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# Simulation of 3 Phase to 3 Phase Power Conversion Using Matrix Converter with Maximum and Minimum Voltage Transfer Ratio

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**ABSTRACT**
This paper proposes a new approach of design and implementation of 3 phase to 3 phase conversion using matrix converter. It includes the design, modeling and implementation. The entire matrix converter circuits are developed by mathematical model so as to reduce computational time and performances of the converter are evaluated using MATLAB/SIMULINK for RL Load. The mathematical expressions relating the input and output of the three phase matrix converter are implemented by using simulink block set. The duty cycles of the matrix converter bidirectional switches are calculated using modified venturini algorithm for maximum (0.866) and minimum (0.5) voltage transfer ratio.

***Keywords -*** 3 phase to 3 phase converter, AC to AC converter, Matrix converter, Multi-phase converter, Power converter.

## I. INTRODUCTION

A matrix converter is an ac/ac converter that can directly convert an ac power supply voltage into an ac voltage of variable amplitude and frequency. It has high power quality and it is fully regenerative. Due to the increasing importance of power quality and energy efficiency issues, the Matrix converter technology has recently attracted the power electronics industry. Direct ac/ac converters have been studied in an attempt to realize high efficiencies, long lifetime, size reduction, and unity power factors. The benefits of using direct ac/ac converters are even greater for medium voltage converters as direct ac/ac converters do not require electrolytic capacitors, which account for most of the volume and cost of medium-voltage converters.

Due to the absence of energy storage elements, Matrix converter has higher power density than PWM inverter drives. However, for the same reason, the ac line side disturbances can degrade its performance and reliability. Therefore the matrix converter drive performance under abnormal input voltage conditions were introduced [1].Timing errors in the switching between the series-connected switches cause a voltage imbalance in the snubber circuit and increase voltage stress. A new bidirectional switch with regenerative snubber to realize simple series connection for matrix converters was proposed [2]. Forced commutations of the high number of semiconductors cause switching losses that reduce the efficiency of the system and imply the use of large heat sinks. Hence a predictive approach to increase efficiency and reduce switching losses on matrix converter was presented [3].Classical modulation techniques are not applicable because of the needed high output frequencies. Hence Bidirectional switch commutation for a Matrix converter supplying a series resonant load was developed [4]. New investigations to develop appropriate digital carrier modulation schemes for controlling conventional and indirect matrix converter with minimized semiconductor commutation count [5].

A single-phase Z-source Buck-Boost matrix converter which can buck and boost with step-changed frequency, and both the frequency and voltage can be stepped up or stepped down was developed [6]. A matrix converter has the potential to offer improved operational performance by evaluating its design and potential operating performance in a marine electric propulsion system [7]. A fault-tolerant matrix converter with reconfigurable and modified switch control schemes, along with a fault diagnosis technique for open-circuited switch failure were proposed [8]. A new control method for a matrix converter based induction machine drive ware introduced. A discrete model of the converter, Motor, and input filter is to predictive the behavior of torque, flux, and input power to the drive [9].

For various industrial adjustable speed ac drives and applications, various analysis and mathematical model is introduced in matrix converter. By varying the Modulation Index (MI), the outputs of the matrix converter are controlled and in ac drives, speeds of the drive were controlled. To reduce the computational time and low memory requirement, a mathematical model has been developed [10]-[16].

In this paper, the converter are designed and implemented for the 3 phase to 3 phase matrix converter in open loop configuration and the power circuit in open loop are implemented by the mathematical modeling. The duty cycle calculation is taken into account for Maximum (0.866) and minimum (0.5) voltage transfer ratios and the mathematical model is realized with the RL load. The entire power circuit is modeled with MATLAB/SIMULINK. Implementation of converter in mathematical modeling includes the modeling of power circuit, Control algorithm, and load. Merits of Mathematical model over conventional power circuit are less computation time and low memory requirement. The proposed model is very simple, flexible and can be accommodated with any type of load. Fig. 1 refers the Basic block diagram of the proposed 3pase to 3 phase Matrix converter.

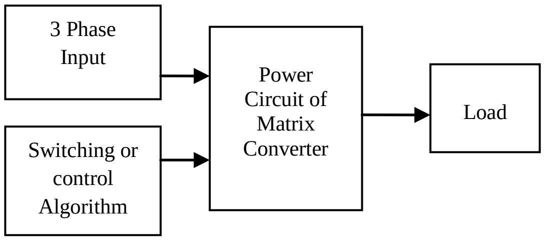


Fig.1. Basic block diagram of 3pase to 3 phase Matrix converter.

