Mathematical Modeling and Simulation of AC-AC Three Phase Matrix Converter with LC Filter driving Static Resistive Load

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Abstract

During the last two decades, it has been seen that power conversion from one form to another form of energy was a serious issue in power electronics. After the production of power converters such as rectifiers that convert AC-DC, inverters that convert DC-AC, voltage regulators, choppers, and cycloconverters make possible power conversion. In 1980, Venturini presented the concept of the Matrix Converter in power electronics; it consists of bidirectional IGBT switches and can conduct current and block reverse and forward voltage. Nowadays matrix converter is frequently utilized for power conversion because it can convert AC-AC, AC-DC, DC-DC, and DC- AC directly without an energy storage device which results in less complexity and cost. In matrix converters, high switching frequency harmonics are produced due to the switching of converters and need to be minimized. In this paper, an LC filter is employed to mitigate the problem of harmonics at the output of the three-phase matrix converter. A three-phase matrix converter with an LC filter is presented in this paper and the SVM technique is used for the generation of pulses. Simulation results are carried out through MATLAB software.

Keywords—Matrix Converter, LC Filter, Resistive Load

1 Introduction

During the last two decades, it has been seen that power conversion from one form to another form of energy was a serious issue in power electronics. After the production of power converters such as rectifiers that convert AC-DC, inverters that convert DC-AC, voltage regulators, choppers, and cycloconverters make possible power conversion[1]. Power converters which require multiple power sources and power conversion stages (ac-dc-ac), are heavy and less reliable, particularly at large capacities [2]. The matrix converter concept is introduced by Venturini in 1980 [3]; it consists of 09 bidirectional Insulated Gate Bipolar Transistor switches and can conduct current in both directions and block reverse and forward voltage [2, 4]. Nowadays matrix converters are frequently utilized for power conversion because it can convert AC-AC, AC-DC, DC-DC, and DC-AC directly, and there is no need for an energy storage device. In this way, complexity and cost are reduced due to all conversions of power in one container [3]. In matrix converters high switching frequency harmonics are produced due to semiconductor IGBT switches being available in the assembly of matrix converters and need to be minimized. In this paper, an LC Low pass filter is employed at the output of the matrix converter to minimize the problem of harmonics.

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2 Three Phase Matrix Converter

It can convert in a single stage and consists of m× n groupings of bidirectional IGBT switches, m is connected directly to the input source and n is connected to the output of the load [4]. Fig.1. shows the IGBTs based three-phase matrix converter and Fig.2. shows the common usage of switching arrangement. The single switch function is defined below.

$$S_{K_j} = \{1,\ Switch\ S_{k_j}\ is\ closed\} \tag{1}$$

$$S_{k_j} = \{0,\ Switch\ S_{k_j}\ is\ open\} \tag{2}$$

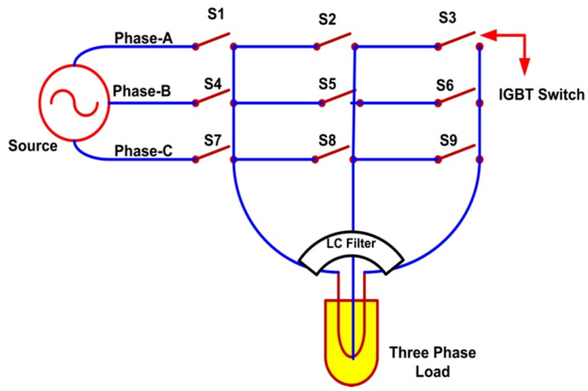

Fig. 1: Simplified 3×3 Matrix Converter

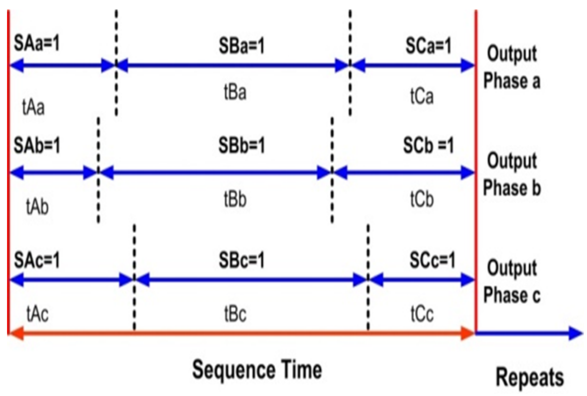

Fig. 2: Common usage of the switching arrangement

$where\ S_{k_j} = \{A, B, C\}\ ,\ j = \{a, b, c\}$
The above equation can be expressed as,

