Design of a Repetitive Controller for Matrix Converter

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Abstract

Matrix converters are an area of interest for industry nowadays as they provide AC-AC power conversion directly with desired variable frequency and magnitude without any intermediate DC-link. It is also regarded as an all silicon solution because it uses bi-directional switches array for the purpose of conversion and no energy storage links are used. High quality waveforms can be generated with minimum losses just by executing the commutation of bidirectional switches in the right way. Matrix Converters can be used in many applications such as variable frequency applications, aircraft power supply applications, induction motors, uninterrupted power supplies *etc*. Many control structures have been proposed for Matrix Converter systems such as sliding mode control, dead beat control and selective harmonic control in order to improve systems performance. Since, Matrix Converter has a high switching frequency thus distortion and periodic errors will exist in the output voltage waveform, which creates a necessity to remove such unwanted periodic errors. Repetitive control structure is most suitable for removal of periodic errors.

In this work, a repetitive controller for Matrix Converter is proposed. Main objective of a repetitive control structure is to track a periodic signal in stable closed loop by generating an extraordinary gain at periodic signal’s fundamental frequency and its multiples. Applications of repetitive controllers include PWM rectifiers/inverters, disk drive systems and robotic manipulators. Repetitive controller proves to have a good steady state performance but it is weak when its transient performance is considered, and that is why repetitive controller is equipped with a linear controller to ensure better performance in different conditions. Results of MATLAB simulation studies show that the repetitive controller proposed in this study is stable and provides exact tracking of the reference signal by the output voltage signal.

Key Words: *Matrix Converter, Repetitive controller, Linear Controller, Switching frequency, Periodic Signal Generator.*

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List of Journal/Conference Papers

- Asad Nawaz, Mohsin Jamil, Raheel Afzal, Muhammad Zubair, Arifeen Ali "Design of an Input Filter for Matrix Converter for the purpose of Harmonics Reduction" International Conference on Recent Trends in Computer Science and Electronics (RTCSE) Malaysia, 2-3 January 2017,

- Raheel Afzal, Mohsin Jamil, Adeel Waqas, Asad Nawaz, Arifeen Ali, Design and Analysis of Second Order Passive Filters for Grid Connected Inverter with Series and Parallel Damping Resistors. Indian Journal of Science and Technology, 9(21) (2016). (SCOPUS).

- Arifeen Ali, Mohsin Jamil, Muhammad Zubair, Raheel Afzal, Asad Nawaz "Design and comparison of PID and Proportional Resonant Controllers for Matrix Converter" International Conference on Recent Trends in Computer Science and Electronics (RTCSE) Malaysia, 2-3 January 2017,

CHAPTER 1

INTRODUCTION

1.1 Background, scope and motivation

With the development of controlled rectifiers in year 1930, a possibility was generated of creating variable frequency alternating currents from fixed frequency alternating currents. Positive and negative rectifiers were integrated providing positive and negative half cycles respectively. Cycloconverters were thus produced, which provided the required conversion. Because of their high power requirements, they are still being used in applications where high power is required. Basic structure of a Cycloconverter includes 36 thyristors, making it a very complicated and large structure. Usually Cycloconverters are used where high power *i.e.* 1 MW or more is required. Applications of Cycloconverters are:

- **Driving Mine Hoists.**
- **Driving Rolling Mills Motors and Cement Mills.**
- **Driving Ball Mills for the purpose of Ore Processing.**
- **Power Supplies for Aircraft.**
- **Scherbius Drives.**

A Cycloconverter, shown in Figure 1, is a combination of back to back connected two converters and is mostly used to convert a waveform of low frequency into a waveform of required frequency [1]. Alesina and Venturini described Matrix Converter for the first time in 1980, proposing its basic model and mathematical theory. Matrix Converter provides conversion of AC power directly into AC power with desired variable frequency and magnitude without any intermediate DC-link. The direct power conversion proved to be very attractive, since losses attributed to DC-link were neglected. Moreover, Matrix Converters also proved to be useful in many applications such as variable frequency applications, aircraft power supply applications, induction motors, uninterrupted power supplies *etc.* [2]. Basic structure of Matrix Converter is given in Figure 2.

