Simulation of Closed Loop Fuzzy Logic Controller for a 3 Phase to 3 Phase Power Conversion Using Matrix Converters

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Abstract: ***This paper proposes a new approach of simulation design and implementation of Fuzzy logic controller for a 3 phase to 3 phase conversion using matrix converter. It includes the 3 phase to 3 phase power conversion by open loop and closed loop configurations. In closed loop real time control is achieved by Fuzzy logic controller. The duty cycles of the matrix converter bidirectional switches are calculated using modified venturini algorithm for minimum and maximum voltage transfer ratio. The entire matrix converter circuits are developed by Mathematical model and performances of the Fuzzy logic controllers 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.***

Keywords: 3 phase to 3 phase converter, Matrix converter, AC to AC conversion, 3 Phase Power conversion, closed loop controller, Fuzzy logic Controller

1. Introduction

The matrix converter (MC) is a single-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 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. Control and modulation techniques that enhance both the ac line and motor load side performance have been well developed. 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 (MC) 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.

To control conventional and indirect matrix converter with minimized semiconductor commutation count, an appropriate digital carrier modulation schemes has been introduced [1]. A high-performance transformer less single-stage high step-up ac–dc matrix converter based on Cockcroft–Walton (CW) voltage multiplier has been proposed for deploying a four bidirectional- switch matrix converter between the ac source and CW circuit, the converter provides high quality of line conditions, adjustable output voltage, and low output ripple [2]. To improve the output performance, a novel Z-source sparse matrix converter and a compensation method based on a fuzzy logic controller to compensate unbalanced input-voltages has been proposed [3]. An improved space vector modulation using amplitude coefficient on a capacitor-clamped multilevel matrix converter has been developed for the MMC that utilizes a multilevel structure on a conventional matrix converter, which allows direct ac-ac conversion without large energy store elements [4]. Direct space vector modulation method for the common mode voltage reduction and the power quality of matrix converters for a low-voltage transfer ratio of less than 0.5 has been proposed [5]. Timing errors in the switching between the series-connected switches cause a voltage imbalance in the snubber circuit and increase voltage stress. Hence a new bidirectional switch with regenerative snubber to realize simple series connection for matrix converters has been developed [6]. Z-source energy conversion is a recent concept introduced for adding voltage-boost functionality to the traditional buck-only dc–ac inverter. The same concept can equally be extended to the indirect ac–ac matrix converter, where only a single Z-source impedance network needs to be inserted to its intermediate dc link. Therefore a new improved modulation scheme for indirect Z-source matrix converter with sinusoidal input and output waveforms has been introduced [7]. To attenuate the peaks of harmonics, three carriers based randomized pulse position modulation schemes are proposed for an indirect matrix converter (IMC) [8]. In order to reduce the cost and to improve reliability of the drive with any control strategy, A Novel single current sensor topology for venturini controlled direct matrix converter has been proposed [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]-[17]. To achieve real time control with quick speed and fast response, new designs of controllers are needed [18]-[22]. Fuzzy logic controllers are the one to sense the output continuously and correct the output at the instant if any disturbance occurred.

In this paper, Fuzzy logic 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 Fuzzy logic 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 Fuzzy logic controllers 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. Figure 1 refers the Basic block diagram of the proposed 3pase to 3 phase Matrix converter.

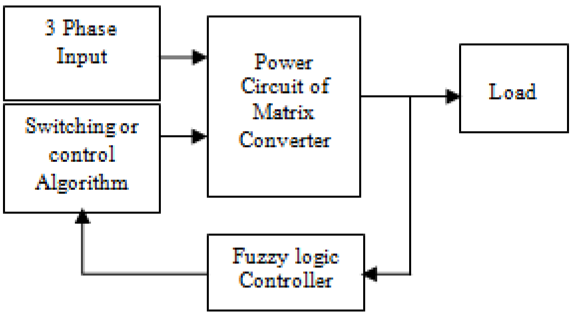

Figure 1: Basic block diagram of 3pase to 3 phase Matrix converter

2. 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 attractive characteristics of a Matrix converter are:

- Unity input power factor at the power supply side.
- Sinusoidal input and output waveforms with minimal higher order harmonics and no sub harmonics;
- Minimal energy storage requirements
- Controllable input power factor
- Bidirectional energy flow capability
- Long life due to absence of a bulky electrolytic capacitor
- Limitations of Matrix converter are as follows:
- The voltage transfer ratio limitation has a maximum value of 0.866
- Sensitive to the power source distortion due to the direct connection between source and load 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 Figure 2.