$$S_{A_j} + S_{B_j} + S_{C_j} = 1, \quad j = \{a, b, c\} \tag{3}$$

In the matrix converter, be careful during the operation of switches, in one state only one switch in each phase should be ON and others will remain under OFF condition [5], otherwise short circuit will occur. The possible 27 switching states are given in table 3. Fig. 3 shows source and load voltages denoted by neutral "0" and can be stated as,

$$V_0 = \begin{bmatrix} V_a^{(t)} \\ V_b^{(t)} \\ V_c^{(t)} \end{bmatrix}, V_i = \begin{bmatrix} V_A^{(t)} \\ V_B^{(t)} \\ V_C^{(t)} \end{bmatrix} \tag{4}$$

The relationship between load and source voltages is,

$$\begin{bmatrix} V_a^{(t)} \\ V_b^{(t)} \\ V_c^{(t)} \end{bmatrix} = \begin{bmatrix} S_{A_a}^{(t)} & S_{B_a}^{(t)} & S_{C_a}^{(t)} \\ S_{A_b}^{(t)} & S_{B_b}^{(t)} & S_{C_b}^{(t)} \\ S_{A_c}^{(t)} & S_{B_c}^{(t)} & S_{C_c}^{(t)} \end{bmatrix} \begin{bmatrix} V_A^{(t)} \\ V_B^{(t)} \\ V_C^{(t)} \end{bmatrix} \tag{5}$$

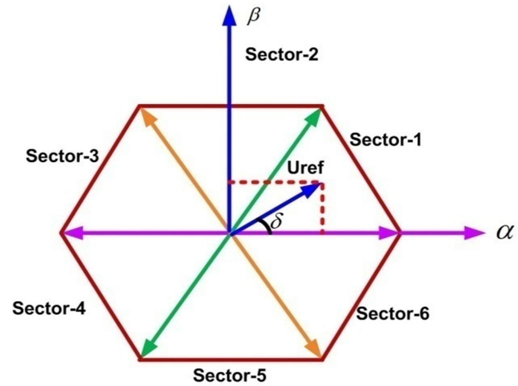

Fig. 3: Output voltage space vectors

$$V_o = T.V_i \tag{6}$$

Where T is the instantaneous transfer function of the matrix converter, similarly below is the relationship between output and input currents.

$$i_i = \begin{bmatrix} i_a^{(t)} \\ i_b^{(t)} \\ i_c^{(t)} \end{bmatrix}, i_0 = \begin{bmatrix} i_A^{(t)} \\ i_B^{(t)} \\ i_C^{(t)} \end{bmatrix} \tag{7}$$

$$i_i = T^T.i_0 \tag{8}$$

Direct connection of input and output quantities are provided in equations (06) and (08). Assume that the IGBT switches are functioning at a high switching frequency. The output voltage of low frequency can be generated through duty cycle modulation of switches by utilization of their particular switching operation. Let the duty cycle of the switch $S_{k_j}\ is\ m_{k_j}^{(t)}$

$$m_{k_j}^{(t)} = \frac{t_{k_j}}{T_{seq}} \tag{9}$$

$where\ 0 < m_{k_j} < 1\ K = \{A, B, C\},\ j = \{a, b, c\}$
The transfer function at low frequency is,

$$M_{(t)} = \begin{bmatrix} m_{A_a}^{(t)} & m_{B_a}^{(t)} & m_{C_a}^{(t)} \\ m_{A_b}^{(t)} & m_{B_b}^{(t)} & m_{C_b}^{(t)} \\ m_{A_c}^{(t)} & m_{B_c}^{(t)} & m_{C_c}^{(t)} \end{bmatrix} \tag{10}$$

The components of output phase voltage at low frequency are,

$$V_0^{(t)} = M_{(t)}.V_i^{(t)} \tag{11}$$

The low-frequency components of the input current are,

$$i_i = M_{(t)}^T.i_0 \tag{12}$$

2.1 Bidirectional Switch

Bidirectional switches are needed for a matrix converter that conducts current and block voltage in both directions, but still, now such type of switch is not available in the market. In this paper, two IGBT switches are joined anti-parallel to create the action of a switch as bidirectional [4].

