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Designing of Closed Loop Controller for 3 Phase to 3 Phase Power Conversion Using Matrix Converter

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Abstract*: This paper proposes a simulation of designing and implementation of a PI controller with increasing and decreasing RL load values for a 3 phase to 3 phase power conversion using matrix converter. Closed loop PI controller is used to achieve real time control for 3 phase to 3 phase matrix converter. The entire matrix converter circuits are developed by Mathematical model so as to achieve less computational time and performances of the controller are evaluated using MATLAB for different RL Load value. The mathematical expressions 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) voltage transfer ratio.

Index Terms: Matrix converter, 3 phase to 3 phase converter, 3 phase AC power conversion, Closed Loop Controller, Closed loop Matrix converter.

I. INTRODUCTION

The matrix converter (MC) is a one stage power converter, capable of feeding an m-phase load from an n-phase source without using energy storage components. It is a direct frequency conversion device that generates variable magnitude variable frequency output voltage from the ac line. It has high power quality and fully regenerative. Recently, direct ac/ac converters are realized for 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. Matrix converters have some advantages when compared to conventional back to back Pulse width modulation voltage-source converters. The MC may be considered more reliable and is smaller because the bulky dc capacitor is eliminated from the topology. Therefore, when MCs are used in ac–ac power conversion, the size and weight of the whole generation system is reduced. For a common mode voltage reduction and the power quality of matrix converters for a low-voltage transfer ratio of less than 0.5, a direct space vector modulation method has been proposed [1]. To interface a MC-based generation system to an unbalanced three-phase stand-alone load, a four-leg MC is required to provide an electrical path for the zero-sequence load current. Hence the application of resonant Controllers to four-leg matrix converters' feeding unbalanced or nonlinear loads has been developed [2]. A new technique improved space vector modulation using amplitude coefficient on a capacitor-clamped multilevel matrix converter. The MMC utilizes a multilevel structure on a conventional matrix converter, which allows direct ac-ac conversion without large energy store elements has been developed [3]. 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 proposed [4]-[11].

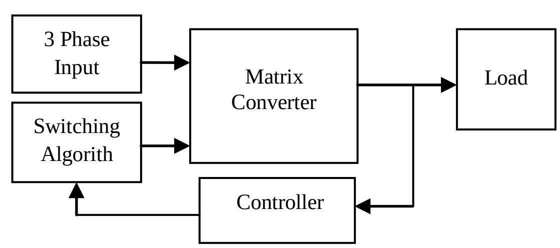

Fig.1. Block diagram of 3pase to 3 phase Matrix converter.

To achieve real time control with quick speed and fast response, new designs of controllers are needed. PI controllers are the one to sense the output continuously and correct the output at the instant if any disturbance occurred. In this paper, PI controllers are designed and implemented for the 3 phase to 3 phase matrix converter in closed loop configuration and the power circuit in closed loop are implemented by the mathematical modeling along with the PI controllers. The duty cycle calculation is taken into account for Maximum voltage transfer ratios and the mathematical model is realized with the RL load. The entire power circuit is modeled with MATLAB/SIMULINK. Implementation of PI controller in mathematical modeling includes the modeling of power circuit, switching algorithm, load and the controller. Merits of Mathematical model over conventional power circuit are less computation time and low memory requirement. Fig. 1 refers the Basic block diagram of the proposed 3pase to 3 phase Matrix converter. The proposed model is very simple, flexible and can be accommodated with any type of load.

