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Modelling of Matrix Converter using Direct Space Vector Modulation

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***Abstract:** Now-a-days the industry needs different types of power converters for their process and sometimes the industry wants converters which operates in different modes and perform different jobs as demanded by the load. Due to the advancement in topologies and control techniques a solo converter can be assigned to perform different functions and have to meet out the performance characteristics as required by the application.*

Hence, the increasing dependence on the power converter and the need to supply quality power has mandated that all power electronic converters should have less harmonic content as well as less total harmonic distortion. For the new requirement of society the Matrix converter is the good option. In this paper the fundamental of Matrix converter is explained as well as the Direct Space vector Modulation technique is used.

Keywords: Matrix Converter, Space Vector Modulation, Direct Space Vector Modulation, Total Harmonic Distortion.

I. INTRODUCTION

The MC is the single stage converter which directly connects an *m* phase voltage source to *n* phase load, for the conversion the MC required *m* x *n* bidirectional power switches. It is a forced commutated converter which consists an array of bi-directional switches as the main element to produce a variable output voltage system with variable frequency. It does not need any storage element hence the dc link is not required.

The introduction of power transistors for the implementation of the bi-directional switches made the MC more attractive. The mathematical analysis for describing the low frequency behavior of the MC is introduced in which the output voltage is obtained by the multiplication of the transfer matrix with the input voltage. This approach is known as the direct transfer function approach and it is given by the Venturini and Alesina.

The another control technique which is called indirect transfer function approach introduced by Rodriguez. In this method the MC is decouple into the virtual inverter and virtual rectifier and the fictious dc link is assumed between them. The switching is arranged in this method, such that each output line is switched between the most positive and most negative lines using pulse width modulation, as used in conventional voltage source inverters

In the MC, for 3-phases, it consists of 9 bi-directional switches which allow connection of output phase to any input phase. The three phase voltage source system is connected to the input terminal generally grid, whereas the output terminals are connected to the 3-phase load system. With its nine bi-directional switches, It is theoretically consider that the MC can have 2^9 i.e. 512 possible combinations, but actually not all are applicable[1]

Considering two constraints of the converter

1) The MC is fed by the voltage source so the input terminal shouldnever be short-circuited.
2) The load is mostly of inductive nature so the output terminal should never be open circuit. [6]

Due to these two constraints, there are only 27 possible switching combinations. In the figure shown below represent the topology of the MC for 3- phase to 3- phase, it shows the connections of the nine switches with the input and output phases. Here the 3- phase input is represented by a, b, c and the output phase is represented by A, B, C.

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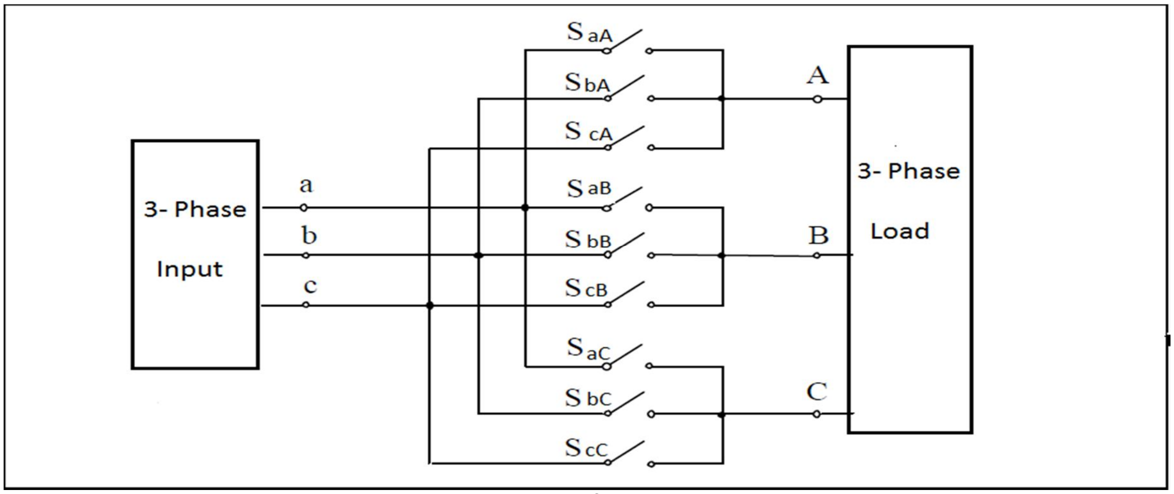

Fig. 1Structure of Matrix Converter

The switching function of a single switch can be defined as:-

$$S_{Kj} = \begin{cases} 1, & switch\ S_{Kj} closed \\ 0, & switch\ S_{Kj} open \end{cases} \quad (1)$$

where K={a, b ,c} & j={A, B, C}

The switching of the MC is a very critical task to do because of the two following constraints
The input lines should not be short circuit as, it will short circuit the input voltage source.