2.2 Space Vector Modulation Method

This type of modulation technique is commonly used for the generation of pulse in inverter circuits for switching purposes. SPVM method is proposed for the production of pulse for matrix converter in this paper [6]. A detailed discussion between SPVM and other methods is available in [7]. In this paper only we have focused on the output voltages. In terms of line-to-line voltage, the voltage space vector of the matrix converter is expressed in equation (13).

$$V_0^{(t)} = \frac{2}{3}(V_{ab} + aV_{bc} + a_{ca}^2) \tag{13}$$

$where\ a = exp(\frac{j2\pi}{3})$

The feasible 27 output vectors can be categorized into three groups.

Group-1

There is no change in the magnitude of output vectors, rotate in any direction and every output line is joined to a dissimilar input line.

Group-II

The output vectors in this group are not constant in magnitude and are stationary in the direction occupied by one of six positions spaced 60^0 apart. The two output lines are connected to a common input line and the other output line is connected to one of the remaining input lines.

Group-III

In this group, the output vectors have zero amplitude and all output lines are coupled to a common input line. The possible output vectors in the hexagon are shown in figure 03.
However $V_0^{(t)}$ could be matched, which lies in the sextant vector 1 and 6. $V_0^{(t)}$ is produced by time-averaging through a selection of time spent in vector $1^{(t1)}$ and vector $6^{(t6)}$ during the switching sequence. It is supposed that the vectors that are large in length are utilized. It is supposed that the vectors that are large in length are utilized and the relationship is shown in Fig. 4 and is expressed in equation (14).

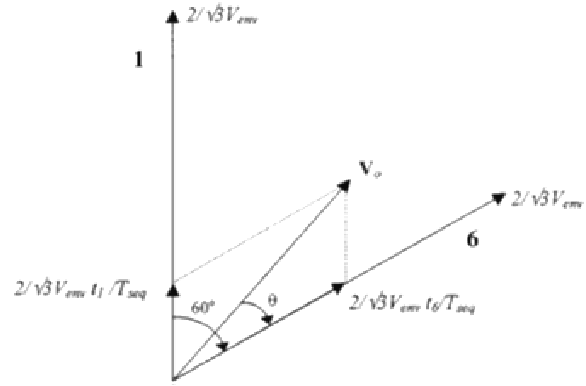

Fig. 4: Output voltage space vectors synthesis

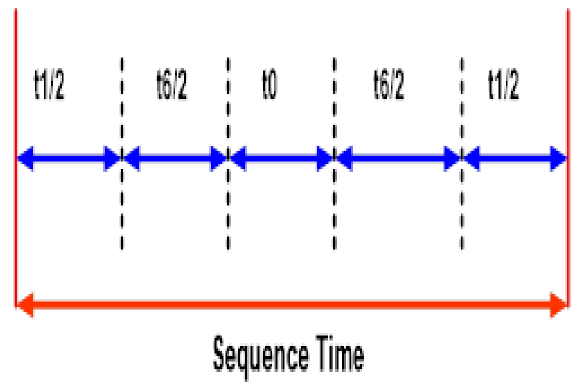

Fig. 5: Possible way of allocation of possible states within switching sequence.

From figure 3 the relationship is expressed in equation (14).
whereas, $t_1 = \frac{V_0}{V_{env}} T_{seq} Sin(\theta)$ and $t_6 = \frac{V_0}{V_{env}} T_{seq} Sin(60-\theta)$ then

$$t_0 = T_{seq} - (t_1 + t_6) \tag{14}$$

where t_0 is consumed time in the zero vectors. There is no method for allocating the time (t_0, t_1, t_6) inside the switching sequence solitary method is shown in Fig. 5.

There is a need to the apply SPVM technique for current control and voltage control to reduce the harmonics. This usually requires 4 active vectors in every switching sequence. Under the balanced condition, the results of the SPVM method is the same as other technique but have useful advantages under the unbalanced condition.