## II. MATRIX CONVERTER

The Matrix converter (MC) is a single stage direct ac to ac converter, which has an array of m x n bi-directional switches that can directly connect m phase voltage source into n phase load. A 3 phase matrix converter consists of 3x3 switches arranged in matrix form. The arrangement of bi-directional switches is such that any of the input phases R,Y,B is connected to any of the output phases r,y,b at any instant. The average output voltage with desired frequency and amplitude can be controlled by the bi-directional switches. The bi-directional 3x3 switches ($2^9$) gives 512 combinations of the switching states. But only 27 switching combinations are allowed to produce the output line voltages and input phase currents. The desirable characteristics of a Matrix converter are as follows:

- ♣ Sinusoidal input and output waveforms with minimal higher order harmonics and no subharmonics;
- ♣ Minimal energy storage requirements
- ♣ Controllable input power factor
- ♣ Bidirectional energy flow capability
- ♣ Compact design
- ♣ Long life due to absence of a bulky electrolytic capacitor
- ♣ Unity input power factor at the power supply side

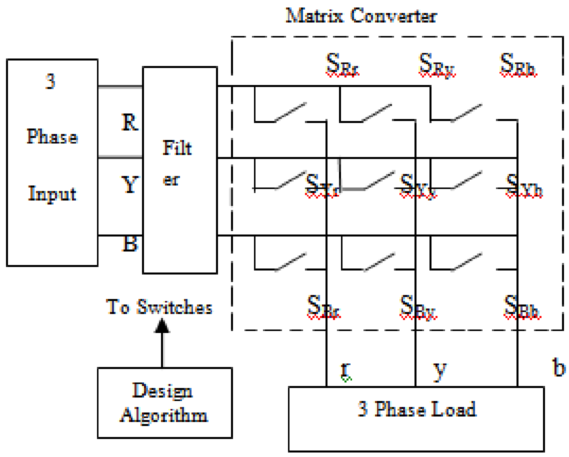


Fig.2. circuit scheme of 3 phase to 3 phase matrix converter

Limitations of Matrix converter are

- ♣ The voltage transfer ratio limitation has a maximum value of 0.866
- ♣ Sensitive to the power source distortion due to the direct connection between input and output sides.

Input filter is needed in order to eliminate the harmonic components of the input current and reduce the input voltage distortion supplied to the Matrix Converter as shown in fig.2.

## III. CONTROL ALGORITHM

When 3 phase to 3 phase converter operated with9 bi-directional switches, the following two basic rules have to be satisfied [10].

- ♣ Two or three input lines should not be connected to the same output line – to avoid short circuit
- ♣ At least one of the switches in each phase should be connected to the output – to avoid open circuit.

The switching function of single switch as

$$S_{Kj} = \begin{cases} 1, \text{switch SKj closed} \\ 0, \text{switch SKj opened} \end{cases} \qquad (1)$$

Where, K = {r, y, b}, j = {R, Y, B}

The above constraints can be expressed by

$$Srj + Syj + Sbj = 1, \quad j = \{R, Y, B\} \qquad (2)$$

With these restrictions, the 3 x 3 matrix converter has 27 possible switching states.

The input or source voltage vector of the 3 phase to 3 phase Matrix converter is

$$V_i = \begin{bmatrix} V_R \\ V_Y \\ V_B \end{bmatrix} = \begin{bmatrix} V_{im}\cos(\omega_i t) \\ V_{im}\cos(\omega_i t + \frac{2\pi}{3}) \\ V_{im}\cos(\omega_i t + \frac{4\pi}{3}) \end{bmatrix} \qquad (3)$$

The output voltage vector of the 3 phase to 3 phase Matrix converter is

$$V_o = \begin{bmatrix} V_r \\ V_y \\ V_b \end{bmatrix} = \begin{bmatrix} V_{om}\cos(\omega_o t) \\ V_{om}\cos(\omega_o t + \frac{2\pi}{3}) \\ V_{om}\cos(\omega_o t + \frac{4\pi}{3}) \end{bmatrix} \quad (4)$$

