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Maximization of Transfer Ratio and Minimization of Harmonics in Three Phase AC/AC Matrix Converter

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Abstract

Energy saving and different working voltage applications are widely employing matrix converters. Matrix converters are used to convert three phase AC input voltages to three phase AC output voltages of required magnitude and frequency. Pulse width modulation is a technique used for converting three phase AC input to three phase AC output. In this research paper, pulse width modulation based matrix converter will be designed to acquire voltage of desired magnitude and frequency. Voltage transfer ratio will be maximized in this technique so that any desired voltage magnitude could be achieved. Secondly, harmonics will be made reduced in this design. Simulations will be performed in Matlab and characteristics of output waveform will be observed with respect to characteristics of input waveforms.

Keywords: Matrix Converters; Pulse Width Modulation; Voltage Transfer Ratio; Harmonics; Matlab

1 Introduction

Energy saving and different working voltage applications are widely employing matrix converters. Matrix converters are used to convert three phase AC input voltages to three phase AC output voltages of required magnitude and frequency [1, 2]. In matrix converter, the basic component is a bidirectional switch. This switch works in a controlled way to generate a variable desired frequency. The control operation of switch makes it possible to work at high frequency that will enable to attain desired voltage. There is no intermediate DC link existing in the matrix converter. The complexity of modulation technique can be reduced by reducing the components in matrix converters according to requirement [3, 4, 5, 6, 7, 8].

Pulse width modulation is a technique used to generate pulsating signal of variable width so that a message or a signal could be encoded [8, 9, 10]. One of the most significant usage of this

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modulation scheme is to control the on/ off operation of the switching devices connected between the load and source when it is required to do so. In this way, not only power transfer is controlled but also the voltage of desired amplitude can be achieved. Since operation of switching is performed at high frequency and high frequency switching leads to high switching losses due to generation of harmonics. Non linear loads connected to supply are also the source of harmonics. Not only the power system operation but also the power system quality is highly affected due to undesirable characteristics of harmonics. Harmonic elimination techniques are employed to eliminate low order harmonics [11, 12]. Higher order harmonics are also made reduced with different techniques for efficient power system operation [13, 14, 15, 16, 17]. Different topologies of active and passive filters are also deployed to uproot harmonics in the system [18, 19, 20].

Power switches like bipolar junction transistors (BJTs), metal oxide silicon field effect transistors (MOSFETs) and insulated gate bipolar junction transistors (IGBTs) have revolutionized the topologies of matrix converter [21]. Matrix converter was made in 1980 by Venturini and Alesia. They developed a converter comprising of bidirectional switches and direct transfer function approach was developed as a modulation scheme for converter. Desired output voltages are obtained by the product of input voltages and modulation matrix [10, 22, 23]. In 1983, Rodriguez developed a fictitious DC link technique for matrix converter. In this technique, the switching of output occurs between the most positive input line and the most negative input line. This technique was further named as indirect transfer function approach [24, 25].

In 1983, Braun and in 1985, Kastner and Rodriguez developed the control method of matrix converter [26, 27]. However, Huber was the first man who published the space modulation scheme for matrix converter as a controlling scheme in 1989 [28]. High spikes of voltage and current should be avoided because these spikes may damage the semi-conductor switches based matrix converter. In 1992, it was experimentally proven by Schauder and Neft that bidirectional switches were the source of high quality of input and output current [29]. However, with the advancement in technology, this problem is resolved with the invention of microprocessor based converter controllers.

In this research paper, pulse width modulation based matrix converter will be designed to acquire voltage of desired magnitude and frequency. Voltage transfer ratio will be maximized in this technique so that any desired voltage magnitude could be achieved. Secondly, harmonics will be made reduced in this design. Simulations will be performed in Matlab and characteristics of output waveform will be observed with respect to characteristics of input waveform.

This research paper consists of following sections. Section II consists of Matrix Converters. Pulse width modulation is described mathematically in section III. Section IV consists of Matlab / Simulink implementation of PWM based matrix converter. Section V comprises of conclusion.

2 Matrix Converters

Matrix converter is employed to alter the frequency of input supply. It consists of a bidirectional switches which connect any output phase to any of the three phase input supply. In this research, a direct approach of converting AC to AC is used without the involvement of an intermediate DC link capacitor [3, 4, 5]. It has three phase input supply voltages. $V_{\alpha o}$, $V_{\beta o}$ and $V_{\gamma o}$ are the three phase output voltages. Nine elements of matrix are mathematically derived from the values of nine bidirectional switches i.e., S_{11} to S_{33}. The three phase input connected to converter is given by (2.1), (2.2) and (2.3).

$$V_{\alpha i} = V_i \cos(\omega_i t) \tag{2.1}$$

$$V_{\beta i} = V_i \cos(\omega_i t + \frac{2\pi}{3}) \tag{2.2}$$

$$V_{\gamma i} = V_i \cos(\omega_i t + \frac{4\pi}{3}) \tag{2.3}$$

and the required three phase output voltages from converter is given by (2.4), (2.5) and (2.6).

$$V_{\alpha o} = V_o \cos(\omega_o t) \tag{2.4}$$

$$V_{\beta o} = V_o \cos(\omega_o t + \frac{2\pi}{3}) \tag{2.5}$$

$$V_{\gamma o} = V_o \cos(\omega_o t + \frac{4\pi}{3}) \tag{2.6}$$

The three phase input to converter is related to the three phase output of converter by the (2.7).

$$\begin{bmatrix} V_{\alpha o}(t) \\ V_{\beta o}(t) \\ V_{\gamma o}(t) \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} \begin{bmatrix} V_{\alpha i}(t) \\ V_{\beta i}(t) \\ V_{\gamma i}(t) \end{bmatrix} \tag{2.7}$$

where M_{11} to M_{33} are the duty cycles of the switches S_{11} to S_{33}.

Voltage source is usually used to feed the matrix converter and switching operation is done in such a way so as to avoid short circuiting of input terminals and open circuiting of the output terminals.

3 Pulse Width Modulation

Pulse width modulation is a technique used to generate pulsating signal of variable width so that a message or a signal could be encoded [9, 8]. One of the most significant usage of this modulation scheme is to control the on/ off operation of the switching devices connected between the load and source when it is required to do so. Switching losses is negligible by using pulse width modulation because of very short transition intervals.

3.1 Modulation Algorithm

Assuming that the switches are ideal, i.e no losses occurs in switches.

