
	5	***+3***	***-2***	***-9***	***+8***	***-9***	***+8***	***+6***	***-5***	***+6***	***-5***	***-3***	***+2***
	6	***-2***	***+1***	***+8***	***-7***	***+8***	***-7***	***-5***	***+4***	***-5***	***+4***	***+2***	***-1***
		I	***II***	***III***	***IV***	***I***	***II***	***III***	***IV***	***I***	***II***	***III***	***IV***

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Table.8 switching configuration selection for a combination of Inverter and Rectifier stage

		S_i											
	Sector	***4***				***5***				***6***			
S_r	***1***	-1	+3	+7	-9	+7	-9	-4	+6	-4	+6	+1	-3
	2	+3	-2	-9	+8	-9	+8	+6	-5	+6	-5	-3	+2
	3	-2	+1	+8	-7	+8	-7	-5	+4	-5	+4	+2	-1
	4	+1	-3	-7	+9	-7	+9	+4	-6	+4	-6	-1	+3
	5	-3	+2	+9	-8	+9	-8	-6	+5	-6	+5	+3	-2
	6	+2	-1	-8	+7	-8	+7	+5	-4	+5	-4	-2	+1
		I	II	III	IV	I	II	III	IV	I	II	II	IV

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