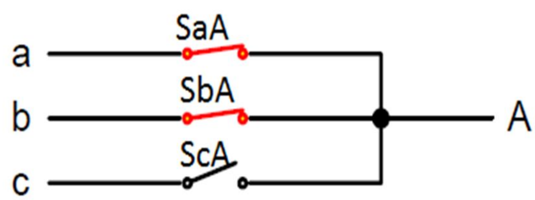

Fig.2 Input phase a and b are short

Here in the fig.2 the switch S_{aA} and S_{bA} are closed which short circuited the input phase a and b which directly short circuited the input voltage source. Hence this condition cannot be applied
The output lines should not be open circuit as it will open circuit load

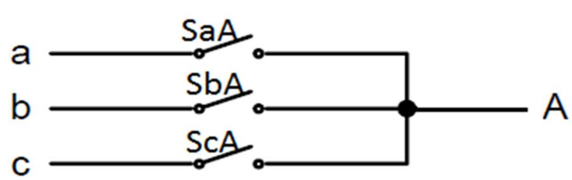

Fig: 3 Output phase A is open

Here in the fig.3 the switch S_{aA}, S_{bA}, S_{cA} all are open, which directly open the output phase A. Hence this condition is also not applied. Hence at any instant only one switch can be closed, and the same is true for the phase B and C .The constraints discussed can be expressed by:-

$$S_{aj}+S_{bj}+S_{cj}=1$$

where j= {A, B, C}

Due to the above restrictions the three phase to three phase MC has only 27 possible switching states.[5]

II. RELATIONSHIP BETWEEN THE INPUT AND OUTPUT QUANTITIES

Here the output voltage and input voltage is defined as:-

$$V_o = \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \quad ; \quad V_i = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (2)$$

Where V_o and V_i are the output and input voltage vector matrix respectively and V_A, V_B,V_C are the output phase voltages and V_a, V_b, V_c are input phase voltages. The relationship between the input and output voltages can be defined as:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{bA} & S_{cA} \\ S_{aB} & S_{bB} & S_{cB} \\ S_{aC} & S_{bC} & S_{cC} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (3)$$

$$\boldsymbol{V_o} = \mathbf{T}.\boldsymbol{V_i} \qquad (4)$$

Here**,** **T** is the instantaneous transfer matrix**.**

Here the output current and input current is defined as:-

$$I_o = \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad ; \quad I_i = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (5)$$

Where $I_o$and I_i are the output and input current vector matrix respectively and I_A, I_B, I_C are the output per phase current and I_a, I_b, I_c are the input per phase current.

Similarly, the relationship is given for the input and output currents:-

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{aB} & S_{aC} \\ S_{bA} & S_{bB} & S_{bC} \\ S_{cA} & S_{cB} & S_{cC} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \qquad (6)$$

$$\mathbf{I_i} = \mathbf{T^T}.\mathbf{I_o} \qquad (7)$$

Here,$\mathbf{T^T}$ is the transpose matrix of T

III. SPACE VECTOR MODULATION

The SVM has become a standard for the switching power converter and many research work is being dedicated to this topic from the past 10 years. In the context of the MC the SVM technique has been succesfully developed in order to completely use the possibility of the MC to control the input power factor regardless the output power factor and to reduce the number of switch commutation in every cycle period and this technique is the best solution to achived the highest voltage transfer ratio.