The three phase input supply is given by (3.1).

$$\begin{bmatrix} V_{\alpha i}(t) \\ V_{\beta i}(t) \\ V_{\gamma i}(t) \end{bmatrix} = \begin{bmatrix} cos(\omega_i t) \\ cos(\omega_i t + \frac{2\pi}{3}) \\ cos(\omega_i t + \frac{4\pi}{3}) \end{bmatrix} \times V_i \tag{3.1}$$

T_s is the switching time sequence after which switching operation is done and is reciprocal to f_s. The switching time T_s is given by (3.2).

$$T_s = t_{\alpha_i \alpha_o} + t_{\beta_i \alpha_o} + t_{\gamma_i \alpha_o} = t_{\alpha_i \beta_o} + t_{\beta_i \beta_o} + t_{\gamma_i \beta_o} = t_{\alpha_i \gamma_o} + t_{\beta_i \gamma_o} + t_{\gamma_i \gamma_o} = \frac{1}{f_s} \tag{3.2}$$

The length of sequences are same which means that switching frequency f_s for all the sequences is same.

The three phase output voltages are displaced from each other by an angle of $120\,^\circ$ and are given in terms of switching time in (3.3), (3.4) and (3.5).

$$V_{\alpha o}(t) = V_i cos(\omega t)\frac{t_{\alpha_i \alpha_o}}{T_s} + V_i cos(\omega t + \frac{2\pi}{3})\frac{t_{\beta_i \alpha_o}}{T_s} + V_i cos(\omega t + \frac{4\pi}{3})\frac{t_{\gamma_i \alpha_o}}{T_s} \tag{3.3}$$

$$V_{\beta o}(t) = V_i cos(\omega t)\frac{t_{\alpha_i \beta_o}}{T_s} + V_i cos(\omega t + \frac{2\pi}{3})\frac{t_{\beta_i \beta_o}}{T_s} + V_i cos(\omega t + \frac{4\pi}{3})\frac{t_{\gamma_i \beta_o}}{T_s} \tag{3.4}$$

$$V_{\gamma o}(t) = V_i cos(\omega t)\frac{t_{\alpha_i \gamma_o}}{T_s} + V_i cos(\omega t + \frac{2\pi}{3})\frac{t_{\beta_i \gamma_o}}{T_s} + V_i cos(\omega t + \frac{4\pi}{3})\frac{t_{\gamma_i \gamma_o}}{T_s} \tag{3.5}$$

Now, modulating frequency ω_m is added in the input frequency ω_i if the input frequency ω_i is increased to ω_o. $\omega_o = \omega_i + \omega_m$.

The switching sequences for V_o at 0° are given in (3.6), (3.7) and (3.8).

$$t_{\alpha_i\alpha_o} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta)) \tag{3.6}$$

$$t_{\beta_i\alpha_o} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{2\pi}{3})) \tag{3.7}$$

$$t_{\gamma_i\alpha_o} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{4\pi}{3})) \tag{3.8}$$

The switching sequences for V_o at 120° are given in (3.9), (3.10) and (3.11).

$$t_{\alpha_i\beta_o} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{4\pi}{3})) \tag{3.9}$$

$$t_{\beta_i\beta_o} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta)) \tag{3.10}$$

$$t_{\gamma_o\beta_o} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{2\pi}{3})) \tag{3.11}$$

The switching sequences for V_o at 240° are given in (3.12), (3.13) and (3.14).

$$t_{\alpha_i\gamma_o} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{2\pi}{3})) \tag{3.12}$$

$$t_{\beta_i\gamma_o} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta - \frac{4\pi}{3})) \tag{3.13}$$

$$t_{\gamma_i\gamma_o} = \frac{T_s}{3}\ (1 + 2qcos(\omega_m t + \theta)) \tag{3.14}$$

Modulation matrices are given in (3.15) and (3.16).

$$[M_1(t)] = \frac{1}{3}\begin{bmatrix} 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t - \frac{2\pi}{3}) & 1+2qcos(\omega_m t - \frac{4\pi}{3}) \\ 1+2qcos(\omega_m t - \frac{4\pi}{3}) & 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t - \frac{2\pi}{3}) \\ 1+2qcos(\omega_m t - \frac{2\pi}{3}) & 1+2qcos(\omega_m t - \frac{4\pi}{3}) & 1+2qcos(\omega_m t) \end{bmatrix} \tag{3.15}$$

with $\omega_m = (\omega_0 - \omega_i)$.

$$[M_2(t)] = \frac{1}{3}\begin{bmatrix} 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t - \frac{2\pi}{3}) & 1+2qcos(\omega_m t - \frac{4\pi}{3}) \\ 1+2qcos(\omega_m t - \frac{2\pi}{3}) & 1+2qcos(\omega_m t - \frac{4\pi}{3}) & 1+2qcos(\omega_m t) \\ 1+2qcos(\omega_m t - \frac{4\pi}{3}) & 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t - \frac{2\pi}{3}) \end{bmatrix} \tag{3.16}$$

with $\omega_m = -(\omega_0 + \omega_i)$. Sum of $M_1(t)$ and $M_2(t)$ is required for the cancellation of phase displacement effect and is given in (3.17) and (3.18).

$$[M(t)] = [M_1(t)] + [M_2(t)] \tag{3.17}$$

$$\begin{aligned} [M(t)] &= \frac{1}{3}\begin{bmatrix} 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t - \frac{2\pi}{3}) & 1+2qcos(\omega_m t - \frac{4\pi}{3}) \\ 1+2qcos(\omega_m t - \frac{4\pi}{3}) & 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t - \frac{2\pi}{3}) \\ 1+2qcos(\omega_m t - \frac{2\pi}{3}) & 1+2qcos(\omega_m t - \frac{4\pi}{3}) & 1+2qcos(\omega_m t) \end{bmatrix} \\ &+ \frac{1}{3}\begin{bmatrix} 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t - \frac{2\pi}{3}) & 1+2qcos(\omega_m t - \frac{4\pi}{3}) \\ 1+2qcos(\omega_m t - \frac{2\pi}{3}) & 1+2qcos(\omega_m t - \frac{4\pi}{3}) & 1+2qcos(\omega_m t) \\ 1+2qcos(\omega_m t - \frac{4\pi}{3}) & 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t - \frac{2\pi}{3}) \end{bmatrix} \end{aligned} \tag{3.18}$$

The output voltage is given by (3.19) and (3.20).

$$V_o(t) = M(t) \cdot V_i(t) \tag{3.19}$$

$$\begin{aligned}
[V_o(t)] &= \frac{1}{3}\begin{bmatrix} 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t-\frac{2\pi}{3}) & 1+2qcos(\omega_m t-\frac{4\pi}{3}) \\ 1+2qcos(\omega_m t-\frac{4\pi}{3}) & 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t-\frac{2\pi}{3}) \\ 1+2qcos(\omega_m t-\frac{2\pi}{3}) & 1+2qcos(\omega_m t-\frac{4\pi}{3}) & 1+2qcos(\omega_m t) \end{bmatrix} \\
&+ \frac{1}{3}\begin{bmatrix} 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t-\frac{2\pi}{3}) & 1+2qcos(\omega_m t-\frac{4\pi}{3}) \\ 1+2qcos(\omega_m t-\frac{2\pi}{3}) & 1+2qcos(\omega_m t-\frac{4\pi}{3}) & 1+2qcos(\omega_m t) \\ 1+2qcos(\omega_m t-\frac{4\pi}{3}) & 1+2qcos(\omega_m t) & 1+2qcos(\omega_m t-\frac{2\pi}{3}) \end{bmatrix} \\
&\times \begin{bmatrix} V_i(\omega_m t) \\ V_i(\omega_m t-\frac{2\pi}{3}) \\ V_i(\omega_m t-\frac{2\pi}{3}) \end{bmatrix}
\end{aligned} \tag{3.20}$$