II. 3 PHASE MATRIX CONVERTER

The Matrix converter (MC) is a one 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. Input filters are 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. The desirable characteristics of a Matrix converter are as follows:

- Sinusoidal input and output waveforms with minimal higher order harmonics
- Controllable input power factor
- Bidirectional energy flow capability and Minimal energy storage requirements
- Long life due to absence of a bulky capacitor

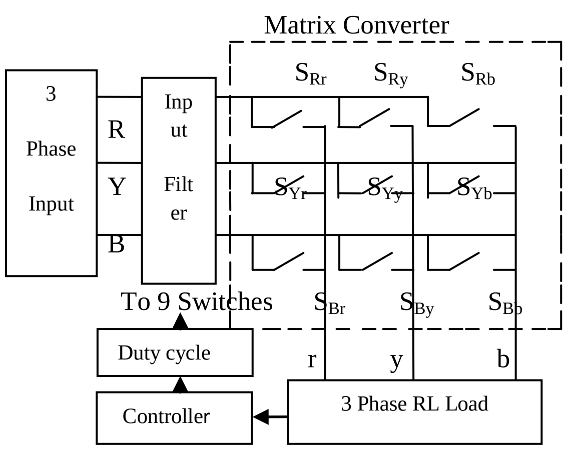

Fig.2. circuit scheme of 3 phase to 3 phase matrix converter

The Matrix converter has the following limitations

- 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.

III. SWITCHING ALGORITHM

While operating 3 phase to 3 phase converter with 9 bi-directional switches, the following two basic rules have to be satisfied.

- 2 or 3 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

$$M_{Kj} = \begin{cases} 1, \text{switch MKj closed} \\ 0, \text{switch MKj opened} \end{cases} \quad (1)$$

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

The above constraints can be expressed by

$$Mrj + Myj + Mbj = 1, \quad j = \{R, Y, B\} \quad (2)$$

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

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

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

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

Similarly, the output current vector of the 3 phase to 3 phase Matrix converter is

$$I_o = \begin{bmatrix} I_r \\ I_y \\ I_b \end{bmatrix} = \begin{bmatrix} I_{om}\cos(\omega_o t) \\ I_{om}\cos(\omega_o t + \frac{2\pi}{3}) \\ I_{om}\cos(\omega_o t + \frac{4\pi}{3}) \end{bmatrix} \quad (5)$$

Where, ω_i - frequency of input voltage and ω_o - frequency of output voltage

The relationship between output and input voltage is given as

$$V_o(t) = M(t).\, V_i(t) \quad (6)$$

The input current is given by $I_{in} = M^T I_o$ (7)

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

$$\begin{aligned} M_{Rr} + M_{Yr} + M_{Br} &= 1 \\ M_{Ry} + M_{Yy} + M_{By} &= 1 \\ M_{Rb} + M_{Yb} + M_{Bb} &= 1 \end{aligned} \quad (8)$$

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. The maximum possible output voltage can be achieved by injecting third harmonics of the input and output frequencies into the output waveform. 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

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01 Feb.2016

third harmonic has a peak value of $V_o/6$.Therefore the output voltage becomes

$$V_{o\gamma} = qV_{im}\ cos(\omega_o t + \psi_\gamma) - \frac{q}{6}\ V_{im}\ cos(3\omega_o t) + \frac{1}{4q_m} V_{im}(3\omega_i t) \quad (9)$$

Where, ψ_γ = 0, 2π/3, 4π/3 corresponding to the output phase r, y, b.

IV. PROPORTIONAL PLUS INTEGRAL CONTROLLER (PI)

The controller output m(t) is proportional to a linear combination of actuating signal e(t) and its time derivative is called PI controller.

$$m = \frac{Kp}{Ti}.e + Kp\frac{de}{dt} \quad (10)$$

Where,

$\frac{de}{dt}$ = rate of change of e with respect to time

Kp = proportional sensitivity

Ti = integral time

In integral form,

$$m = \frac{Kp}{Ti}\int e\ dt + K_p + M \quad (11)$$

In operational form,

$$m = Kp\left(\frac{1}{TiS} + 1\right) e \quad (12)$$

Figure 3 shows the transfer function block diagram of a PI controller with positive feedback.

The transfer function of PI controller is

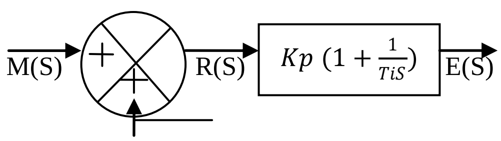

Fig. 3 Transfer function of PI controller.