The input or source current vector of the 3 phase to 3 phase Matrix converter is

$$I_i = \begin{bmatrix} I_R \\ I_Y \\ I_B \end{bmatrix} = \begin{bmatrix} I_{im}\cos(\omega_i t) \\ I_{im}\cos(\omega_i t + \frac{2\pi}{3}) \\ I_{im}\cos(\omega_i t + \frac{4\pi}{3}) \end{bmatrix} \quad (5)$$

The output current vector of the 3 phase to 3 phase Matrix converter is

$$I_o = \begin{bmatrix} I_r \\ I_y \\ I_b \end{bmatrix} = \begin{bmatrix} I_{om}\cos(\omega_o t) \\ I_{om}\cos(\omega_o t + \frac{2\pi}{3}) \\ I_{om}\cos(\omega_o t + \frac{4\pi}{3}) \end{bmatrix} \quad (6)$$

Where, $\omega_i$ - frequency of input voltage and $\omega_o$ - frequency of output voltage

The relationship between output and input voltage is given as

$$V_o(t) = M(t).\,V_i(t) \quad (7)$$

Where $M_t$ is the transfer Matrix and is given by

$$M(t) = \begin{bmatrix} M_{Rr} & M_{Yr} & M_{Br} \\ M_{Ry} & M_{Yy} & M_{By} \\ M_{Rb} & M_{Yb} & M_{Bb} \end{bmatrix} \quad (8)$$

where, $M_{Rr} = t_{Rr} / T_s$, duty cycle switch $S_{Rr}$, Ts is the sampling period. The input current is given by

$$I_{in} = M^T I_o \quad (9)$$

Duty cycle must satisfy the following condition in order to avoid short circuit on the input side.

$$M_{Rr} + M_{Yr} + M_{Br} = 1 \quad (10)$$
$$M_{Ry} + M_{Yy} + M_{By} = 1 \quad (11)$$
$$M_{Rb} + M_{Yb} + M_{Bb} = 1 \quad (12)$$

The above condition is fulfilled by calculation of duty cycle using modified venturini algorithm.

In venturini switching algorithm, the maximum voltage transfer ratio is restricted to 0.5.This limit can be overcome by using modified venturini algorithm [16]. The maximum possible output voltage can be achieved by injecting third harmonics of the input and output frequencies into the output waveform [11]. This will increase the available output voltage range to 0.75 of the input when third harmonics has a peak value of $V_i$/4. Further increasing of the transfer ratio can be achieved by subtracting a third harmonic at the output frequency from all target output voltages. Hence the maximum transfer ratio of 0.75/0.866 = 0.866 of $V_i$ when this third harmonic has a peak value of $V_o$/6.Therefore the output voltage becomes

$$V_{o\gamma} = qV_{im}\cos(\omega_o t + \psi_\gamma) - \frac{q}{6} V_{im}\cos(3\omega_o t) + \frac{1}{4q_m} V_{im}(3\omega_i t) \quad (13)$$

Where, $\psi_\gamma$ = 0, 2π/3, 4π/3 corresponding to the output phase r, y, b [11], [15], [16].

## IV. DESIGNING OF MATRIX CONVERTER

The actual MATLAB/SIMULINK model of 3 phase to 3 phase Matrix converter is shown in fig.3. it comprises normally 3 sections.

### 4.1 Designing of Control Algorithm

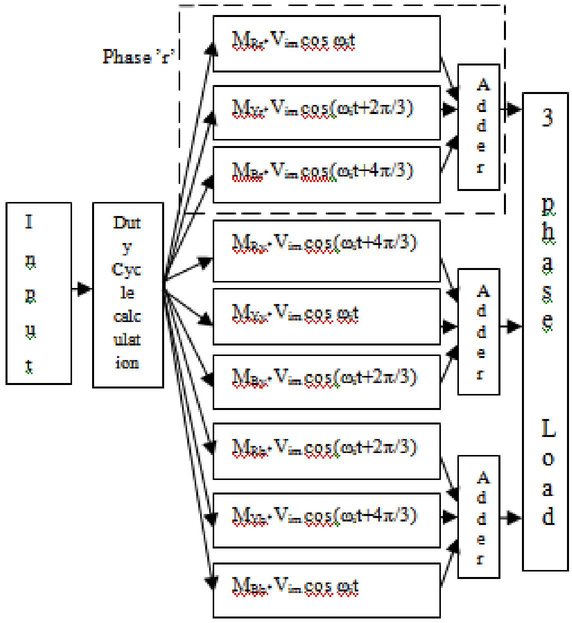


Fig.3. Mathematical Designing of 3 phase to 3 phase Matrix converter.