4 Matlab / Simulink Implementation

Matlab/ Simulink is employed to develop the pulse width modulation based matrix converter. Initially, a three phase source is required whose amplitude and frequency can be changed by user. Matlab embedded function is used to design a three phase source have a phase difference of 120° between two phases. A digital clock is used to design a sampling time for a three phase source. Matlab embedded modulation function block requires input voltages, input frequency to produce the required output voltages and output frequency. This block also develops the switching intervals for the nine bidirectional switches. PWM signal is generated by gate signal generator for nine bidirectional IGBT based switches. Each switch consists of two IGBTs. s_{11} to s_{33} are the gates for applying gate signals to bidirectional switches.

Simulations are performed on Matlab / Simulink to verify the model developed for pulse width modulation based matrix converter and is given in 1,2,3. This model is tested for different scenarios to verify the fact that this model is maximizing the voltage transfer ratio and minimizing the harmonics.

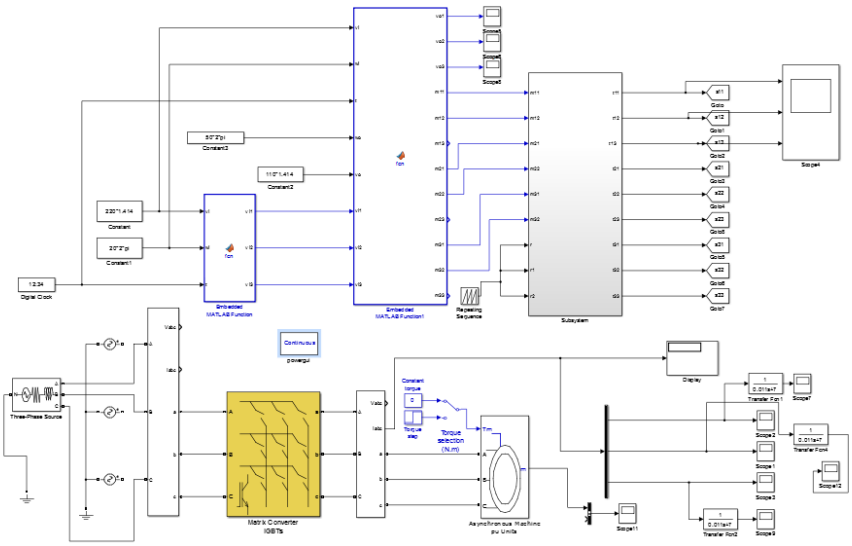

Figure 1: Matlab/Simulink model of PWM based Matrix Converter

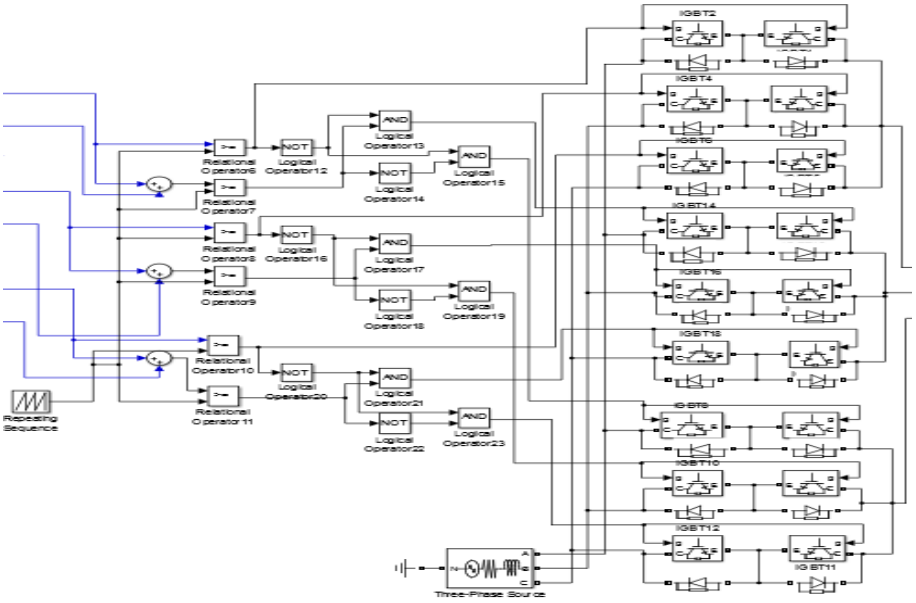

Figure 2: Internal structure of Matrix Converters

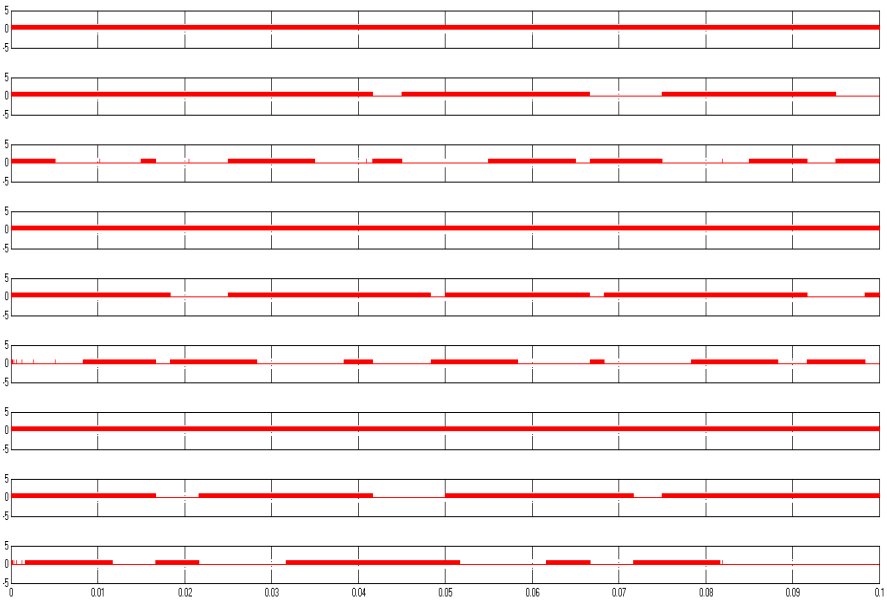

Figure 3: Timing Diagram of Switches of Matrix Converters

4.1 Modulation Block with fixed Input Frequency of 50 Hz

Input frequency of the system is made fixed i.e., at 50 Hz. Output frequency is varied according to the requirement of load. Simulations are performed for this design setup and it is verified that any desired frequency can be achieved irrespective of input frequency and hence variable frequency loads can work smoothly without taking into consideration of input frequency and it is shown in 4,5,6,7,8,9,10.