The proportional plus integral controller produces an output signal, u(t) consisting of two terms-one proportional to input signal, e(t) and the other proportional to the integral of input signal, e(t). The PI controller reduces the Steady state error. In PI controller,

$$u(t)\ \alpha\ [e(t) + \int e(t)\ dt] \quad (13)$$

$$u(t) = K_p\, e(t) + K_i \int e(t)\ dt \quad (14)$$

Where,

K_i is the proportional gain = $-\omega_1 \sin\theta / A_1$ and

K_p is the integral constant or gain = $\cos\theta / A_1$

On taking Laplace transform of equation (14) with zero initial condition we get,

$$U(s) = K_p\, E(s) + K_i \frac{E(s)}{S} = E(s)\left(K_P + \frac{Ki}{S}\right) \quad (15)$$

Transfer function of PI Controller is

$$G_c(s) = U(s)/E(s) = K_p + \frac{Ki}{S} \quad (16)$$

The PI controller reduces the steady state error. The introduction on PI controller increases the order and type number of the system by one

V. MATRIX CONVERTER DESIGN

The actual MATLAB/SIMULINK model of 3 phase to 3 phase Matrix converter is shown in fig.4. It comprises normally 4 sections.

5.1 Control Algorithm Design

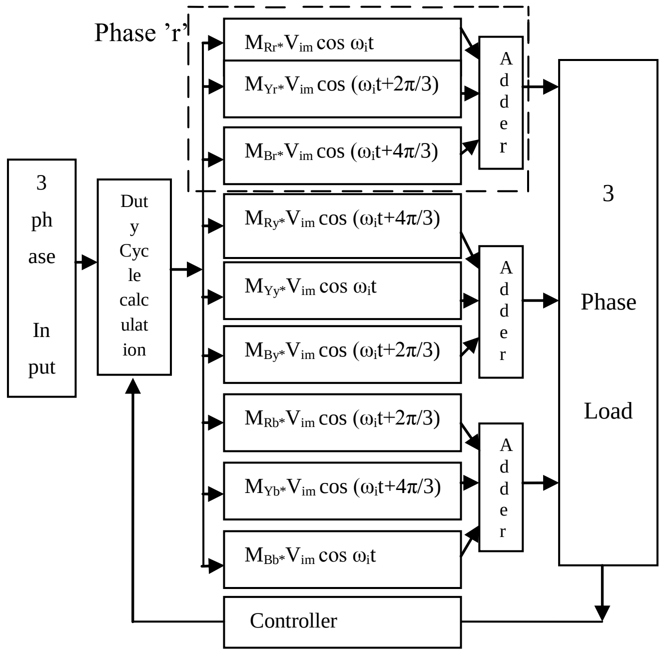

Fig.4. Mathematical Modeling of 3 phase to 3 phase Matrix converter.

The required voltage transfer ratio (q), output frequency (f_o) and switching frequency (f_s) are the inputs required for calculation of duty cycle. The duty cycle calculations for voltage transfer ratio of 0.5 and 0.866 are realized in the form of m-file in Mat lab. There are two modulation techniques to be considered for matrix converter design.

$$\omega_m = \omega_o - \omega_i \quad \& \quad \omega_m = \omega_o + \omega_i \quad (17)$$

For $\omega_m = \omega_o - \omega_i$, the phase displacement is in forward sequence i.e. R, Y, B

M_t is the Transfer matrix and is given by

$$M(t) = \begin{bmatrix} M_{Rr} & M_{Yr} & M_{Br} \\ M_{Ry} & M_{Yy} & M_{By} \\ M_{Rb} & M_{Yb} & M_{Bb} \end{bmatrix} \quad (18)$$

Where, $M_{Rr} = t_{Rr} / T_s$, duty cycle switch S_{Rr}, Ts is the sampling period.

