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Modeling and Implementation of Closed Loop PI Controller for 3 Phase to 3 Phase Power Conversion Using Matrix Converter

[1]B.Muthuvel, [2]Dr.T.S.Anandhi, [3]Dr.P.Sivagnanam, [4]M.Janani raj

[1] Department of EEE, AKT Memorial college of Engineering and Technology, Villupuram, India.
[2] Electronics & Instrumentation Engineering, Annamalai University, Annamalai Nagar, India.
[3] Principal, Krishnasamy college of Engineering and Technology, Cuddalore, India.
[4] Department of EEE, Vivekananda Polytechnic College, Cuddalore, India.

Abstract: *This paper proposes a simulation of modeling and implementation of PI controller 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 PI controller are evaluated using MATLAB/SIMULINK for RL Load. 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 voltage transfer ratio.*

Key Words: *3 phase to 3 phase converter, AC to AC conversion, closed loop Matrix converter, Matrix converter, PI Controller.*

I. Introduction

The matrix converter (MC) is a single-stage power converter, capable of feeding an m-phase load from a 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 it is fully regenerative.. Recently, 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. The matrix converter presents a promising topology that needs to overcome certain barriers like complexity of modulation and control techniques, protection systems etc, in order to gain a foothold in the industry. Traditionally, the MC has 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. 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 proposed [1]. 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 introduced [2].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 focused [3].

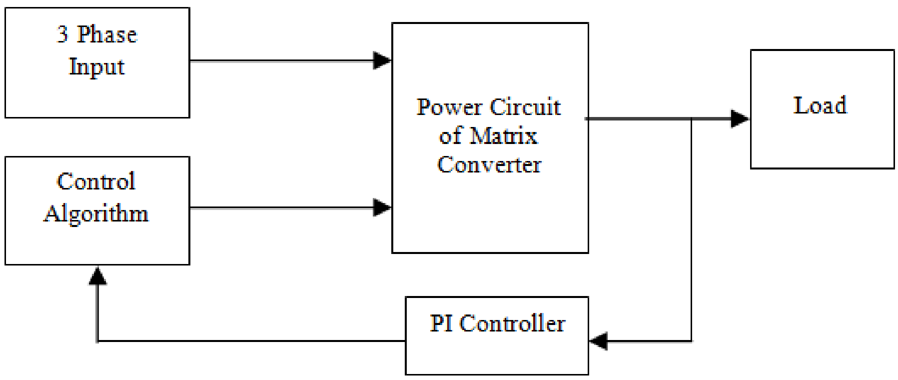

Fig.1. Basic block diagram of 3pase to 3 phase Matrix converter

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 [4]-[11].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. 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.

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) give 512 combinations of the switching states. But only 27 switching combinations are allowed to produce the output line voltages and input phase currents.

The attractive characteristics of a Matrix converter are as follows:

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

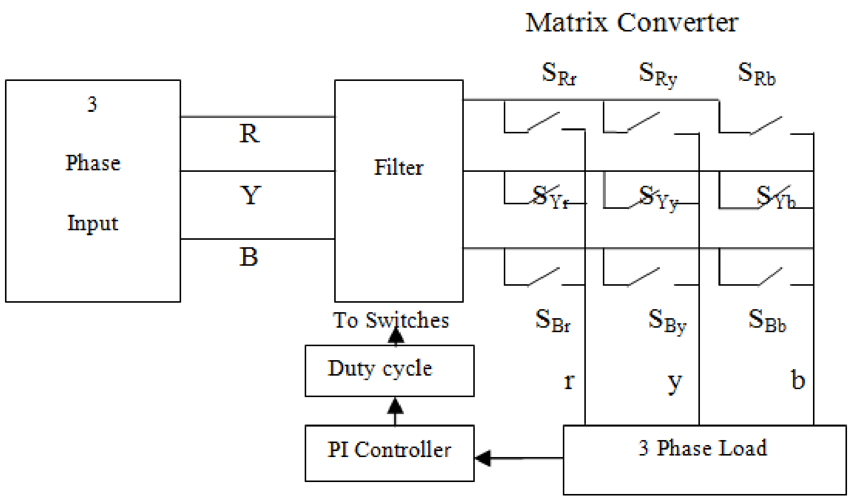

Fig.2. circuit scheme of 3 phase to 3 phase matrix converter

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 with 9 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