3 Filter

In this paper, an LC Low Pass filter is proposed which is commonly used in converters to reduce the harmonics due to switching of converters. LC filter is

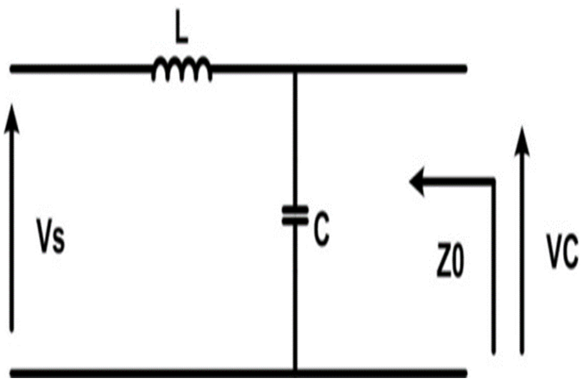

Fig. 6: LC filter

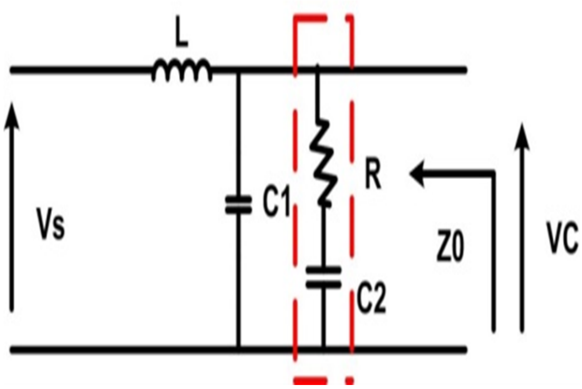

Fig. 7: The improved LC filter

shown in Fig. 6.

With the addition of a damping resistor and additional capacitor (C2), the Performance of the LC filter can be improved [8]. The improved LC filter is shown in figure 07. Through equations 16 and 17 we can determine the output impedance and voltage gain of the LC filter.

$$Z_0 = \frac{S_L(1+sRC_2)}{s^3LRC_1C_2 + s^2L(C_1+C_2) + sRC_2 + 1} \tag{15}$$

$$\frac{V_c}{V_s} = \frac{1+sRC_2}{s^3LRC_1C_2 + s^2L(C_1+C_2) + sRC_2 + 1} \tag{16}$$

By re-arranging equation (16) we obtained equation (17).

$$H(s) = -R = -\frac{1}{k} = \frac{s^2L(C_1+C_2+1}{s^3LC_1C_2 + sC_2} \tag{17}$$

Where $H(s)$ is the root locus plot of a closed loop system with an open loop transfer function and K is the variable feedback gain.

TABLE 1: Simulation Parameters for Root Locus Plot

S.No	Parameter	value
1	Resistance (R)	3.7 Ω(Ohm)
2	Inductance (L)	90 μH (micro Henry)
3	Capacitance (C1)	500 (micro Farad)
4	Capacitance (C2)	10 mF (millifarad)

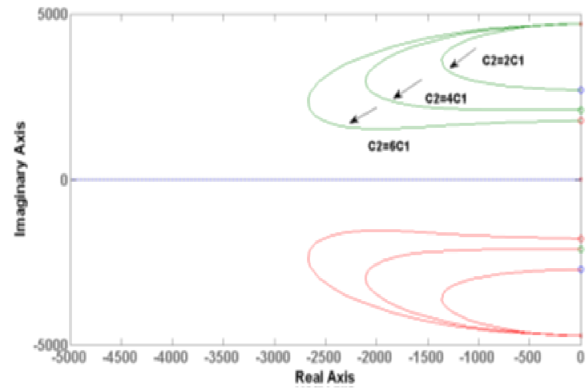

Fig. 8: simulated root locus plot

Fig. 8 shows the simulated root locus plot, it has been seen that the system is more reliable by increasing the value of $C2$, which results in increasing the pole locus to the half-plane.