Duty cycles for maximum voltage transfer ratio are;

$$\begin{bmatrix} \frac{1}{3}(1+2q\cos(\omega_m t+\theta)) & \frac{1}{3}(1+2q\cos(\omega_m t+\theta-\frac{2\pi}{3})) & \frac{1}{3}(1+2q\cos(\omega_m t+\theta-\frac{4\pi}{3})) \\ \frac{1}{3}(1+2q\cos(\omega_m t+\theta-\frac{4\pi}{3})) & \frac{1}{3}(1+2q\cos(\omega_m t+\theta)) & \frac{1}{3}(1+2q\cos(\omega_m t+\theta-\frac{2\pi}{3})) \\ \frac{1}{3}(1+2q\cos(\omega_m t+\theta-\frac{2\pi}{3})) & \frac{1}{3}(1+2q\cos(\omega_m t+\theta-\frac{4\pi}{3})) & \frac{1}{3}(1+2q\cos(\omega_m t+\theta)) \end{bmatrix}$$

For $\omega_m = \omega_o + \omega_i$, the phase displacement is in reverse sequence i.e. R, B, Y. 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;

$$T_{\beta\gamma} = \frac{T_s}{3}\left[1 + \frac{2V_{o\gamma}V_{i\beta}}{{V_{im}}^2} + \frac{2q}{3q_m}\sin(\omega_i t + \psi_\beta)\sin(3\omega_i t)\right] \quad (19)$$

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Where, ψ_β = 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.

5.2 Power Circuit Design

The modeling of power circuit is derived from basic output voltage equations.

$$V_r(t) = M_{Rr}\ V_R(t) + M_{Yr}\ V_Y(t) + M_{Br}\ V_B(t)$$
$$V_y(t) = M_{Ry}\ V_R(t) + M_{Yy}\ V_Y(t) + M_{By}\ V_B(t) \qquad (20)$$
$$V_b(t) = M_{Rb}\ V_R(t) + M_{Yb}\ V_Y(t) + M_{Bb}\ V_B(t)$$

Fig.5 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

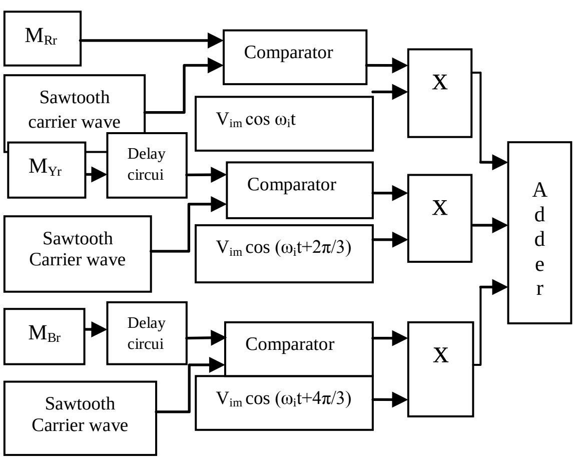

Fig.5. Modeling block of power circuit of 'r' phase in 3 phase to 3 phase Matrix converter.

5.3 RL Load Design

The transfer function of mathematical modeling of RL load is

$$\frac{I(S)}{V(S)} = \frac{1}{Ls+R} \qquad (21)$$

5.4 Controller Design

The PI controller model was developed using Simulink Blockset. In PI controller,

$$u(t) = K_p\, e(t) + K_i \int e(t)\, dt \qquad (22)$$

Transfer function of PI Controller is $G_c(s) = U(s)/E(s) = K_p + K_i/s$ (23)