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

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

The above constraints can be expressed by

Srj + Syj + Sbj = 1, j = {R, Y, B} (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

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

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

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

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

The relationship between output and input voltage is given as $V_o(t) = M(t). V_i(t)$ (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 $I_{in} = M^T I_o$ (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, ψ_γ = 0, 2π/3, 4π/3 corresponding to the output phase r, y, b [11], [15], [16].

IV. Modeling of Matrix Converter

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

4.1 Modeling of Control Algorithm

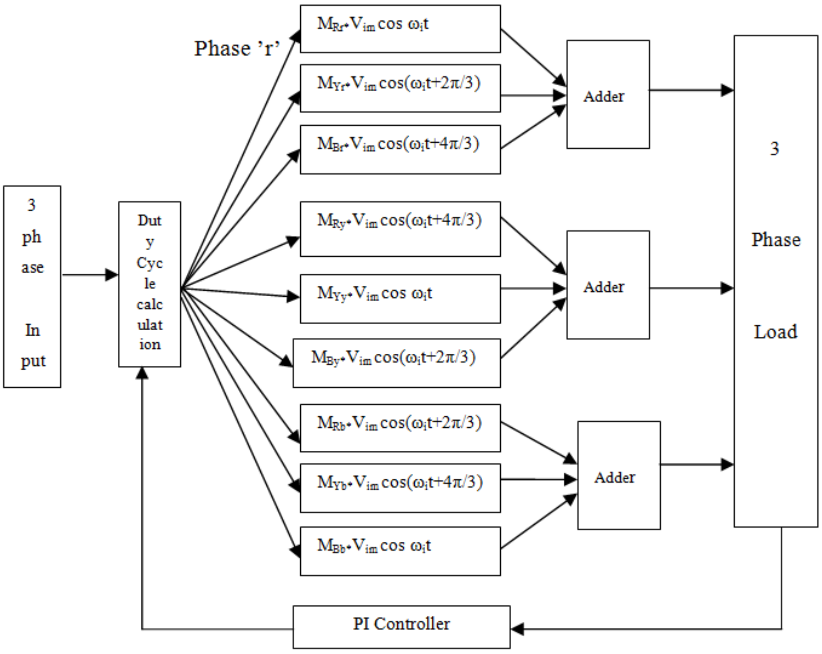

Fig.3. Mathematical Modeling of 3 phase to 3 phase Matrix converter.

The required voltage transfer ratio (q), output frequency (f_o) and switching frequency (f_s) are the inputs required for calculation of duty cycle 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;

$$M_{Rr} = \frac{1}{3}\left(1 + 2q\, cos(\omega_m t + \theta)\right) \quad (14)$$

$$M_{Yr} = \frac{1}{3}\left(1 + 2q\, cos(\omega_m t + \theta - \frac{2\pi}{3})\right) \quad (15)$$

$$M_{Br} = \frac{1}{3}\left(1 + 2q\, cos(\omega_m t + \theta - \frac{4\pi}{3})\right) \quad (16)$$

$$M_{Ry} = \frac{1}{3}\left(1 + 2q\, cos(\omega_m t + \theta - \frac{4\pi}{3})\right) \quad (17)$$

$$M_{Yy} = \frac{1}{3}\left(1 + 2q\, cos(\omega_m t + \theta)\right) \quad (18)$$

$$M_{By} = \frac{1}{3}\left(1 + 2q\, cos(\omega_m t + \theta - \frac{2\pi}{3})\right) \quad (19)$$

$$M_{Rb} = \frac{1}{3}\left(1 + 2q\, cos(\omega_m t + \theta - \frac{2\pi}{3})\right) \quad (20)$$

$$M_{Yb} = \frac{1}{3}\left(1 + 2q\, cos(\omega_m t + \theta - \frac{4\pi}{3})\right) \quad (21)$$

$$M_{Bb} = \frac{1}{3}\left(1 + 2q\, cos(\omega_m t + \theta)\right) \quad (22)$$

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, 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.