Space vector output voltage in complex notation is given by:-

$$v_o = \frac{2}{3}(v_{AB} + a v_{BC} + a^2 v_{CA}) \qquad (8)$$

where $a = e^{j2\pi/3}$

$\frac{2}{3}$ is the scaling factor

v_o is the output voltage

v_{AB} v_{BC} v_{CA} are the line voltages

Where, the line voltages are given by:

$$v_{AB} = V_o \cos(w_o + \pi/6) \qquad (9)$$

$$v_{BC} = V_o \cos(w_o + \pi/6 - 2\pi/3) \qquad (10)$$

$$v_{CA} = V_o \cos(w_o + \pi/6 + 2\pi/3) \qquad (11)$$

The Space vector output current, input voltage, input current can be define as:-

$$i_o = \frac{2}{3}(i_A + a i_B + a^2 i_C) \qquad (12)$$

$$v_i = \frac{2}{3}(v_a + a v_b + a^2 v_c) \qquad (13)$$

$$i_i = \frac{2}{3}(i_a + a i_b + a^2 i_c) \qquad (14)$$

Here i_o, v_i, i_i are the output current, input voltage and the input current respectively.
We can obtain the conversion of three phase a, b, c coordinate system into two phase $\alpha - \beta$ coordinate system which is given by:-

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{15}$$

Where V_α and V_β are the voltage of α - phase and β - phase respectively and V_a, V_b, V_c are the per phase voltages of phase a, b, c respectively.

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{16}$$

Where I_α and I_β are the voltage of α - phase and β - phase respectively and I_a, I_b, I_c are the per phase currents of phase a, b, c respectively.

IV. DIRECT SPACE VECTOR MODULATION

This section shows the implementation of the DSVM for the matrix converter. In this technique the SVM is applied directly to the MC without the use of the fictious dc-link. There are 27 possible combination for a MC which can be further classified into three groups with the following characteristics.[3]

1) *Group 1:* In this group each of the output line is connected to the different input line. For example in fig.(4) the output phase A is connected to the input phase a, output phase B is connected to the input phase b and output phase C is connected to the input phase c. Similarly the other five combination can also be made. Here the output voltage vector and the input current vector are constant in amplitude but have varaiable directions and therefore the reference vector cannot be synthesised usefully.

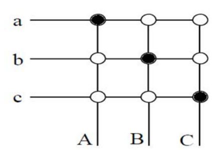

Fig.4 Group 1 arrangement

2) *Group 2:* In this group the two output lines are connected to a common input lines and the remaining one output line is connected to the other input lines. For example in fig.(5) the output phase A is connected to the input phase a and the output phase B and C both are connected to the input phase b. Similarly the other 17 combination can be made. The group 2 vector are also called as the active vectors.

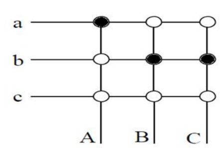

Fig.5 Group 2 arrangement

3) *Group 3:* In this group all of the output lines are connected to the common input line, i.e located on the origin.For example in fig. (6) the all the three output phase A, B, C are connected to the input phase c. The group 3 vector are also called as the zero vector.

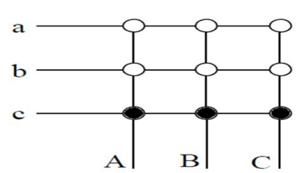

Fig.6 Group 3 arrangement

In the the group 1 vector are not used and the desired output is synthesised from the group 2 (active vectors) and the group 3 (zero vector). These 21 vectors from which 18 vectors are from the Group 2 (active vectors) and 3 vectors from the Group 3 (zero vector) are listed in the Table 1

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Table 1 Switching Configuration and Vector used in a Direct Matrix Converter [2]