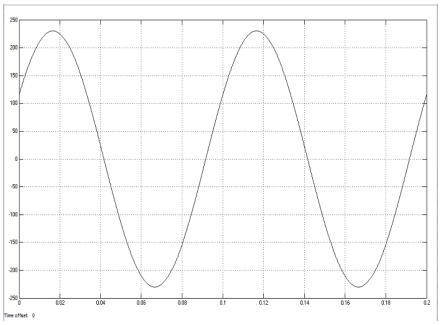

Figure 4: 10Hz Output Signal with 50Hz Input Signal Frequency.

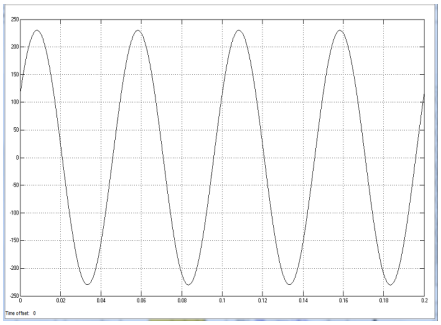

Figure 5: 20Hz Output Signal with 50Hz Input Signal Frequency.

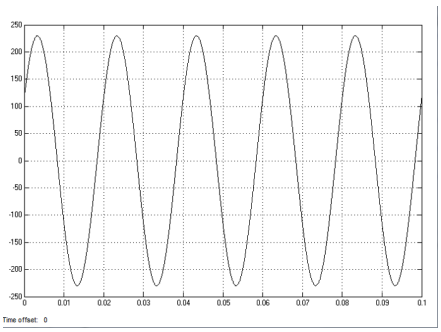

Figure 6: 50Hz Output Signal with 50Hz Input Signal Frequency.

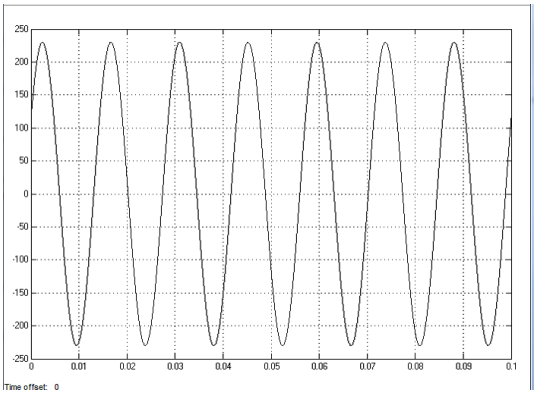

Figure 7: 70Hz Output Signal with 50Hz Input Signal Frequency.

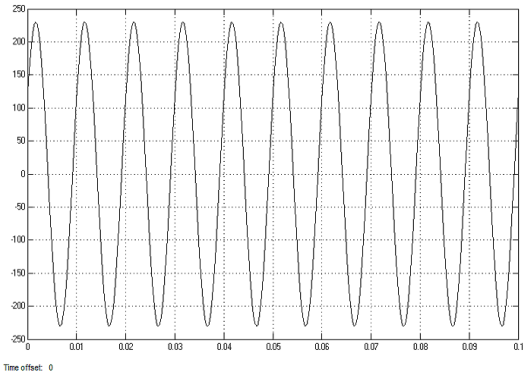

Figure 8: 100Hz Output Signal with 50Hz Input Signal Frequency.

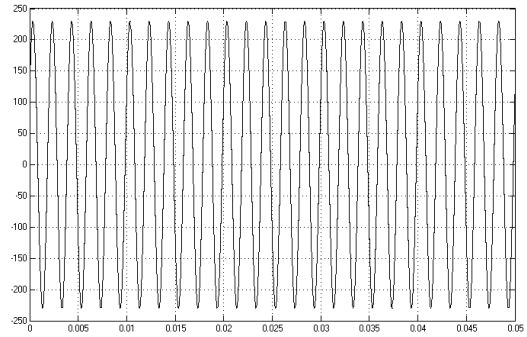

Figure 9: 500Hz Output Signal with 50Hz Input Signal Frequency.

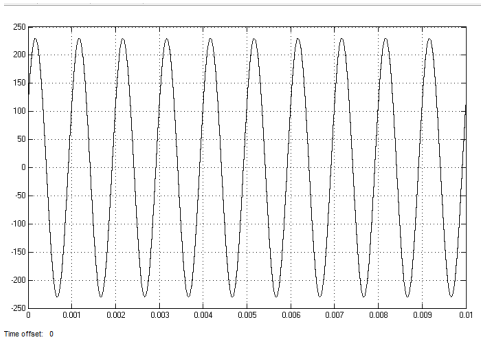

Figure 10: 1000Hz Output Signal with 50Hz Input Signal Frequency.

4.2 Modulation Block with fixed Output Frequency of 50 Hz

Output frequency of the system is made fixed i.e., at 50 Hz. Input frequency is varied according to the requirement of sources. Simulations are performed for this design setup and it is verified that any desired input frequency can not affect output frequency and hence constant frequency loads can work smoothly without taking into consideration of input frequency and it is shown in 11, 12,13,14,15,16, 17.

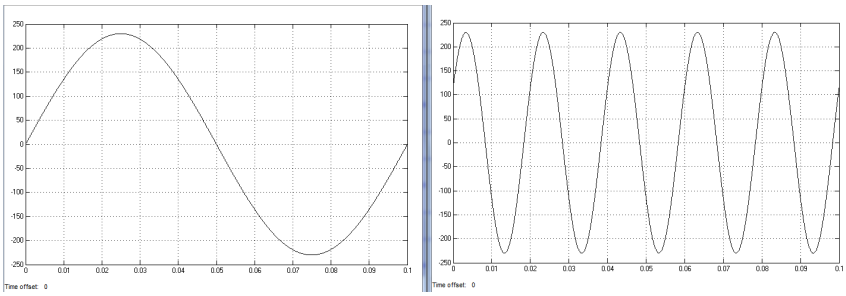

Figure 11: 10Hz Input Signal with 50Hz Output Signal.

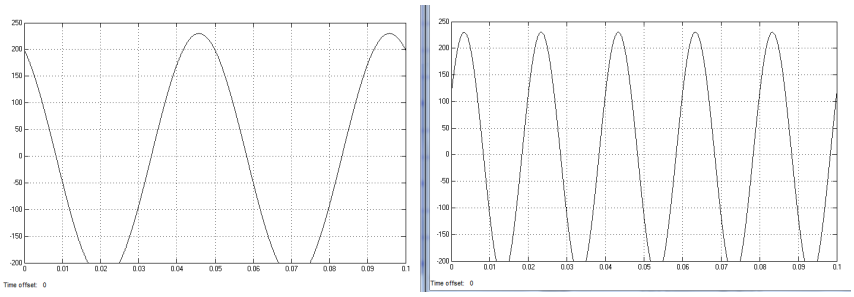

Figure 12: 20Hz Input Signal with 50Hz Output Signal.