VI.SIMULATION OUTPUT RESULTS AND DISCUSSION

Simulations results are performed for a reference current of 6 Amps and 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. The reference current is set to 6 Amps. The output is again feedback to the input of the matrix converter through PI controller to achieve the real time control. Fig. 6 shows the Input waveform for 'I_{ref}'=6 amps and Amplitude =325.26V in 'r' Phases. The average Output Voltage and Current waveforms in 'r' 'y' 'b' Phases for 'I_{ref}'=6 amps as shown in Fig.7&8. Fig.9&10 shows the Average Output Voltage and Current waveform for R=10 Ω and L=20mH of load. Fig.11&12 shows the Average Output Voltage and Current waveform for R=20 Ω and L=10mH of load. Fig.13&14 shows the Average Output Voltage and Current waveform for R=5 Ω and L=30mH of load. Fig.15&16 shows the Average Output Voltage and current waveform for R=20 Ω and L=20mH of load. Fig.17&18 shows the Average Output Voltage and Current waveform for R=10 Ω and L=50mH of load. Fig.19&20 shows the Average Output Voltage and Current waveform for R=50 Ω and L=20mH of load.

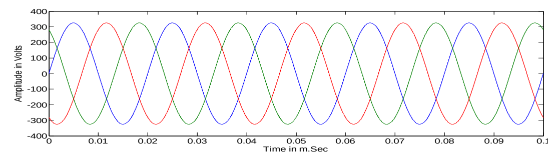

Fig.6. Input waveform for 'I_{ref}'=6 amps and Amplitude =325.26V in 'r' Phase

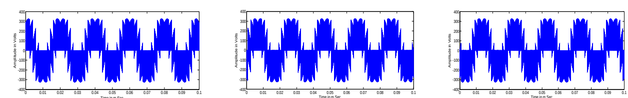

Fig.7. Output Voltage for 'I_{ref}'=6 amps in 'r' 'y' 'b' Phases.

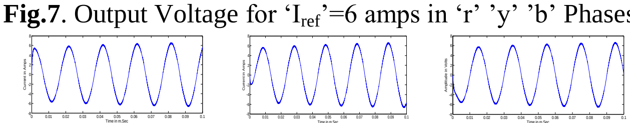

Fig.8. Output Current for 'I_{ref}'=6 amps in 'r' 'y' 'b' Phases

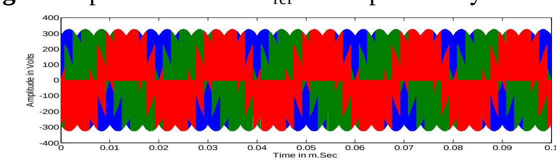

Fig.9. Output Voltage waveform for 3 phase to 3 phase Matrix converter for R=10 Ω & L=20mH load

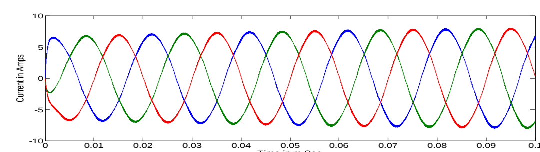

Fig.10. Output Current waveform for 3 phase to 3 phase Matrix converter for R=10 Ω & L=20mH load

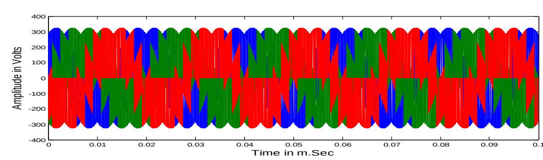

Fig.11. Output Voltage waveform for 3 phase to 3 phase Matrix converter for R=20 Ω & L=10mH load

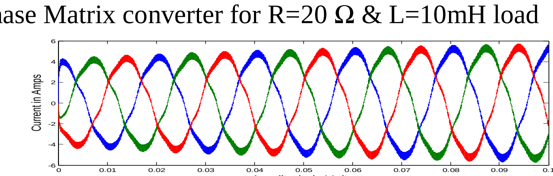

Fig.12. Output Current waveform for 3 phase to 3 phase Matrix converter for R=20 Ω & L=10mH load

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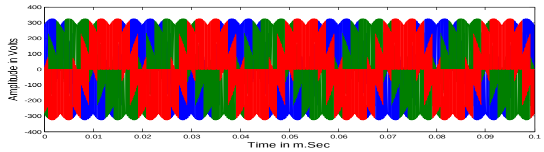