The required voltage transfer ratio (q), output frequency ($f_o$) and switching frequency ($f_s$) are the inputs required for calculation of duty cycle matrix M. the duty cycle calculations for voltage transfer ratio of 0.5 and 0.866 are realized in the form of m-file in Matlab.

Duty cycles for 0.5 & 0.866 voltage transfer ratio are;

$$M_{Rr} = \frac{1}{3}(1 + 2q\cos(\omega_m t + \theta)) \quad (14)$$
$$M_{Yr} = \frac{1}{3}(1 + 2q\cos(\omega_m t + \theta - \frac{2\pi}{3})) \quad (15)$$
$$M_{Br} = \frac{1}{3}(1 + 2q\cos(\omega_m t + \theta - \frac{4\pi}{3})) \quad (16)$$

$$M_{Ry} = \frac{1}{3}(1 + 2q\cos(\omega_m t + \theta - \frac{4\pi}{3})) \quad (17)$$
$$M_{Yy} = \frac{1}{3}(1 + 2q\cos(\omega_m t + \theta)) \quad (18)$$
$$M_{By} = \frac{1}{3}(1 + 2q\cos(\omega_m t + \theta - \frac{2\pi}{3})) \quad (19)$$

$$M_{Rb} = \frac{1}{3}(1 + 2q\cos(\omega_m t + \theta - \frac{2\pi}{3})) \quad (20)$$
$$M_{Yb} = \frac{1}{3}(1 + 2q\cos(\omega_m t + \theta - \frac{4\pi}{3})) \quad (21)$$
$$M_{Bb} = \frac{1}{3}(1 + 2q\cos(\omega_m t + \theta)) \quad (22)$$

Where, $\omega_m = \omega_o - \omega_i$ = modulation frequency
θ = relative phase of output, q =voltage transfer ratio
Switching time for voltage transfer ratio of 0.866 are;

$$T_{\beta\gamma} = \frac{T_s}{3}\left[1 + \frac{2V_{o\gamma}V_{i\beta}}{V_{im}^{2}} + \frac{2q}{3q_m}\sin(\omega_i t + \psi_\beta)\sin(3\omega_i t)\right] \quad (23)$$

where, $\psi_\beta$ = 0, 2π/3, 4π/3 corresponding to the input phases R,Y,B, $q_m$ = maximum voltage transfer ratio, q = required voltage ratio, $V_{im}$ =input voltage vector magnitude, $T_s$ = sampling period.

### 4.2 Designing of power circuit

The modeling of power circuit is derived from basic output voltage equations [17], [18].

$V_r(t) = M_{Rr}\ V_R(t) + M_{Yr}\ V_Y(t) + M_{Br}\ V_B(t)$ (24)

$V_y(t) = M_{Ry}\ V_R(t) + M_{Yy}\ V_Y(t) + M_{By}\ V_B(t)$ (25)

$V_b(t) = M_{Rb}\ V_R(t) + M_{Yb}\ V_Y(t) + M_{Bb}\ V_B(t)$ (26)

Fig.4 shows the realization of modeling block of power circuit of 'r' phase in 3 phase to 3 phase Matrix converter. The switching pulses for the bi-directional switches are realized by comparing the duty cycles with a saw tooth waveform having very high switching frequency

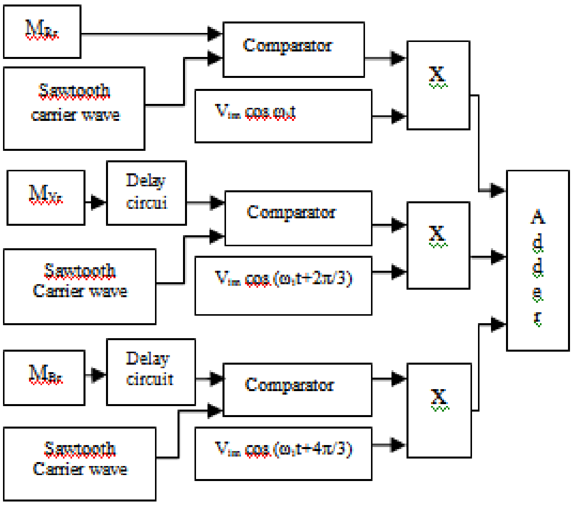


Fig.4. Designing block of power circuit of 'r' phase in 3 phase to 3 phase Matrix converter.