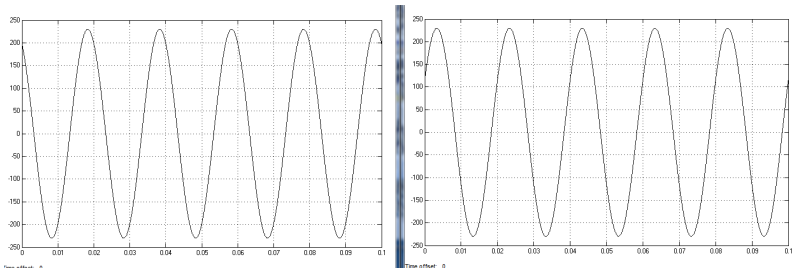

Figure 13: 50Hz Input Signal with 50Hz Output Signal.

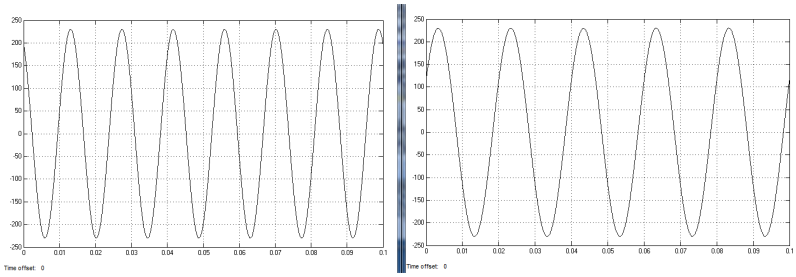

Figure 14: 70Hz Input Signal with 50Hz Output Signal.

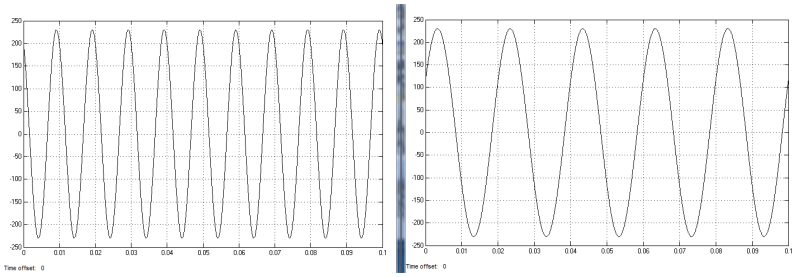

Figure 15: 100Hz Input Signal with 50Hz Output Signal.

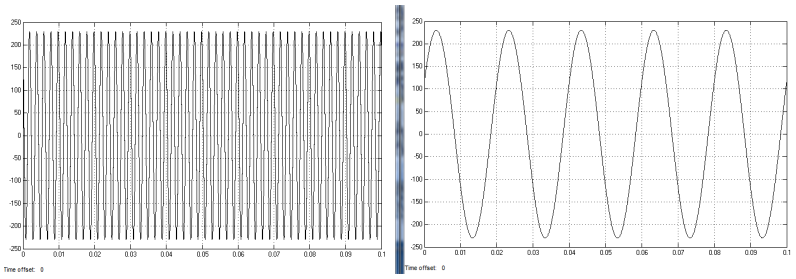

Figure 16: 500Hz Input Signal with 50Hz Output Signal.

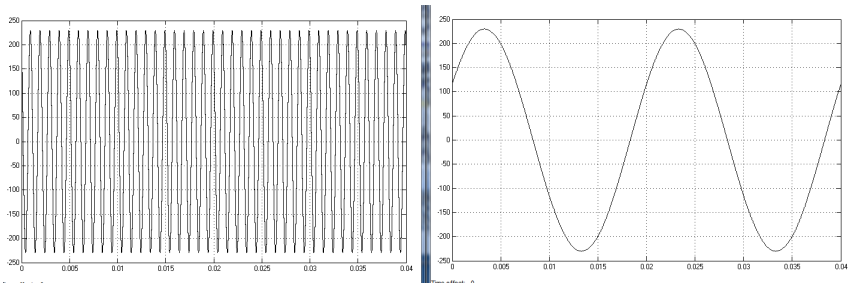

Figure 17: 1000Hz Input Signal with 50Hz Output Signal.

4.3 Modulation Block with fixed Input Voltage of 220 V

Input voltage of the system is made fixed i.e., at 220 V. Output voltage is made varied according to the load requirement. Simulations are carried out and it is verified that variable voltage based loads can work efficiently over any desired operating voltages and input voltage or source voltage has nothing to do with it. It is shown in 18,19,20.

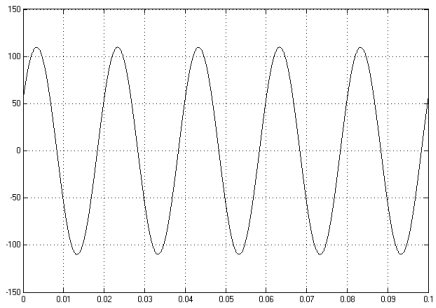

Figure 18: 110V Output Voltage with 220V Input Voltage.

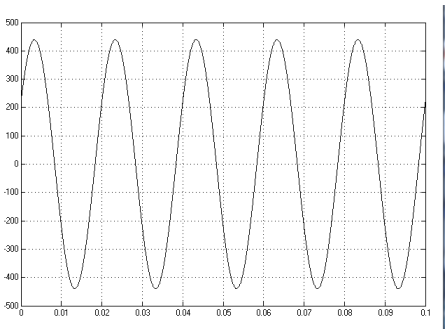

Figure 19: 440V Output Voltage with 220V Input Voltage.

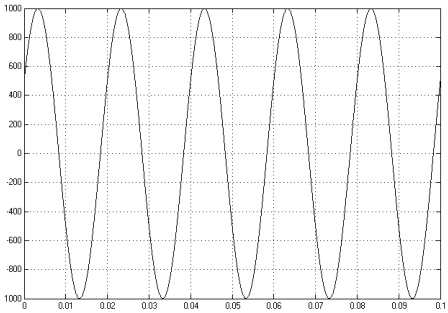

Figure 20: 1000V Output Voltage with 220V Input Voltage.

4.4 Modulation Block With fixed Output Voltage of 220V

Output voltage of the system is made fixed i.e., at 220 V. Input voltage is made varied according to the load requirement. Simulations are carried out and it is verified that loads can work efficiently with any variable voltage source due to some unwanted reasons. Safety can be much ensured for sensitive loads which are usually shut down due to change in voltages. It is shown in 21,22,23.