4.2 Modeling 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)

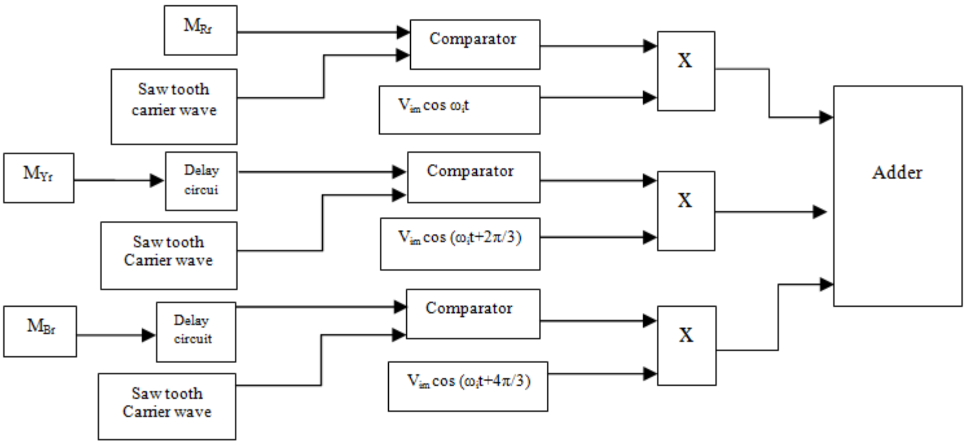

Fig.4. Modeling block of power circuit of 'r' phase in 3 phase to 3 phase Matrix converter.

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

4.3 Modeling of Load

The transfer function of mathematical modeling of RL load is

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

4.4 Modeling 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. The PI controller model was developed using Simulink Blockset.

In PI controller, $u(t)\ \alpha\ [e(t) + \int e(t)\,dt]$ (28)

$$u(t) = K_p\, e(t) + K_i \int e(t)\, dt \quad (29)$$

Where, K_p is the proportional gain = $-\omega_1 \sin\theta / A_1$ and K_i is the integral constant or gain = $\cos\theta / A_1$

Transfer function of PI Controller is $G_c(s) = U(s)/E(s) = K_p + K_i/s$ (30)

V. Simulation Results and Discussion

The simulation of 3 phase to 3 phase Matrix converter for closed loop PI controller are carried out using simulink blockset. In closed loop configuration, PI controller was realized as real time controller.

Simulations results are performed for a reference current of 7 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 7 Amps. The output is again feedback to the input of the matrix converter through PI controller to achieve the real time control. Fig. 5-7 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 'I_{ref}'=7 amps. Fig. 8 shows the Input waveform for 'I_{ref}'=7 amps and Amplitude =325.26V in 'r' Phase. The Output Voltage and current waveforms in 'r' Phase for 'I_{ref}'=7 amps as shown in Fig.9&10. The Output Voltage and current waveforms in 'y' Phase for 'I_{ref}'=7 amps as shown in Fig.11&12. The Output Voltage and current waveforms in 'b' Phase for 'I_{ref}'=7 amps as shown in Fig.13&14. Fig.15. shows the Simulation waveform for 'THD' in 'r' Phase. Fig.16 shows the. Simulation waveform for reference Current 'I_{ref}'=7 amps. Fig.17. shows the Average Output Voltage waveform for 3 phase to 3 phase Matrix converter (for 'r', 'y', 'b' Phases). Similarly, Fig.18 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 Amps.