Fig.13. Output Voltage waveform for 3 phase to 3 phase Matrix converter for R=5 Ω & L=30mH load

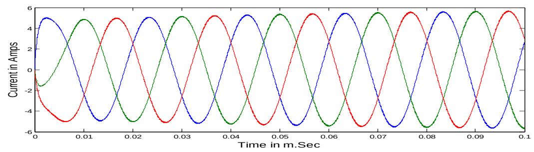

Fig.14. Output Current waveform for 3 phase to 3 phase Matrix converter for R=5 Ω & L=30mH load

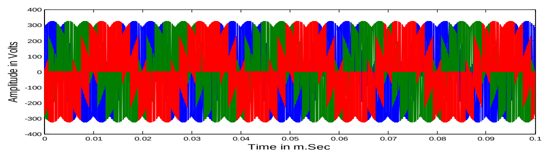

Fig.15. Output Voltage waveform for 3 phase to 3 phase Matrix converter for R=20 Ω & L=20mH load

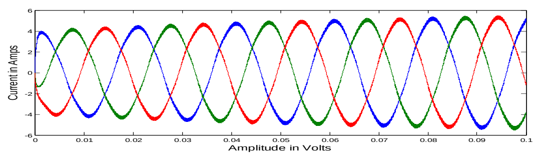

Fig.16. Output Current waveform for 3 phase to 3 phase Matrix converter for R=20 Ω & L=20mH load

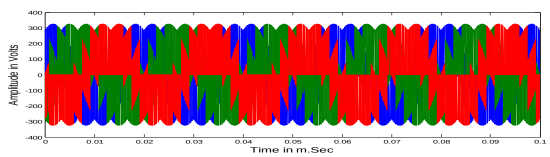

Fig.17. Output Voltage waveform for 3 phase to 3 phase Matrix converter for R=10 Ω & L=50mH load

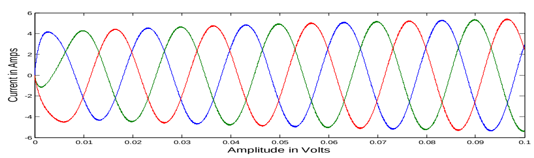

Fig.18. Output Current waveform for 3 phase to 3 phase Matrix converter for R=10 Ω & L=50mH load

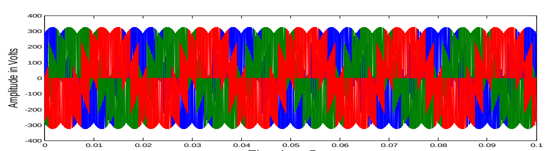

Fig.19. Output Voltage waveform for 3 phase to 3 phase Matrix converter for R=50 Ω & L=10mH load

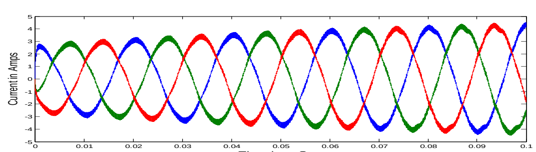

Fig.20. Output Current waveform for 3 phase to 3 phase Matrix converter for R=50 Ω & L=10mH load

From the above various simulation outputs, it is clear that the R value should be chosen less and L value should be chosen more for smoothening the output current.

VII CONCLUSION

Simulation of mathematical modeling and implementation of closed loop PI controller for 3 phase to 3 phase power conversion using matrix converter has been presented in this paper. A mathematical model is developed for Matrix converter using MATLAB/Simulink which is also utilized for closed loop PI controller configuration. In closed loop configuration, a real time control has been achieved for PI controller with less computational time. The output was realized by different RL load values and the simulation results are taken for maximum voltage transfer ratio. The simulation output results are satisfactory and the future extension of this paper is possible for closed loop Fuzzy logic control in three phase to 'n' phase Matrix converter with different voltage transfer ratio and various passive loads.

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