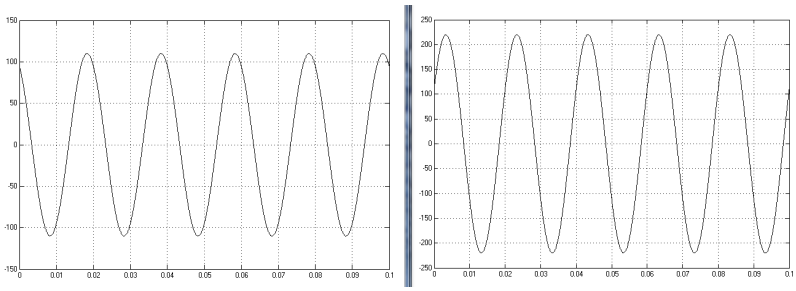

Figure 21: 110V Input Voltage with 220V Output Voltage.

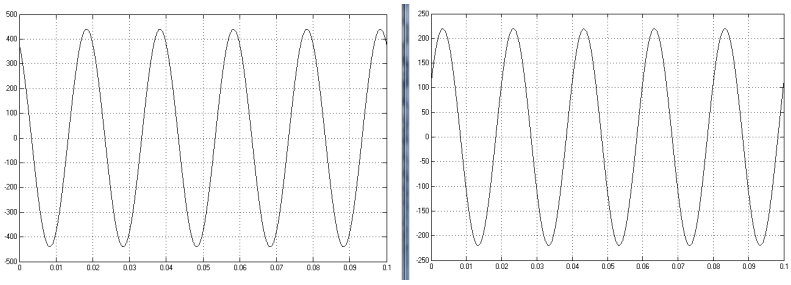

Figure 22: 440V Input Voltage with 220V Output Voltage.

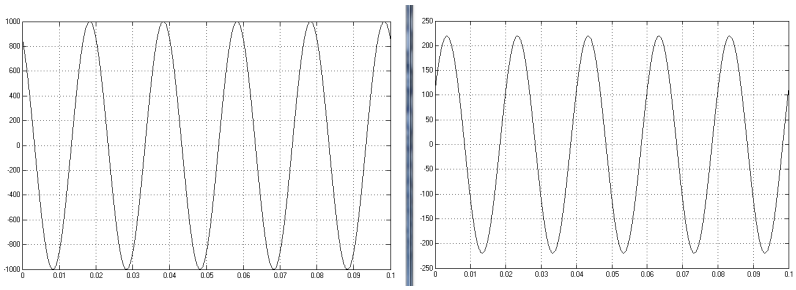

Figure 23: 1000V Input Voltage with 220V Output Voltage.

4.5 Harmonic Analysis with fixed Input Frequency of 50 Hz

Input frequency of the system is made fixed i.e., at 50 Hz. Output frequency is varied according to the requirement of load. Simulations are performed for this design setup and it is verified that any desired output frequency is achieved with less higher or lower order desired frequency components. In other words, any desired frequency can be attained with less harmonic losses. It is shown in 24, 25,26,27,29.

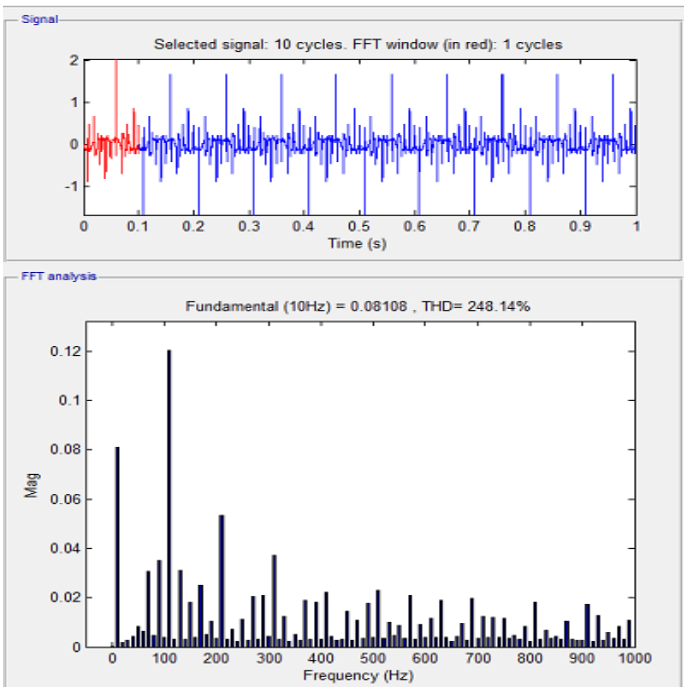

Figure 24: FFT analysis of 10Hz Output Signal with 50Hz Input Signal.

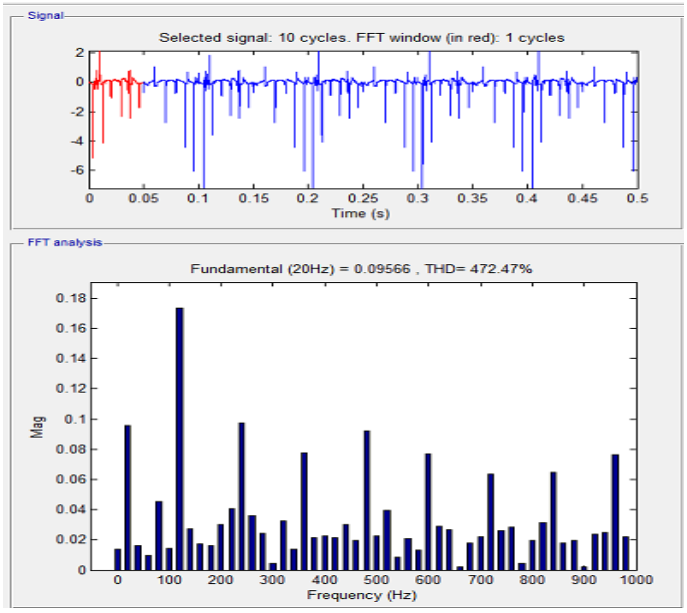

Figure 25: FFT analysis of 20Hz Output Signal with 50Hz Input Signal.