N0.	A B C	$\|V_o\|$	$\angle V_o$	$\|I_i\|$	$\angle I_i$
1+	a b b	$2/\sqrt{3}\,v_{ab}$	$\pi/6$	$2/\sqrt{3}\,i_A$	$-\pi/6$
1-	b a a	$2/\sqrt{3}\,v_{ab}$	$-5\pi/6$	$2/\sqrt{3}\,i_A$	$5\pi/6$
2+	b c c	$2/\sqrt{3}\,v_{bc}$	$\pi/6$	$2/\sqrt{3}\,i_A$	$\pi/2$
2-	c b b	$2/\sqrt{3}\,v_{bc}$	$-5\pi/6$	$2/\sqrt{3}\,i_A$	$-\pi/2$
3+	c a a	$2/\sqrt{3}\,v_{ca}$	$\pi/6$	$2/\sqrt{3}\,i_A$	$-5\pi/6$
3-	a c c	$2/\sqrt{3}\,v_{ca}$	$-5\pi/6$	$2/\sqrt{3}\,i_A$	$\pi/6$
4+	b a b	$2/\sqrt{3}\,v_{ab}$	$5\pi/6$	$2/\sqrt{3}\,i_B$	$-\pi/6$
4-	a b a	$2/\sqrt{3}\,v_{ab}$	$-\pi/6$	$2/\sqrt{3}\,i_B$	$5\pi/6$
5+	c b c	$2/\sqrt{3}\,v_{bc}$	$5\pi/6$	$2/\sqrt{3}\,i_B$	$\pi/2$
5-	b c b	$2/\sqrt{3}\,v_{bc}$	$-\pi/6$	$2/\sqrt{3}\,i_B$	$-\pi/2$
6+	a c a	$2/\sqrt{3}\,v_{ca}$	$5\pi/6$	$2/\sqrt{3}\,i_B$	$-5\pi/6$
6-	c a c	$2/\sqrt{3}\,v_{ca}$	$-\pi/6$	$2/\sqrt{3}\,i_B$	$\pi/6$
7+	b b a	$2/\sqrt{3}\,v_{ab}$	$-\pi/2$	$2/\sqrt{3}\,i_C$	$-\pi/6$
7-	a a b	$2/\sqrt{3}\,v_{ab}$	$\pi/2$	$2/\sqrt{3}\,i_C$	$5\pi/6$
8+	c c b	$2/\sqrt{3}\,v_{bc}$	$-\pi/2$	$2/\sqrt{3}\,i_C$	$\pi/2$
8-	b b c	$2/\sqrt{3}\,v_{bc}$	$\pi/2$	$2/\sqrt{3}\,i_C$	$-\pi/2$
9+	a a c	$2/\sqrt{3}\,v_{ca}$	$-\pi/2$	$2/\sqrt{3}\,i_C$	$-5\pi/6$
9-	c c a	$2/\sqrt{3}\,v_{ca}$	$\pi/2$	$2/\sqrt{3}\,i_C$	$\pi/6$
O_a	a a a	0	-	0	-
O_b	b b b	0	-	0	-
O_c	c c c	0	-	0	-

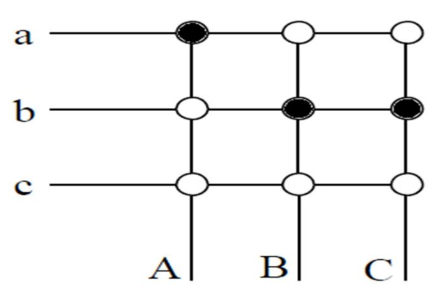

Fig.7 Arrangement for abb configuration

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Volume 9 Issue III Mar 2021- Available at www.ijraset.com

The switching configuration for each vector is identified by the one number and the three letters. For example, the configuration for abb shows that the output phase A is connected to the input phase a, output phase B is connected to the input phase b and the output phase C is connected to the input phase b. Now the input current and output voltage is calcuated for switching configuration abb and its position can be computed by the angle it made by the reference.

the input current $i_a = i_A$, $i_b = -i_A$ and $i_c = 0$

then, $$I_i = \frac{2}{3}\left(i_a + a i_b + a^2 i_c\right) = \frac{2}{\sqrt{3}} i_A e^{-j\pi/6}$$

the output voltage $v_{AB} = v_{ab}$, $v_{BC} = 0$ and $v_{BC} = -v_{ab}$

$$V_o = \frac{2}{3}\left(v_{AB} + a v_{BC} + a^2 v_{CA}\right) = \frac{2}{\sqrt{3}} i_A e^{j\pi/6}$$

Here, how the switching configuration abb is decoded, the similar procedure can be applied for the other configuration. The output voltage and input current vectors referring to the 18 active vector configurations are shown and how the gauss plane is divided in sectors is shown [4]