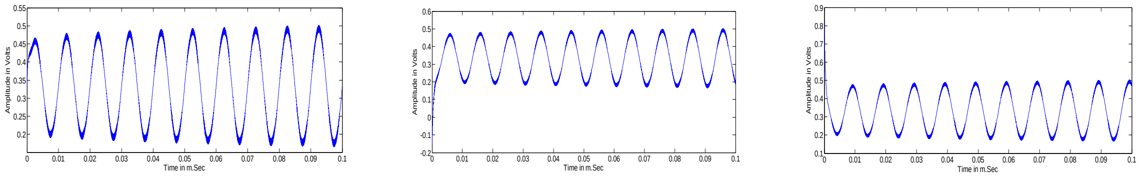

Fig.5. Duty cycle for M_{Rr}, M_{Yr}, M_{Br} Phases.

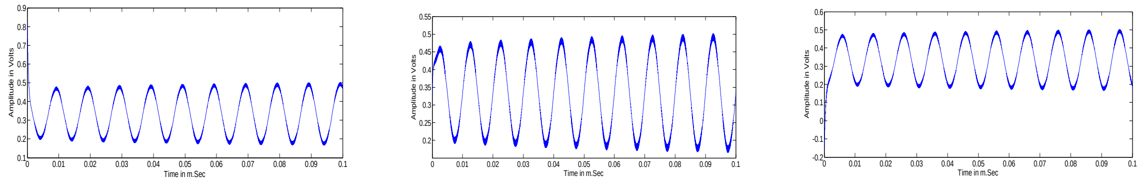

Fig.6. Duty cycle for M_{Yy}, M_{Ry}, M_{By} Phases.

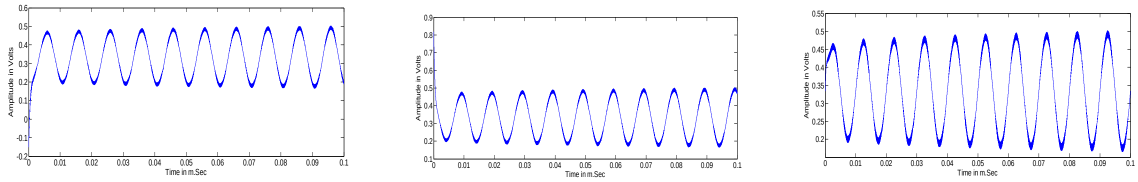

Fig.7. Duty cycle for M_{Rb}, M_{Yb}, M_{Bb} Phases.

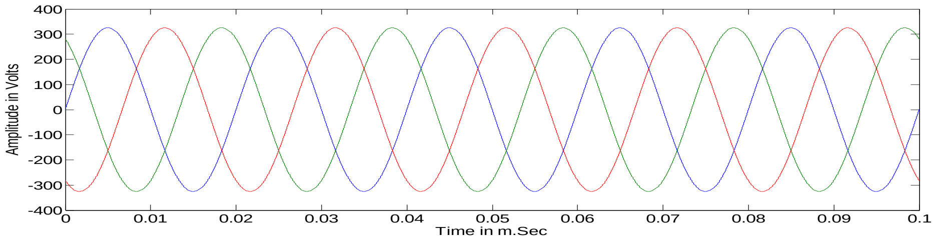

Fig.8. Input waveform for ‘I_{ref}’=7 amps and Amplitude =325.26V in ‘r’ Phase

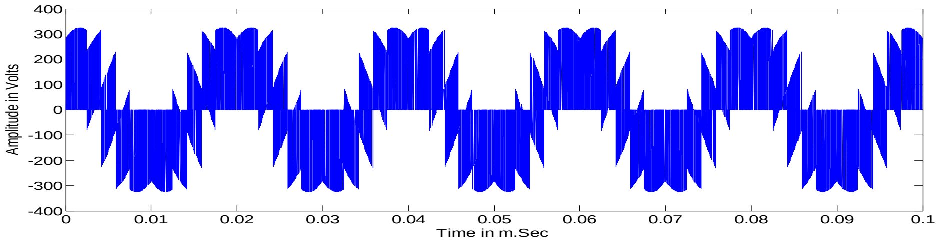

Fig.9. Output Voltage waveform for ‘I_{ref}’=7 amps in ‘r’ Phase.