### 4.3 Designing of Load

The transfer function of mathematical modeling of RL load is

$$\frac{I(S)}{V(S)} = \frac{1}{Ls+R} \quad (27)$$

## V. SIMULATION RESULTS AND DISCUSSION

The simulation of 3 phase to 3 phase Matrix converter for open loop are carried out using simulink blockset.

### 5.1. Simulation output of 3 phase to 3 phase Matrix converter for Maximum Modulation Index (0.866)

Simulations are performed for maximum voltage transfer ratio 'q' = 0.0.866 (Duty cycle), Amplitude =325.26V and time limit is 0.1 m.Sec. The output is realized with 3 phase passive RL load for R= 10 Ω and L= 20 mH. Fig 9-11 shows the results of control waveform for all the 9 Bi-directional Switches from '$S_{Rr}$' to '$S_{Bb}$'($M_{Rr}$ to $M_{Bb}$) with the maximum voltage transfer ratio 'q' =0.866. Fig.12. shows the Input waveform for 'q'=0.866 and Amplitude =325.26V related to 'r' Phase. The Output Voltage and current waveforms in 'r' Phase for 'q'=0.866 as shown in Fig.13&14. The Output Voltage and current waveforms in 'y' Phase for 'q'=0.866 as shown in Fig.15&16. The Output Voltage and current waveforms in 'b' Phase for 'q'=0.866 as shown in Fig.17&18. Fig.19 shows the Simulation waveform for Voltage Transfer ratio of 'q'=0.866. Fig.20. shows the Simulation waveform for 'THD' in 'r' Phase. Fig.21. shows the Average Output Voltage waveform for 3 phase to 3 phase Matrix converter (for 'r', 'y', 'b' Phases). Similarly, Fig.22 shows the Output Current waveform for 3 phase to 3 phase Matrix converter (for 'r', 'y', 'b' Phases). The average output voltage is =325.26V and the average output current is 24.8 Amps.

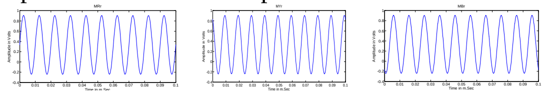

Fig.9. Duty cycle 'q'=0.866 for $M_{Rr}$, $M_{Yr}$, $M_{Br}$ Phase.

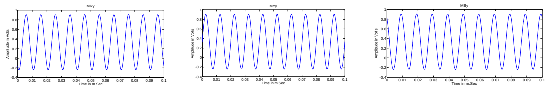

Fig.10. Duty cycle 'q'=0.866 for $M_{Yy}$,$M_{Ry}$,$M_{By}$ Phase.

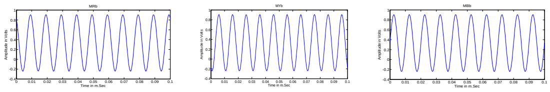

Fig.11. Duty cycle 'q'=0.866 for $M_{Rb}$,$M_{Yb}$,$M_{Bb}$ Phase.

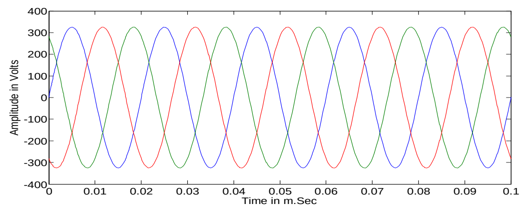


Fig.12. Input waveform for 'q'=0.866 and Amplitude =325.26V in 'r' Phase

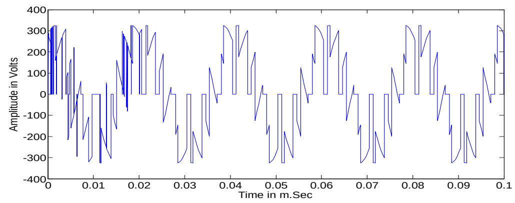


Fig.13. Output Voltage waveform for 'q'=0.866 in 'r' Phase.

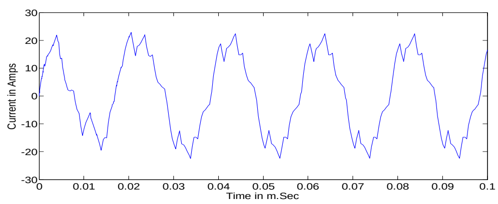

Fig.14. Output current waveform for 'q'=0.866 in 'r' Phase.