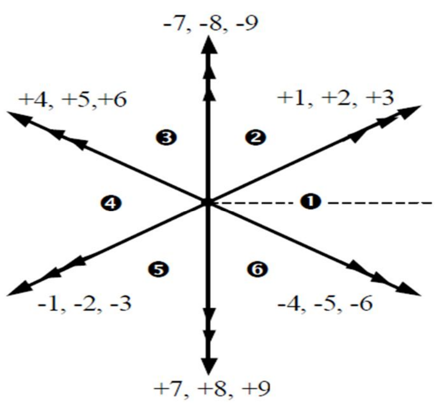

Fig.8 Output Voltage Space Vectors for Active and Zero configuration

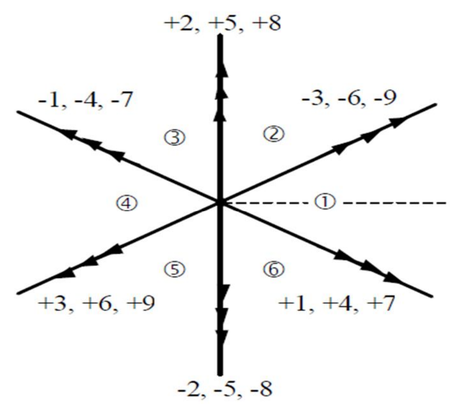

Fig.9 Input Current Space Vector for Active and Zero configuration

In the DSVM, the selection of the four suitable active vectors to produce the reference output voltage vector can be explained by taking an example. For example both the voltage and current vector are lying in the sector 1, then the desired output voltage vector v_o can be synthesized using two vectors $v_o{}'$ and $v_o{}''$ and the component of these two vector can be synthesized using the two of the six possible switching configuration ±1, ±2, ±3 and ±4, ±5, ±6 respectively. Furthermore the switching configuration ±3, ±6, ±9 and ±1, ±4, ±7 are used to generate the input current vector in the sector 1. Among of these above switching configuration the four common with two higher voltage magnitude are chosen, from these analysis four switching configuration -3,+1,+6,-4 are selected for the case of sector 1 of both the voltage and current. Using the same method, the four switches configurations corresponding to the applicable combination of the selected sectors of the output voltage and input current can be determined

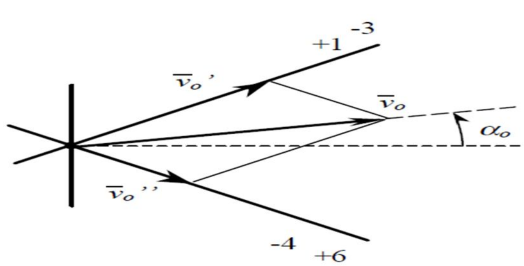

Fig. 10 Space Vector Modulation of reference output voltage vector

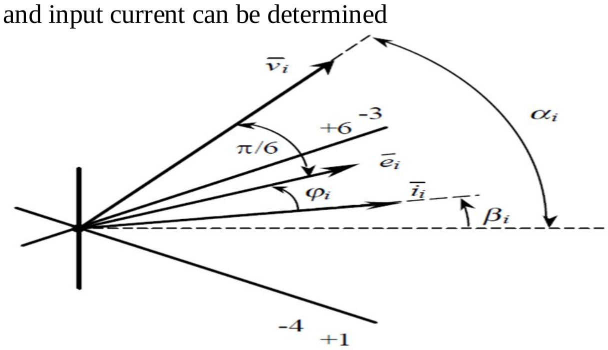

Fig. 11 Space Vector Modulation of reference input current vector

The all possible combinations of the sector of output voltage and input current are listed in the Table 2, where v_o represent the output voltage sector and i_i represent the input current sectors.

Table 2 Matrix Configurations for Each Combination of Output Voltage and Input current

i_i \ v_o	1	2	3	4	5	6
1	-3 +1 +6 -4	+9 -7 -3 +1	-6 +4 +9 -7	+3 -1 -6 +4	-9 +7 +3 -1	+6 -4 -9 +7
2	+2 -3 -5 +6	-8 +9 +2 -3	+5 -6 -8 +9	-2 +3 +5 -6	+8 -5 -2 +3	-5 +6 +8 -9
3	-1 +2 +4 -5	+7 -8 -1 +2	-4 +5 +7 -8	+1 -2 -4 +5	-7 +8 +1 -2	+4 -5 -7 +8
4	+3 -1 -6 +4	-9 +7 +3 -1	+6 -4 -9 +7	-3 +1 +6 -4	+9 -7 -3+1	-6 +4 +9 -7
5	-2 +3 +5 -6	+8 -5 -2 +3	-5 +6 +8 -9	+2 -3 -5 +6	-8 +5 +2 -3	+5 -6 -8 +9
6	+1 -2 -4 +5	-7 +8 +1 -2	+4 -5 -7 +8	-1 +2 +4 -5	+7 -8 -1 +2	-4 +5 +7 -8