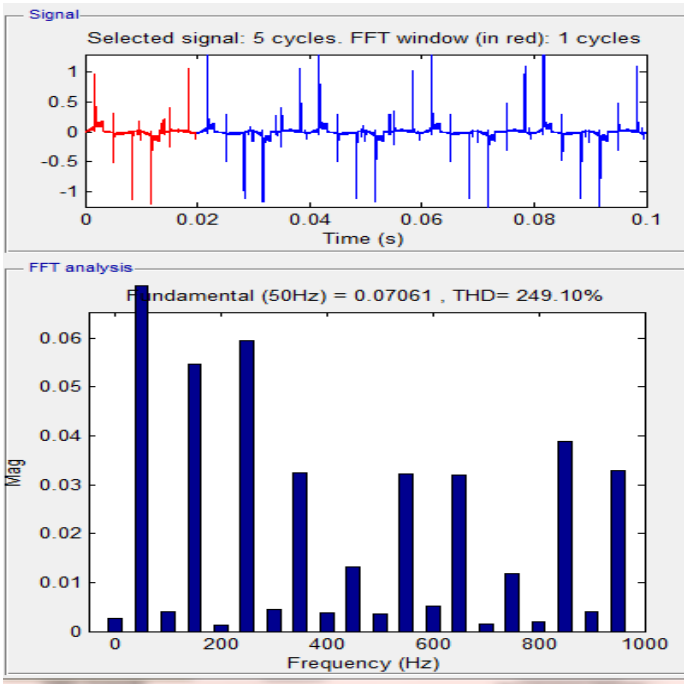

Figure 26: FFT analysis of 50Hz Output Signal with 50Hz Input Signal.

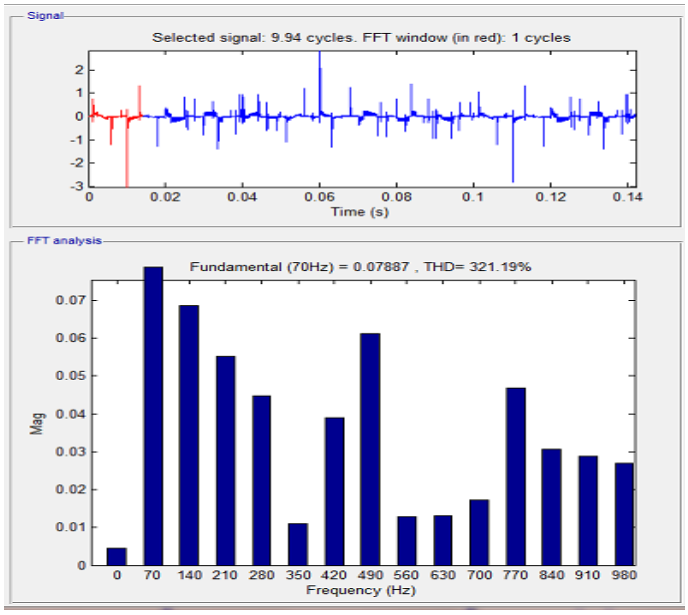

Figure 27: FFT analysis of 70Hz Output Signal with 50Hz Input Signal.

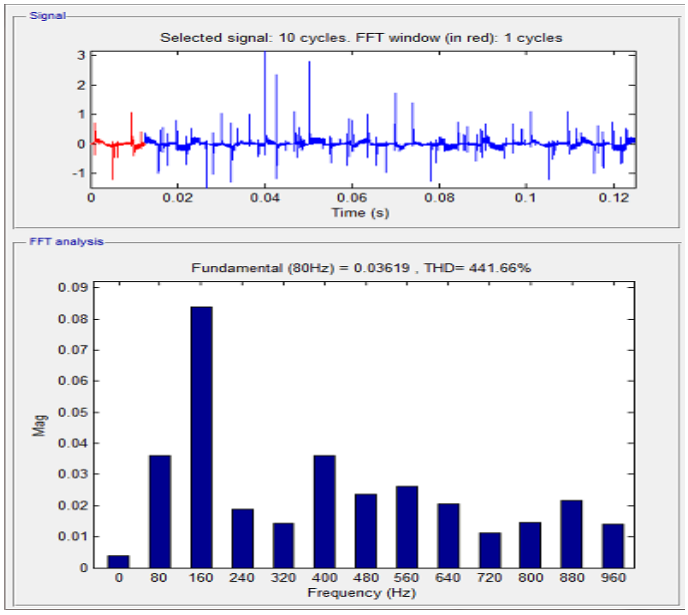

Figure 28: FFT analysis of 80Hz Output Signal with 50Hz Input Signal.

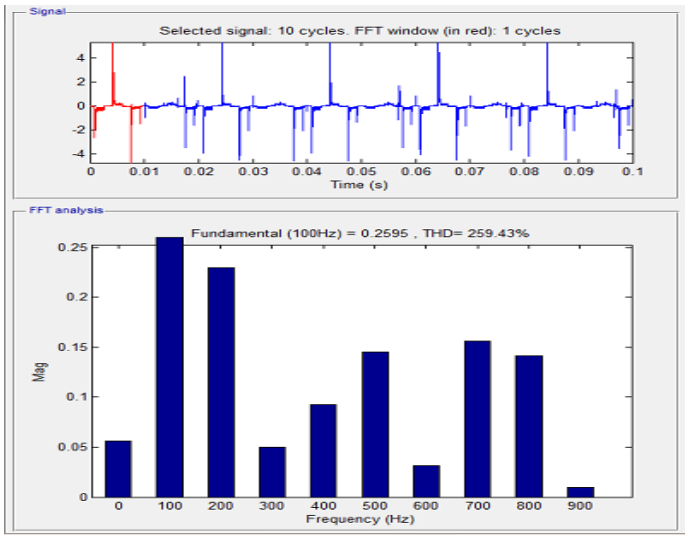

Figure 29: FFT analysis of 100Hz Output Signal with 50Hz Input Signal.

4.6 Pulse Width Modulation with fixed Output Frequency of 50 Hz

Output frequency of the system is made fixed i.e., at 50 Hz. Input frequency is varied. Simulations are performed for this design setup and it is verified that output frequency cannot be affected by change in input frequency due to unwanted reasons and output frequency can be made constant with less harmonic contents. It is shown in 30, 31,32,33,34.

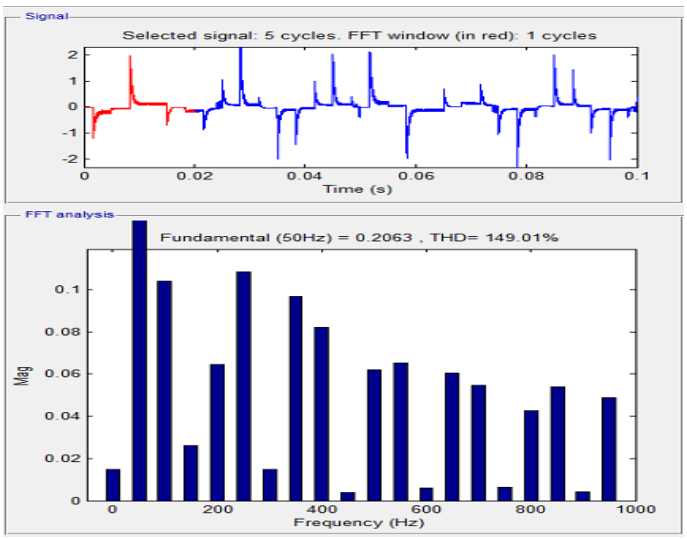

Figure 30: FFT analysis of Fixed Output 50Hz with 10Hz input Signal.