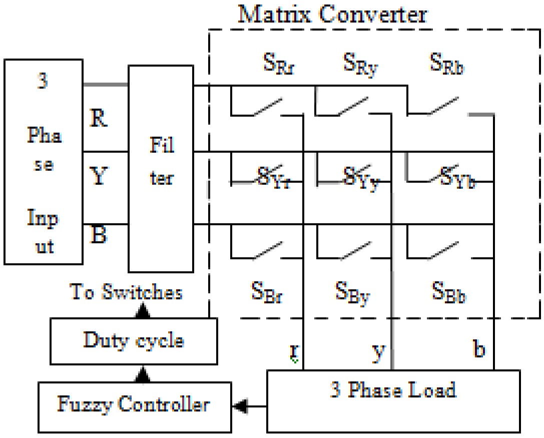

Figure 2: Scheme of 3 phase to 3 phase matrix converter

3. Switching 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 so as to avoid short circuit
- At least one of the switches in each phase should be connected to the output so as to avoid open circuit.

The switching function of single switch as

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

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

The above constraints can be expressed by

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

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

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

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,

ψ_γ = 0, 2π/3, 4π/3 corresponding to the output phase r, y, b [11], [15], [16].

4. Modeling of Matrix Converter

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

4.1 Modeling of Control Algorithm

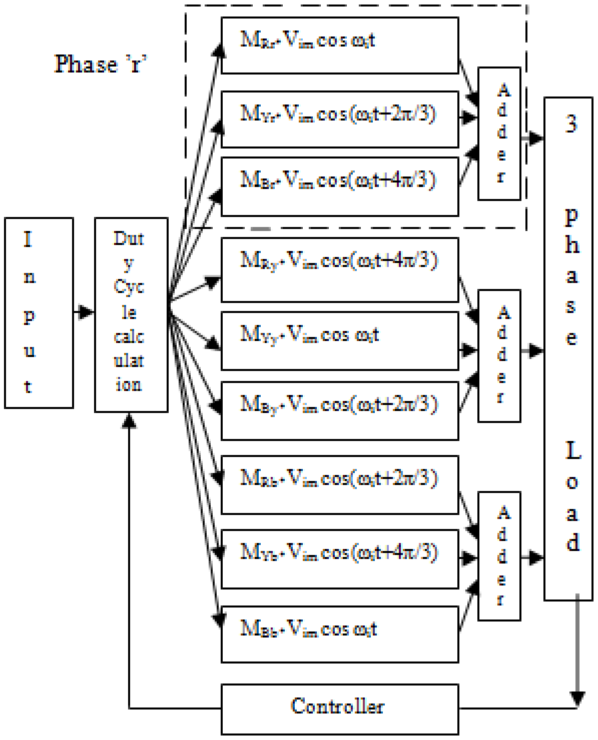

Figure 3: Mathematical Modeling of 3 phase to 3 phase Matrix converter

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 Mat lab.

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;

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

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 and T_s = sampling period.

4.2 Modeling of power circuit

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

$$V_r(t) = M_{Rr}\,V_R(t) + M_{Yr}\,V_Y(t) + M_{Br}\,V_B(t) \quad (24)$$
$$V_y(t) = M_{Ry}\,V_R(t) + M_{Yy}\,V_Y(t) + M_{By}\,V_B(t) \quad (25)$$
$$V_b(t) = M_{Rb}\,V_R(t) + M_{Yb}\,V_Y(t) + M_{Bb}\,V_B(t) \quad (26)$$

Figure 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

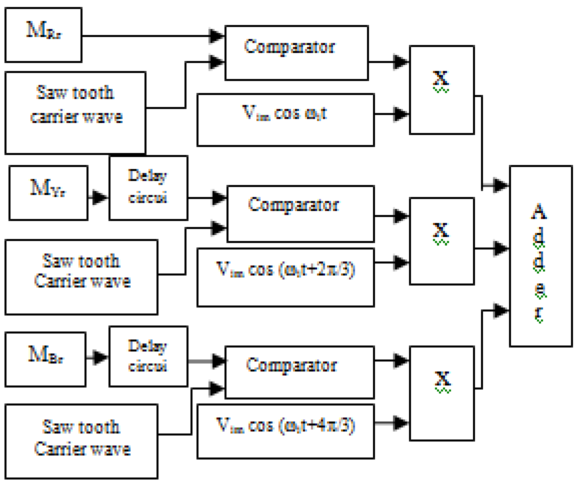

Figure 4: Modeling block of power circuit of 'r' phase in 3 phase to 3 phase Matrix converter

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 Fuzzy Logic Controller

A fuzzy control system is based on fuzzy logic—a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0. Fuzzy logic control system has the following merits,

- It can be easily modified
- It can use multiple input and output sources
- Simple than linear algebraic equations
- Quick and easy to implement

The Fuzzy logic controller model was developed using Simulink Blockset.Figure.5. shows the basic block diagram of a Fuzzy logic controller and fiqure.6&7 shows the membership function of the input variables 'e' & 'ce'. Figure.8. shows the membership function of the output variable 'o'.