4 Possible connections of Damping Resistor

The output and input transfer function of fig. 9 is given in equation (18).

$$\frac{V_c}{V_s} = \frac{R}{S^2RLC + sL + R} \tag{18}$$

The output and input transfer function of Fig. 10 is given in equation (19).

$$\frac{V_c}{V_s} = \frac{sRC+1}{S^2LC + sRC + 1} \tag{19}$$

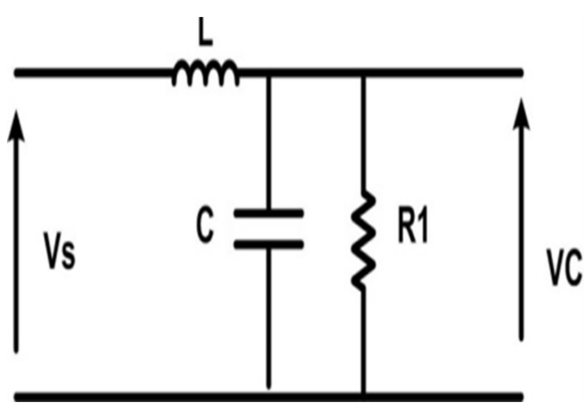

Fig. 9: Resistor connected in parallel to the Capacitor

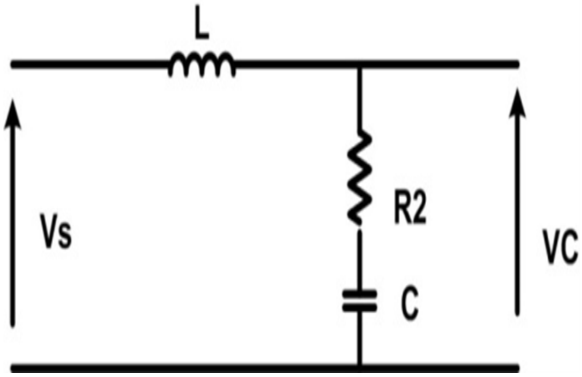

Fig. 10: Resistor connected in series to the capacitor

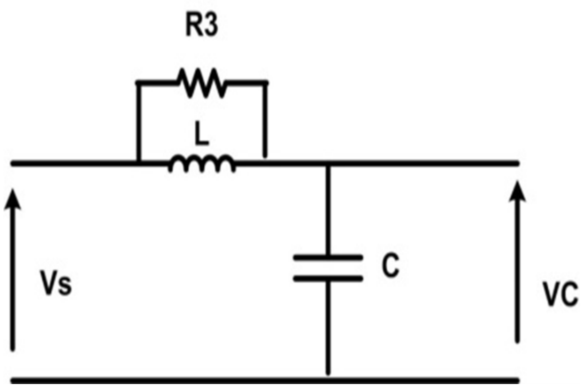

Fig. 11: Resistor connected in parallel to the inductor

The output and input transfer function of Fig. 11 is given in equation (20).

$$\frac{V_c}{V_s} = \frac{sL + R}{S^2RLC + sL} \tag{20}$$

The output and input transfer function of Fig. 12 is given in equation (21).

$$\frac{V_c}{V_s} = \frac{1}{s^2LC + sRC + 1} \tag{21}$$

It has been seen in Fig. 13, the circuit topology is less peaking in Fig. 9 (R1) than others, which means that the system is reliable. Therefore, the connection of a resistor in parallel with a capacitor is the best for input filter design.

5 Static Resistive Load

The load which consumes electrical energy is referred to as the electrical load. A load in which voltage (V) and current (I) remains in phase is referred to as a resistive load and the power factor remains unity. Static resistive loads are such as a heater, and filament lamps [9]. The active power of the static resistive is given in equation (22).