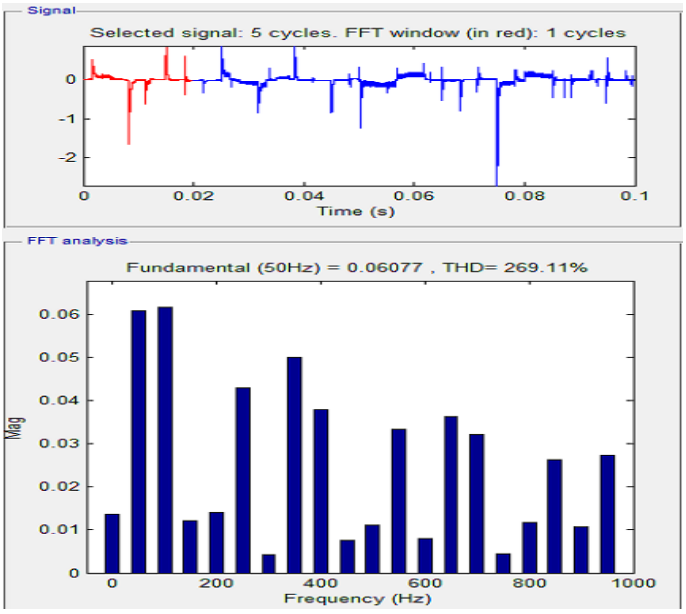

Figure 31: FFT analysis of Fixed Output 50Hz with 20Hz Input Signal.

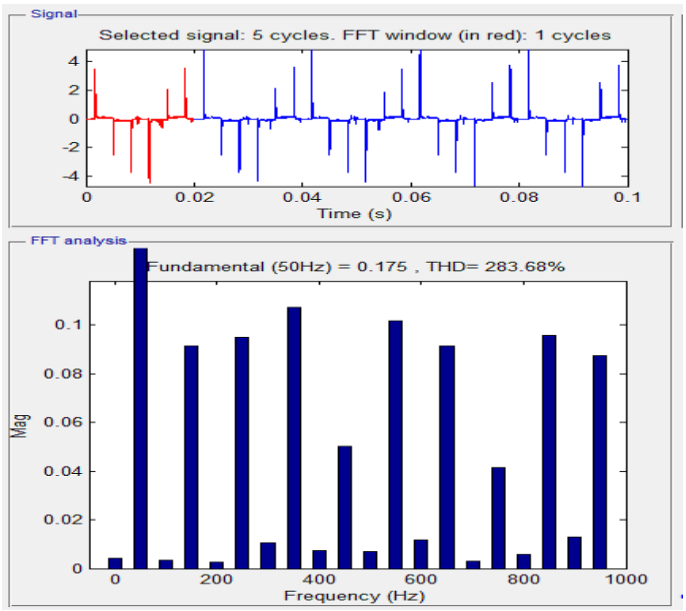

Figure 32: FFT analysis of Fixed Output 50Hz with 50Hz input Signal.

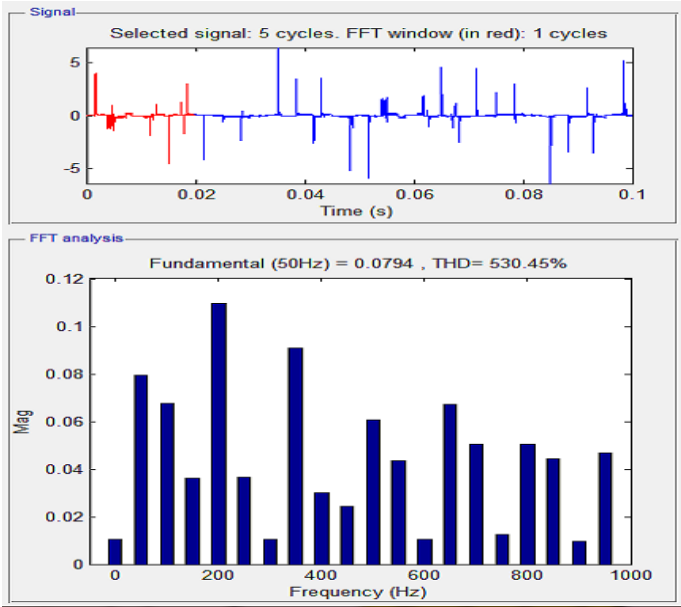

Figure 33: FFT analysis of Fixed Output 50Hz with 70Hz input Signal.

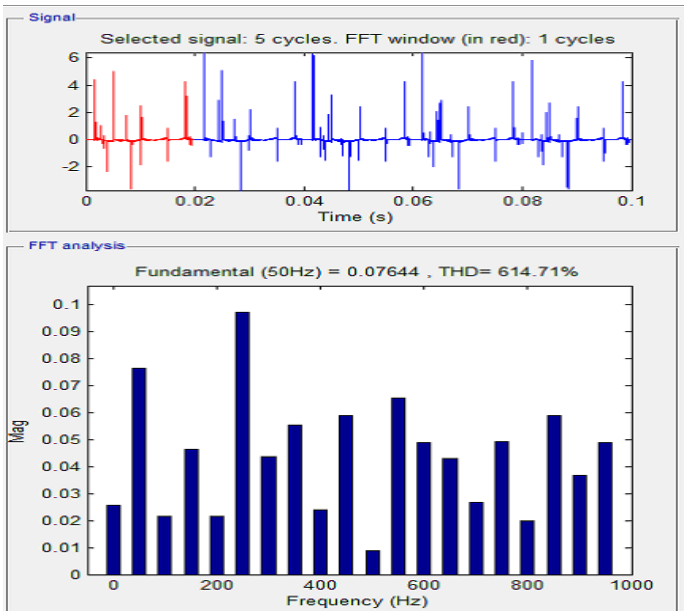

Figure 34: FFT analysis of Fixed Output 50Hz with 100Hz input Signal.

5 Conclusion

The designed model of pulse width modulation based matrix converter is simulated on Matlab. It is verified from simulation that the objectives of maximizing voltage transfer ratio and minimization of

harmonics are achieved. Any desired output voltage can be achieved irrespective of input voltage with much reduced harmonics. Changes in input voltage due to unwanted reasons or due to faults in the power generating equipments do not affect the load. In other words, this model provides an isolation between the in input and output. Changes in output voltages due to faults in the loads and deterioration of insulation do not affect the source voltages when connected via this model. Hence, the other loads connected to this source voltage are not affected. Further, this model provides low harmonic contents and any desired frequency can be achieved at the output side irrespective of input frequency with less harmonics. This objective helps to connect the variable frequency and variable speed drives via this model. Changes in the input frequency due to loss of synchronism time and again do not affect the loads as this model has the ability to not to transfer the input frequency changes at the output side. In-short, this designed model will revolutionize the implementation of matrix converters to fields of variable frequency drives, efficient controlling of power sources and loads, synchronization, insulation coordination, electric arc furnaces and welding.

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