The duty ratio of the four selected vectors as per the selected sector are define below, Here, $\widetilde{\alpha}_o$ and $\widetilde{\beta}_\iota$ are the output voltage and input current phase angle respectively referred to the bisecting line of the corresponding sector and where $\emptyset_i$ is the input current displacement angle.

$$d_1 = \frac{2}{\sqrt{3}} \frac{v_o}{v_i} \frac{\cos(\widetilde{\alpha_o} - \frac{\pi}{3}) \cos(\widetilde{\beta_\iota} - \frac{\pi}{3})}{\cos \emptyset_i} \quad (17)$$

$$d_2 = \frac{2}{\sqrt{3}} \frac{v_o}{v_i} \frac{\cos(\widetilde{\alpha_o} - \frac{\pi}{3}) \cos(\widetilde{\beta_\iota} + \frac{\pi}{3})}{\cos \emptyset_i} \quad (18)$$

$$d_3 = \frac{2}{\sqrt{3}} \frac{v_o}{v_i} \frac{\cos(\widetilde{\alpha_o} + \frac{\pi}{3}) \cos(\widetilde{\beta_\iota} - \frac{\pi}{3})}{\cos \emptyset_i} \quad (19)$$

$$d_4 = \frac{2}{\sqrt{3}} \frac{v_o}{v_i} \frac{\cos(\widetilde{\alpha_o} + \frac{\pi}{3}) \cos(\widetilde{\beta_\iota} + \frac{\pi}{3})}{\cos \emptyset_i} \quad (20)$$

$$d_0 = 1 - d_1 - d_2 - d_3 - d_4 \quad (21)$$

Here the d_1, d_2, d_3, d_4 are the duty ratio of the selected active vectors and d_0 is the duty ratio of the zero vectors.

V. DIRECT MATRIX CONVERTER WITH RL LOAD

Here RL load is used for the MC, with direct SVM as the control strategy is used, the input/output current and voltage characteristics are appeared below.