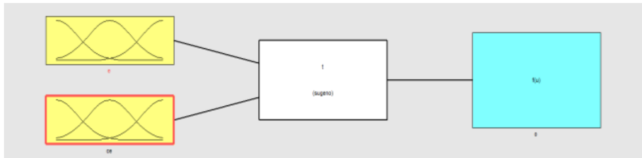

Figure 5: Block Diagram of Fuzzy logic controller

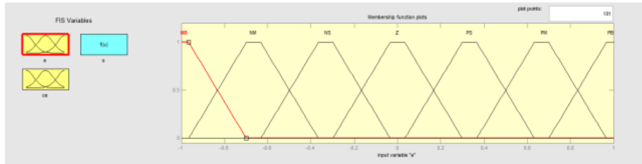

Figure 6: Block Diagram of Input Variable 'e' Membership Function

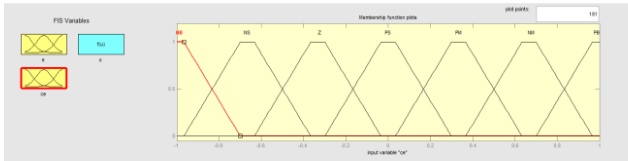

Figure 7: Block Diagram of Input Variable 'ce' Membership Function

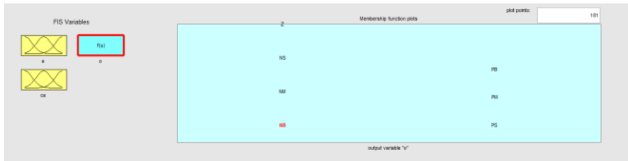

Figure 8: Block Diagram of Output Variable 'o' Membership Function

5. Simulation Results and Discussion

The simulation of 3 phase to 3 phase Matrix converter for open loop and closed loop are carried out using simulink blockset. In closed loop configuration, Fuzzy logic controller was realized as real time controllers. The simulation output comprises of two sections.

5.1 3 Phase to 3 Phase Matrix Converter in Closed Loop Configuration with Fuzzy Logic Controller

Simulations results are performed for a reference current of 5 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 5 Amps. The output is again feedback to the input of the matrix converter through Fuzzy logic controller to achieve the real time control. Figure 9. shows the Input waveform for 'I_{ref}'=5 amps and Amplitude =325.26V in 'r' Phase. The Output Voltage and current waveforms in 'r' Phase for 'I_{ref}'=5 amps as shown in Figure 10 &11. The Output Voltage and current waveforms in 'y' Phase for 'I_{ref}'=5 amps as shown in Figure 12 & 13. The Output Voltage and current waveforms in 'b' Phase for 'I_{ref}'=5 amps as shown in Figure 14 & 15. Figure 16 shows the Simulation waveform for 'THD' in 'r' Phase. Figure 17 shows simulation diagram of a reference current for ''I_{ref}'=5 amps. Figure 18 shows the Average Output Voltage waveform for 3 phase to 3 phase Matrix converter (for 'r', 'y', 'b' Phases). Similarly, Figure 19 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 5 Amps.

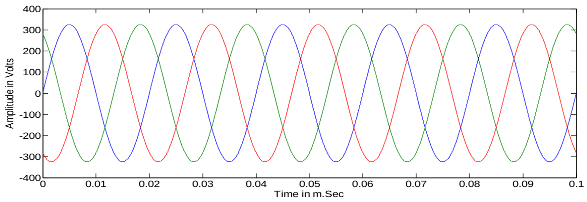

Figure 9: Input waveform for ''I_{ref}'=5 amps and Amplitude =325.26V in 'r' Phase

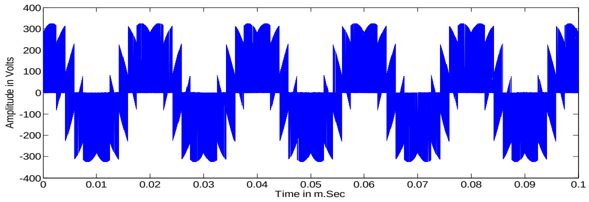

Figure 10: Output Voltage waveform for I_{ref}'=5 amps in 'r' Phase.

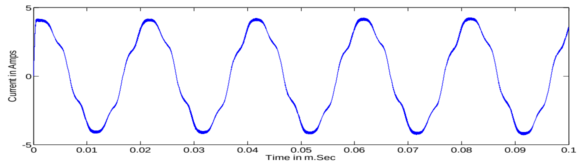

Figure 11: Output Current waveform for 'I_{ref}'=5 amps in 'r' Phase.