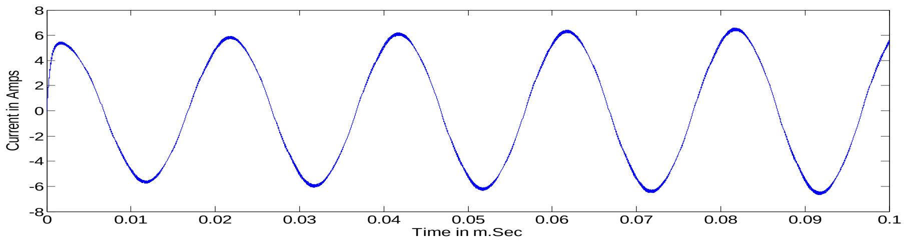

Fig.10. Output Current waveform for ‘I_{ref}’=7 amps in ‘r’ Phase.

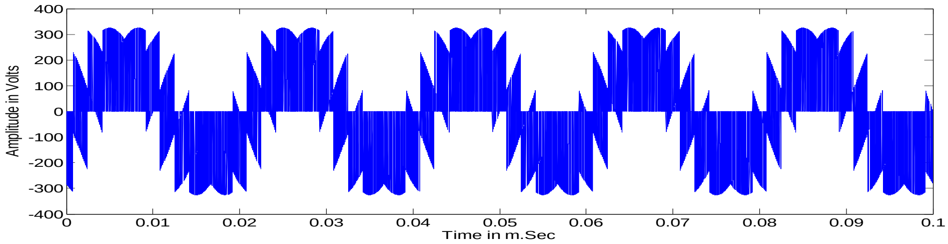

Fig.11. Output Voltage waveform for ‘I_{ref}’=7 amps in ‘y’ Phase.

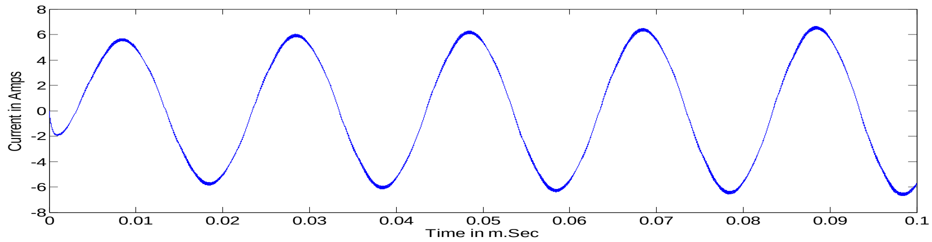

Fig.12. Output Current waveform for ‘I_{ref}’=7 amps in y‘’ Phase.

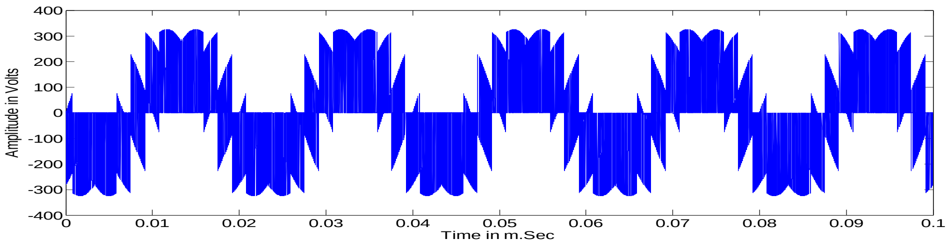

Fig.13. Output Voltage waveform for ‘‘I_{ref}’=7 amps in ‘b’ Phase.

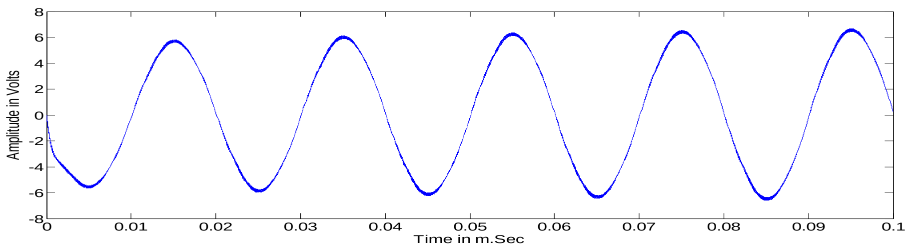

Fig.14. Output Current waveform for ‘I_{ref}’=7 amps in ‘b’ Phase.