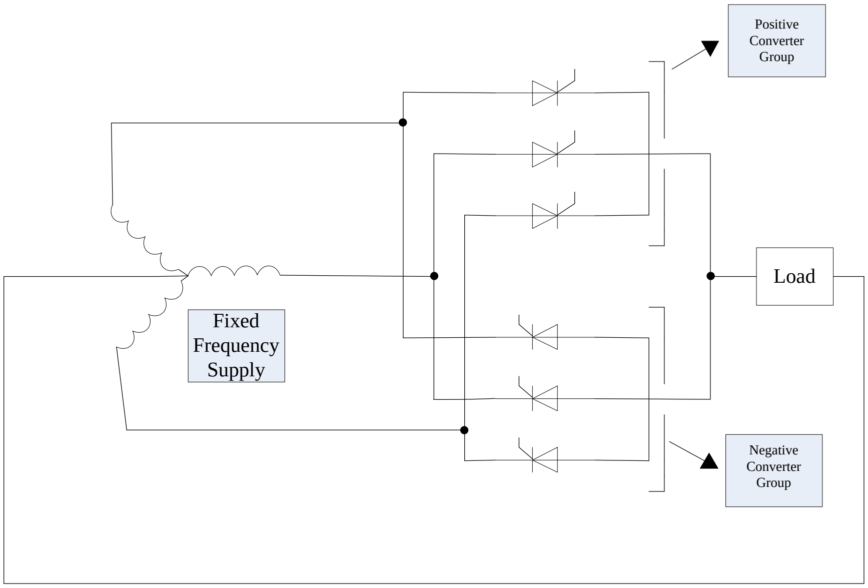


Figure 1: Basic Structure of Cycloconverter

1.2 Matrix Converter

Matrix converter provides conversion of AC power directly into AC power with desired variable frequency and magnitude without any intermediate DC-link. It is also regarded as an all silicon solution because it uses bi-directional switches array for the purpose of conversion and no energy storage links are used. High quality waveforms can be generated with minimum losses just by executing the commutation of bidirectional switches. Matrix Converters can be used in many applications such as variable frequency applications, aircraft power supply applications, induction motors, uninterrupted power supplies etc.

Alesina and Venturini described Matrix Converter for the first time in 1980, proposing its basic model and mathematical theory [3]. They also described a modulation strategy commonly known as Venturini Modulation Strategy, and also suggested a suitable control strategy for Matrix Converter. They also highlighted a limitation i-e the possible maximum input to output transformation ratio of the proposed converter to be 0.866 [4]**.** In year 1983, a new technique was introduced by Rodriguez i-e indirect transfer function technique [5]. The technique introduced was the same PWM technique used already in voltage source inverters. Moreover Space Vector Modulation strategy was first proposed by Huber and Borojevic in 1989 [6] and in year 2002 Casadei presented a modulation strategy based on Space Vector representation which provided control over both output voltage and input power factor [7].

Matrix Converter is advantageous in the sense that it has only nine bidirectional switches and has less filtering requirements. Switches are arranged like a matrix, such that at any time, any output phase and any input phase can be connected to each other. Other advantages of Matrix Converter include bi-directional energy flow capability, full control over input power factor, sinusoidal inputs and outputs and its energy requirements are extremely low thus allowing to discard costly and limited lifetime energy storage elements. There are also some limitations with Matrix Converter which include transfer ratio limited to 87% of input and output voltage in case of sinusoidal waveforms, when compared to indirect AC-AC frequency converters, Matrix Converter requires more semiconductor devices and furthermore Matrix Converter is sensitive to input voltage changes producing higher order harmonics.

1.3 Literature Review

For high power conversion applications AC to AC converters are extensively used in industry. Different converter topologies lacking a DC-link structure have been suggested in literature. Matrix converter provides AC power with desired variable frequency and magnitude without any intermediate DC-link. It uses bi-directional switches array for the purpose of conversion and no energy storage links are used. Matrix Converters can be used in many applications such as variable frequency applications, aircraft power supply applications, induction motors, uninterrupted power supplies etc.

There are many advantages of Matrix Converter over traditional AC-AC converters which include capability of bi-directional energy flow, full control over input power factor, sinusoidal inputs and outputs and its energy requirements are extremely low thus allowing to discard costly and limited lifetime energy storage elements. There are also some limitations with Matrix Converter which include transfer ratio limited to 87% of input and output voltage in case of sinusoidal waveforms, when compared to indirect AC-AC frequency converters Matrix Converter requires more semiconductor devices and furthermore Matrix Converter is sensitive to input voltage changes producing higher order harmonics [8]. Matrix Converter possesses 9 bi-directional switches in its basic structure which connects the input to output. Figure 2 shows basic structure of Matrix Converter.

After years of dedicated continuous efforts, there now exists several control and modulation strategies for Matrix Converter. Moreover, after intensive research Matrix Converter is also now used in industries. Yaskawa which produces power converters on large scales now offers Matrix Converter units for medium voltage (200-6000 KVA) and low voltage (9-114 KVA).[2]