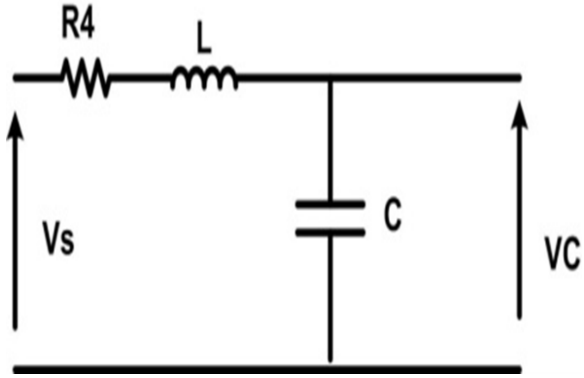

Fig. 12: Resistor connected in series to the inductor

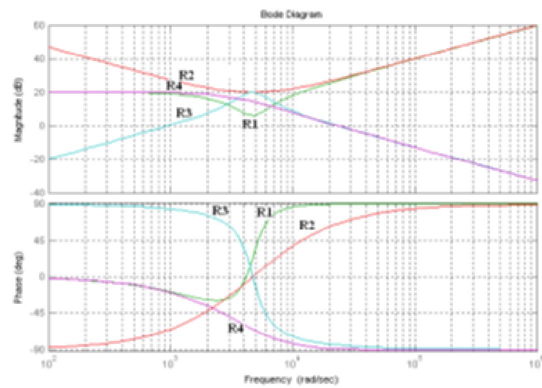

Fig. 13: Voltage transfer functions of each resistor connection

TABLE 2: Simulation Model Parameters

S.No	Parameter	Value
1	Source voltage (Vs)	400volts
2	Resistive load per phase	2 Ω (ohm)
3	Damping Resistor	3.7 Ω (ohm)
4	Filter Inductance	90 μH (micro Henry)
5	Filter Capacitance	500 μF (micro Farad)

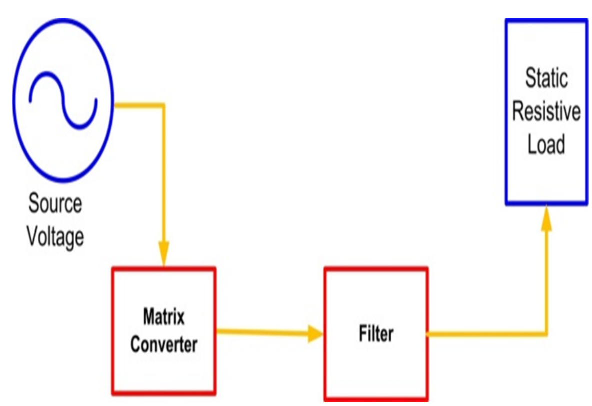

Fig. 14: Block diagram of Three Phase AC to AC Matrix Converter driving Static Resistive Load

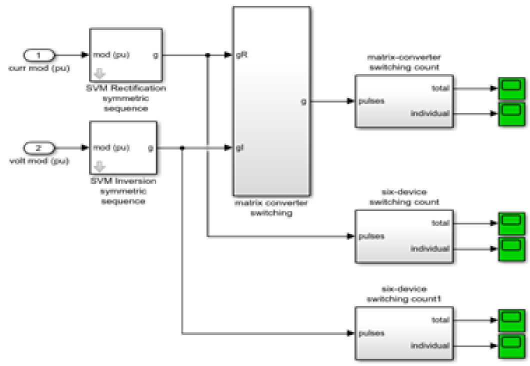

Fig. 15: Simulation Model of Three Phase Matrix Converter

$$P = V^2[R_1(1 + \alpha_1\tau)]^{-1} \tag{22}$$

Where V is the RMS value of applied voltage, α_1 is the temperature coefficient of temperature, and R_1 is the resistance in ohm. When temperature is changed to final value τ_final, and then τ is signified as,

$$\tau = \tau_final(1 - e^{-\tau/T)} \tag{23}$$

Where T is the time constant

Reactive power consumption is absent in the resistive loads since the influence of the frequency on the active power consumption is neglected.

6 Simulation results of three phase Matrix Converter

The block diagram of proposed three phase matrix converter driving static restive load is shown in Fig. 14 and simulation model is shown in Fig. 15. The parameters in table 2 were utilized in MATLAB Simulink software to get the simulation results.

7 Discussion

The three-phase matrix converter is the best power converting technique which gives results in less cost and a reduction in the complexity of the system. All conversion techniques (ac-ac, ac-dc, dc-ac, and dc-dc) are conceivable in matrix converter. The simulation results of matrix converters output voltage and currents with and without LC filters are shown in Figs. 16(a), 16(b), and 16(c).