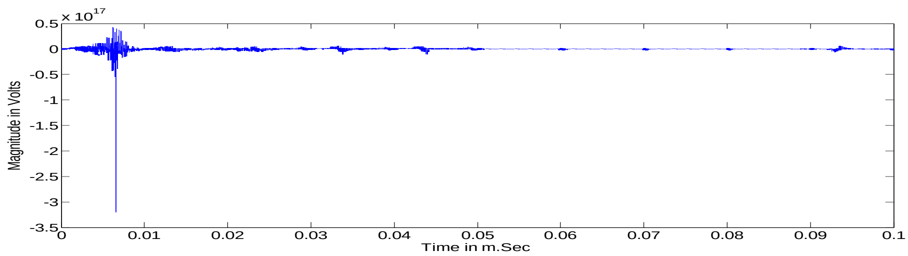

Fig.15. Simulation waveform for ‘THD’ in ‘r’ Phase.

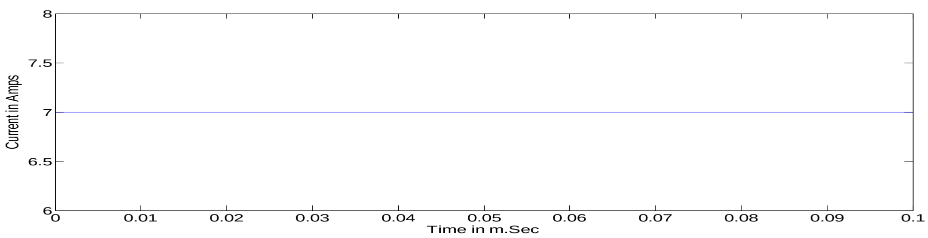

Fig.16. Simulation waveform for reference current ‘I_{ref}’=7 amps

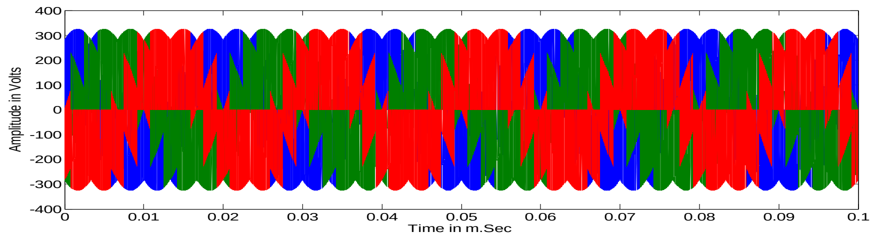

Fig.17. Output Voltage waveform for 3 phase to 3 phase Matrix converter ('r', 'y', 'b' Phases)

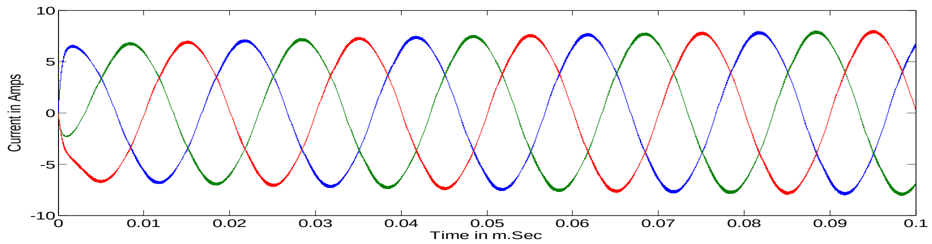

Fig.18. Output Current waveform for 3 phase to 3 phase Matrix converter ('r', 'y', 'b' Phases)

VI. 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 RL load 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 various passive loads and different voltage transfer ratio.

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