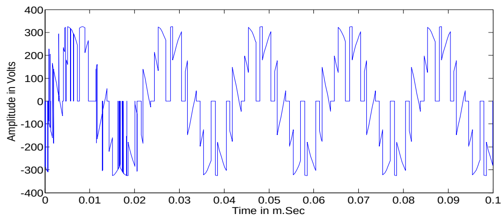

Fig.15. Output Voltage waveform for 'q'=0.866 in 'y' Phase.

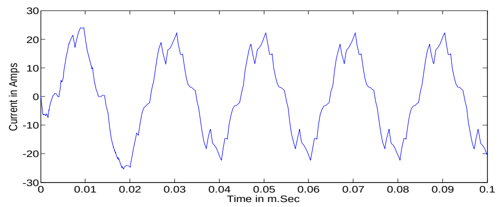

Fig.16. Output current waveform for 'q'=0.866 in 'y' Phase

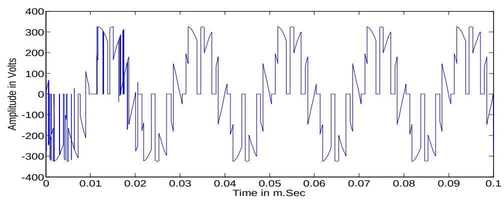

Fig.17. Output Voltage waveform for 'q'=0.866 in 'b' Phase.

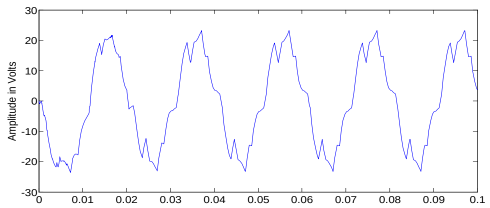

Fig.18. Output current waveform for 'q'=0.866 in 'b' Phase.

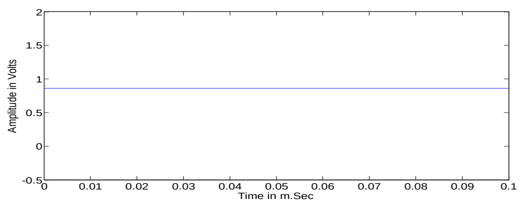

Fig.19. Simulation waveform for Voltage Transfer ratio 'q'=0.866.

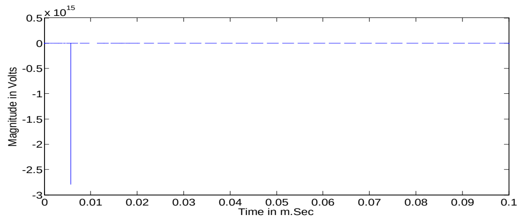

Fig.20. Simulation waveform for 'THD' in 'r' Phase.

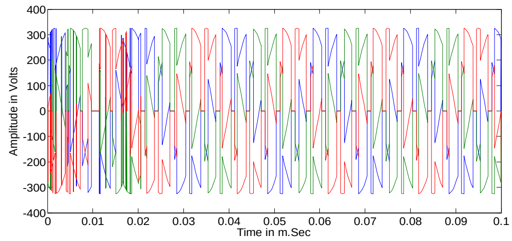

Fig.21. Output Voltage waveform for 3 phase to 3 phase Matrix converter ('r', 'y', 'b' Phases)

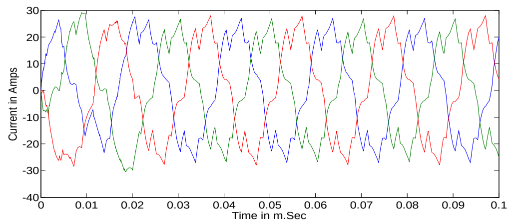

Fig.22. Output Current waveform for 3 phase to 3 phase Matrix converter ('r', 'y', 'b' Phases)