8 Conclusion

Matrix converter consists of bidirectional IGBT switches and can conduct the current in both directions and block reverse and forward voltage. The Matrix converters are frequently utilized for power conversion because of their converting ability from AC-AC, AC-DC, DC-DC, DC- AC directly, and there is no need of an energy storage device which results in less cost and reduced complexity of the system. Harmonics are produced due to the switching of the matrix converter so a filter circuit is necessary to mitigate the harmonics. Therefore the LC filter with the connection of a damping resistor in parallel with a capacitor is the best for input filter design and helps in mitigating the harmonics. So it is concluded that the three-phase AC to AC matrix converter with LC filter is the best for conversion of power.

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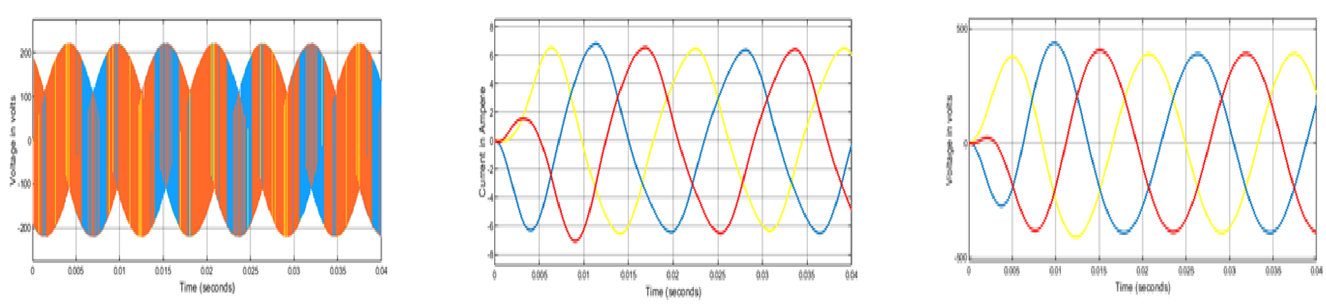
TABLE 3: Switching States of Three Phase Matrix Converter

state	Phase			Switching Function								
	A	B	C	S_{A_a}	S_{A_b}	S_{A_c}	S_{B_a}	S_{B_b}	S_{B_c}	S_{C_a}	S_{C_b}	S_{C_c}
1	A	B	C	1	0	0	0	1	0	0	0	1
2	A	C	B	1	0	0	0	0	1	0	1	0
3	B	A	C	0	1	0	1	0	0	0	0	1
4	B	C	A	0	1	0	0	0	1	1	0	0
5	C	A	A	0	0	1	1	0	0	1	0	0
6	C	B	A	0	0	1	0	1	0	1	0	0
7	A	C	C	1	0	0	0	0	1	0	0	1
8	A	C	C	0	1	0	0	0	1	0	0	1
9	B	A	A	0	1	0	1	0	0	1	0	0
10	C	A	A	0	0	1	1	0	0	1	0	0
11	C	B	B	0	0	1	0	1	0	0	1	0
12	A	A	B	1	0	0	1	0	0	0	1	0
13	C	A	C	0	0	1	1	0	0	0	0	1
14	C	B	C	0	0	1	0	1	0	0	0	1
15	A	B	A	1	0	0	0	1	0	1	0	0
16	A	C	A	1	0	0	0	0	1	1	0	0
17	B	C	A	0	1	0	0	0	1	0	1	0
18	B	A	B	0	1	0	1	0	0	0	1	0
19	C	C	A	0	0	1	0	0	1	1	0	0
20	C	C	B	0	0	1	0	0	1	0	1	0
21	A	A	B	1	0	0	1	0	0	0	1	0
22	A	A	C	1	0	0	1	0	0	0	0	1
23	B	B	C	0	1	0	0	1	0	0	0	1
24	B	B	A	0	1	0	0	1	0	1	0	0
25	A	A	A	1	0	0	1	0	0	1	0	0
26	B	B	B	0	1	0	0	1	0	0	1	0
27	C	C	C	0	0	1	0	0	1	0	0	1



(a) Output Voltage of Three phase Matrix Converter driving Static Load without LC filter

(b) Output Current waveform of three-phase Matrix Converter driving Static Load with LC filter

(c) The output Voltage waveform of three phase Matrix Converter driving Static Load with LC filter

Fig. 16: various Output characteristics of Three phase Matrix Converter driving Static Load with and without LC filter