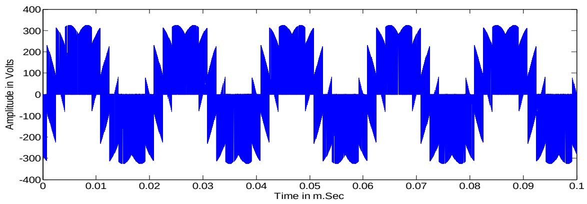

Figure 12: Output Voltage waveform for 'I_{ref}'=5 amps in 'y' Phase

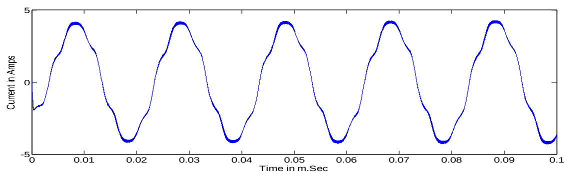

Figure 13: Output Current waveform for 'I_{ref}'=5 amps in 'y' Phase

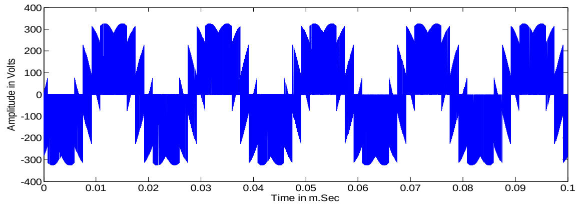

Figure 14: Output Voltage waveform for 'I_{ref}'=5 amps in 'b' Phase

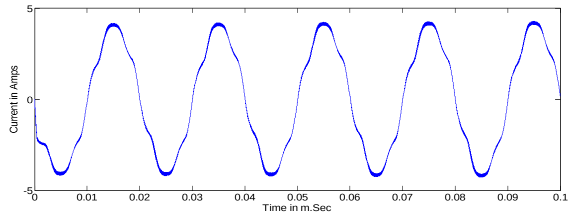

Figure 15: Output Current waveform for 'I_{ref}'=5 amps in 'b' Phase

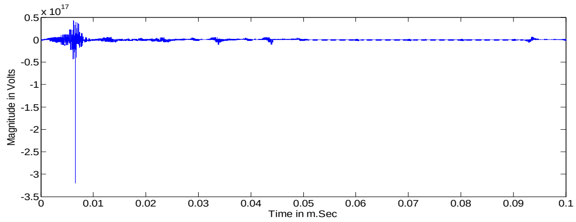

Figure 16: Simulation waveform for 'THD' in 'r' Phase.

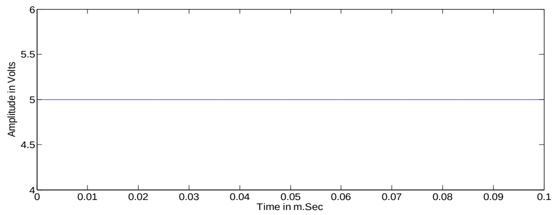

Figure 17: Simulation waveform for reference Current 'I_{ref}'=5 amps.

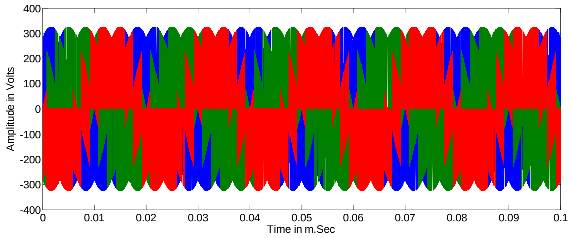

Figure 18: Output Voltage waveform for 3 phase to 3 phase Matrix converter ('r', 'y', 'b' Phases)

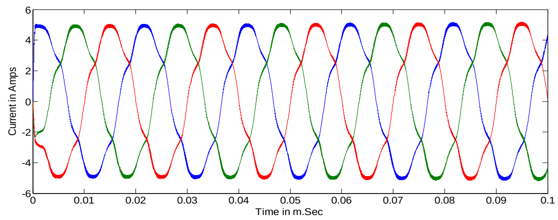

Figure 19: Output Current waveform for 3 phase to 3 phase Matrix converter ('r', 'y', 'b' Phases)

6. Conclusion

Design and implementation of Fuzzy logic controller for 3 phase to 3 phase 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 fuzzy logic controller configuration. In closed loop fuzzy logic control configuration, a real time control has been achieved with less computational time. The output was realized by RL load and the simulation results are taken for maximum voltage transfer ratio. The average output current can be controlled by varying the values of Rand L. The simulation output results are satisfactory and the future extension of this paper is possible for three phase to 'n' phase Matrix converter with various passive loads and different voltage transfer ratio.

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