### 5.2. Simulation output of 3 phase to 3 phase Matrix converter for Minimum Modulation Index (0.5)

Simulations are performed for minimum voltage transfer ratio 'q' = 0.5 (Duty cycle), Amplitude =325.26V and time limit is 0.1 m.Sec. The output is realized with 3 phase passive RL load for R= 10 Ω and L= 20 mH. Fig 23-25 shows the results of control waveform for all the 9 Bi-directional Switches from '$S_{Rr}$' to '$S_{Bb}$'($M_{Rr}$ to $M_{Bb}$) with the minimum voltage transfer ratio 'q' =0.5. Fig.126. shows the Input waveform for 'q'=0.5 and Amplitude =325.26V related to 'r' Phase. The Output Voltage and current waveforms in 'r' Phase for 'q'=0.5 as shown in Fig.27&28. The Output Voltage and current waveforms in 'y' Phase for 'q'=0.5 as shown in Fig.29&30. The Output Voltage and current waveforms in 'b' Phase for 'q'=0.5 as shown in Fig.31&32. Fig.33 shows the Simulation waveform for Voltage Transfer ratio of 'q'=0.5. Fig.34. shows the Simulation waveform for 'THD' in 'r' Phase. Fig.35. shows the Average Output Voltage waveform for 3 phase to 3 phase Matrix converter (for 'r', 'y', 'b' Phases). Similarly, Fig.36 shows the Output Current waveform for 3 phase to 3 phase Matrix converter (for 'r', 'y', 'b' Phases). The average output voltage is =325.26V and the average output current is 7.955 Amps.

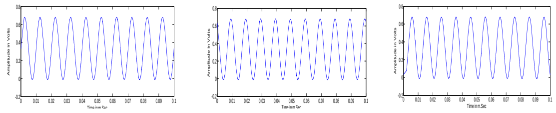

Fig.23. Duty cycle ‘q’=0.5 for $M_{Rr}$, $M_{Yr}$, $M_{Br}$ Phase

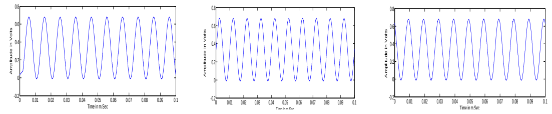

Fig.24. Duty cycle ‘q’=0.5 for $M_{Yy}$, $M_{Ry}$, $M_{By}$Phase

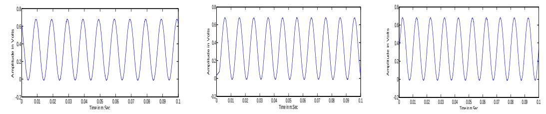

Fig.25. Duty cycle ‘q’=0.5 for $M_{Rb}$, $M_{Yb}$, $M_{Bb}$ Phase.

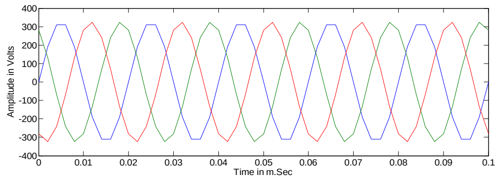


Fig.26. Input waveform for ‘q’=0.5and Amplitude =325.26 V in ‘r’ Phase

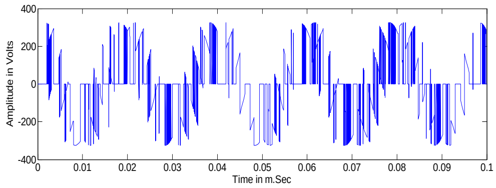


Fig.27. Output Voltage waveform for ‘q’=0.5 in ‘r’ Phase.

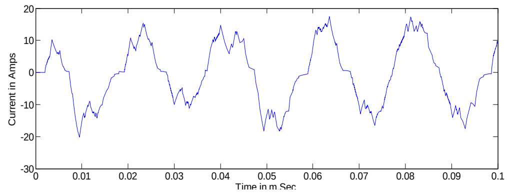


Fig.28. Output current waveform for ‘q’=0.5 in ‘r’ Phase

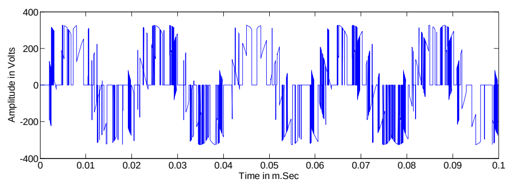


Fig.29. Output Voltage waveform for ‘q’=0.5 in ‘y’ Phase.