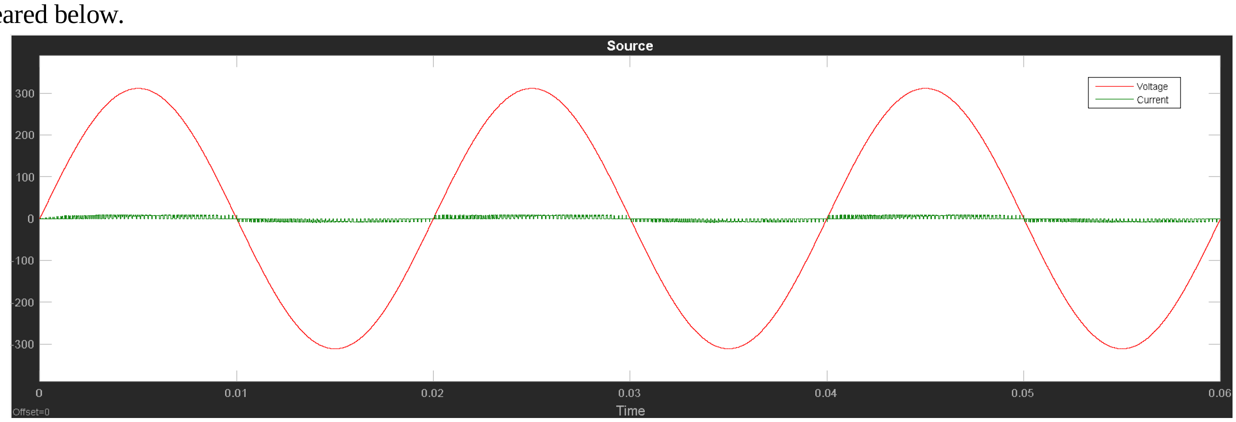

Fig.12 Input Voltage and Current Waveform for RL Load

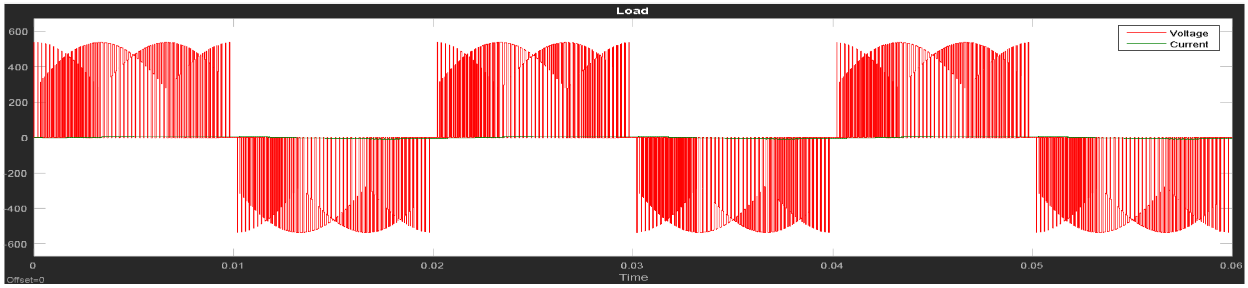

Fig.13 Output Voltage and Current Waveform for RL load

The THD for the input current is observed as 4.00% and for output current it is observed as 1.62 % by using the DSVM as the control strategy.

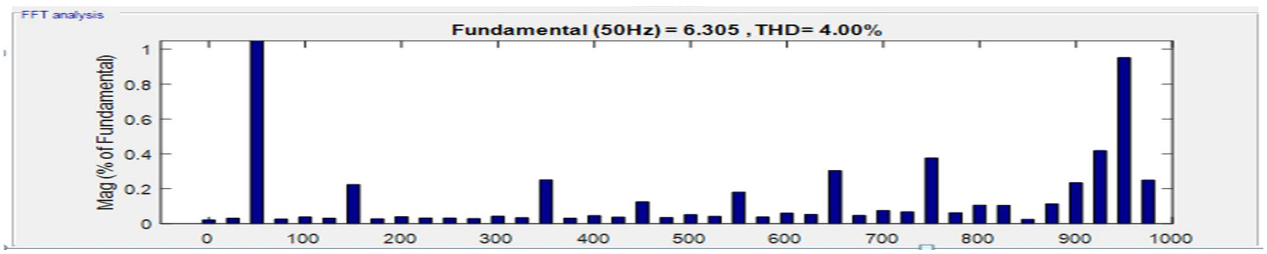

Fig.14 Harmonic analysis of input current (DMC)

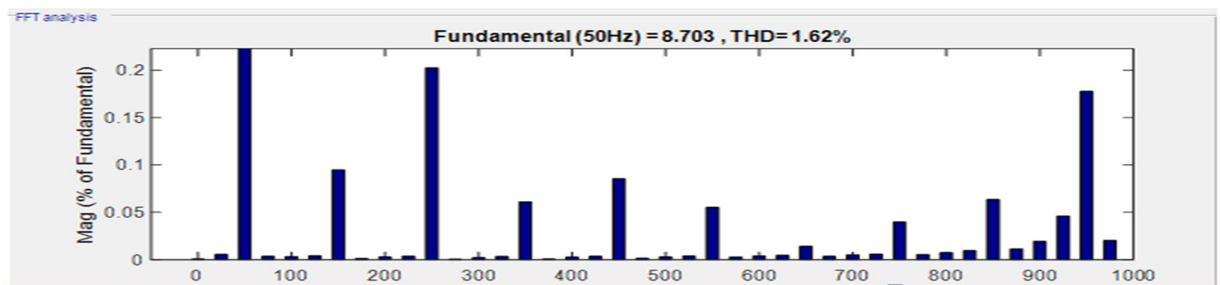

Fig.15 Harmonic analysis of output current (DMC)

VI. CONCLUSION

This paper present the fundamental of MC and its characteristics, the DSVM technique is also applied in MC using RL load. By the result we observed that the THD in input current is 4.00% and for output it is 1.62%, which is very less in comparison to the conventional converter and there are also many other advantages of MC over the conventional converter , Hence the MC is a good alternative to fulfill the modern demand of the industries.

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