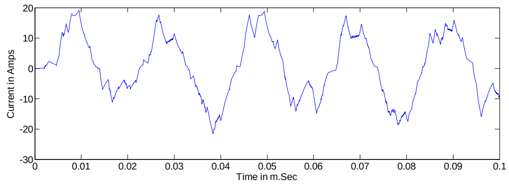


Fig.30. Output current waveform for ‘q’=0.5 in ‘y’ Phase

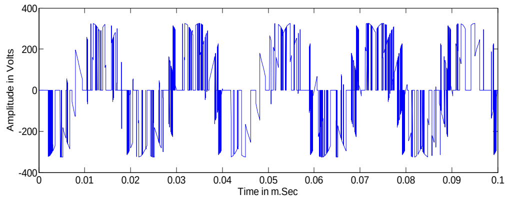


Fig.31. Output Voltage waveform for ‘q’=0.5 in ‘b’ Phase

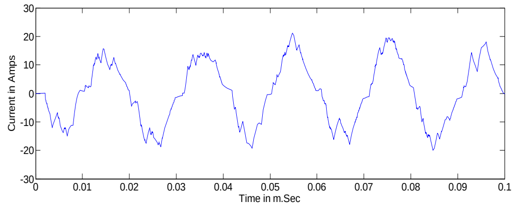


Fig.32. Output current waveform for ‘q’=0.5 in ‘b’ Phase.

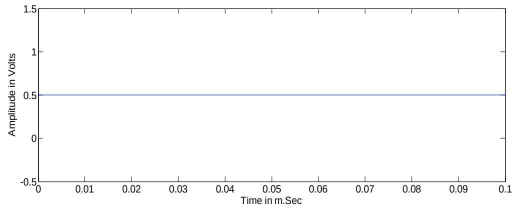


Fig.33. Simulation waveform for Voltage Transfer ratio ‘q’=0.5

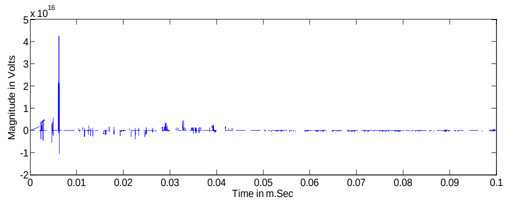


Fig.34. Simulation waveform for ‘THD’ in ‘r’ Phase

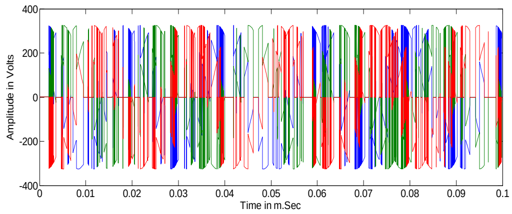


Fig.35. Output Voltage waveform for 3 phase to 3 phase Matrix converter (‘r’, ‘y’, ‘b’ Phases)

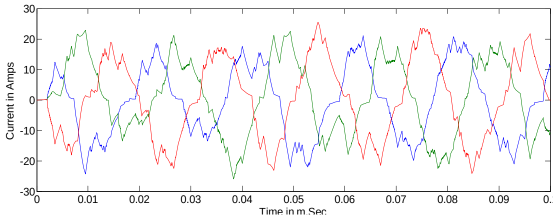


Fig.36. Output Current waveform for 3 phase to 3 phase Matrix converter ('r', 'y', 'b' Phases)

TABLE-1 Output current for different MI

| Modulation Index MI (q) | Average Output Current | Average Output Voltage | Type of Load |
|---|---|---|---|
| 0.50 | 7.955 | 325.26 | RL Load |
| 0.575 | 12.03 | 325.26 | |
| 0.65 | 17.79 | 325.26 | |
| 0.70 | 19.64 | 325.26 | |
| 0.75 | 21.65 | 325.26 | |
| 0.80 | 23.17 | 325.26 | |
| 0.866 | 24.80 | 325.26 | |

As a result, by increasing Modulation Index will increases the average output current without change in average output voltage as shown in TABLE-1. Also the average output current will increases by increasing the value of load resistance. Similarly, the output current increases by decreasing the value of load Inductance

## VI. CONCLUSION

A simulation design and implementation of 3 phase to 3 phase Matrix converter has been presented in this paper. A mathematical model is developed for open loop Matrix converter using MATLAB/Simulink so as to achieve less computational time. The output was realized by RL load and the simulation results are taken for maximum and minimum voltage transfer ratio. The simulation output results are satisfactory and the future extension of this paper is possible for closed loop configuration with various controllers and three phase to 'n' phase Matrix converter with various passive loads and different voltage transfer ratio.

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