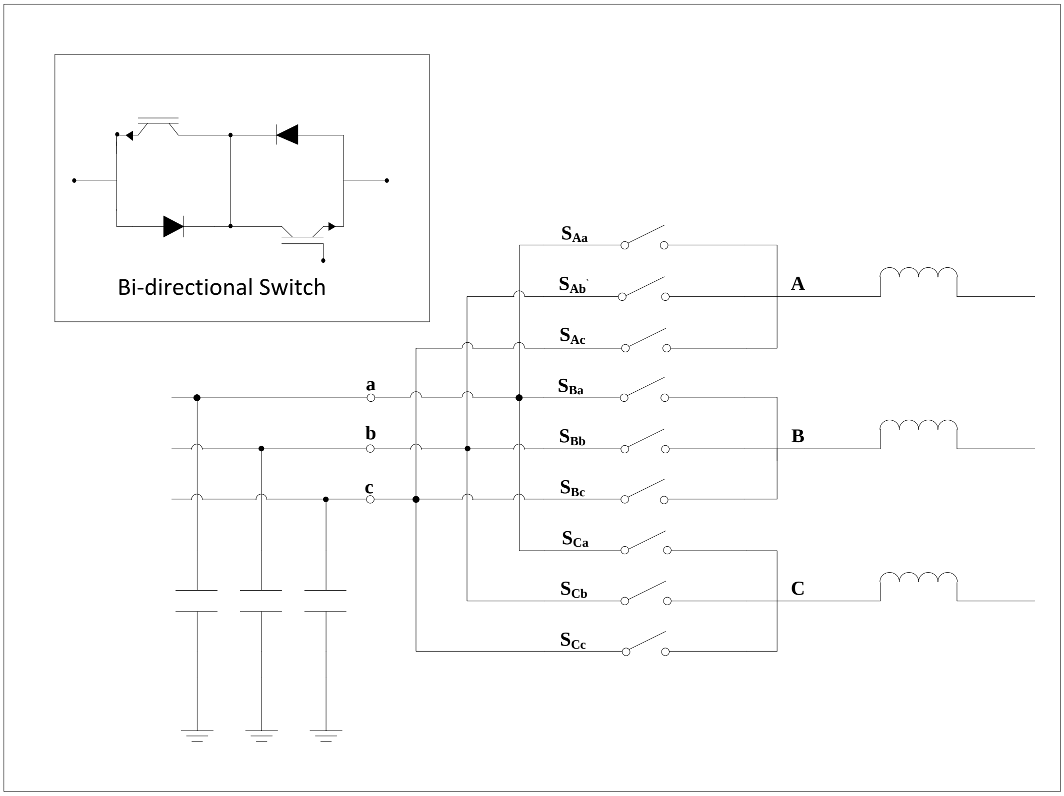


Figure 2: Matrix Converter Basic Configuration

1.3.1 Matrix Converter's Components

Major components of Matrix Converter are described in this section, such as structure of input and output filter are investigated first. Secondly basic configurations of bidirectional switches are discussed.

1.3.1.1 Input filter

Although Matrix Converter does not possess any energy storage elements and is sometimes referred to as silicon solution but it still has some reactive components comprising of input and output filters. Input filter in an interface between the converter and the input power supply. Purpose of input filter in power converters is to reduce voltage distortion at input and to improve the quality of input current. In case of matrix converter, the input filter should possess following features [9]:

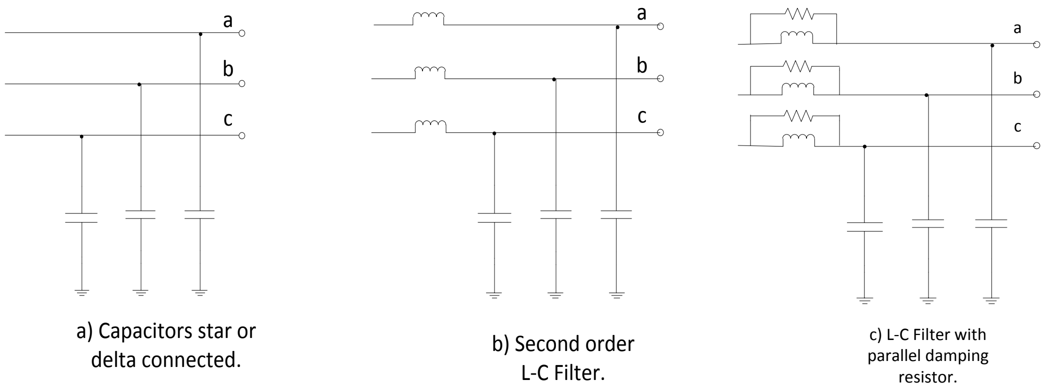
- During each PWM cycle, input filter should oppose any significant changes in the input supply.
- Undesirable harmonics should not be allowed to flow back to input power supply.
- Filter should satisfy the requirements of electromagnetic interference.

- Filter should be able to protect the converter in case transients appearing at the input side.

Design of input filter should be based on following criteria's [9]:

- Cut off frequency should be one decade higher than the supply frequency at least and one decade lower than the converters switching frequency.
- Power losses should be controlled in the damping resistor.
- Ripples in the supply current should be reduced.
- The displacement factor should be reduced between voltages of supply and those applied to converter.
- Voltage drop on the input filter inductance should be kept be low for the purpose of providing maximum voltage transfer ratio.

Different topologies of input filter for matrix converter are shown below.



a) Capacitors star or delta connected.

b) Second order L-C Filter.

c) L-C Filter with parallel damping resistor.

Figure 3: Different Topologies of Input Filter for Matrix Converter

Out of these topologies, this topology is commonly used because it possesses minimum number of components and provides better frequency response. Transfer function and figure of LCR filter (Single phase) used in this work are shown below:

$$TF = \frac{V_{out}}{V_{in}} = \frac{\left(\frac{1}{RC}\right)S + \left(\frac{r}{RLC} + \frac{1}{LC}\right)}{S^2 + \left(\frac{r}{L} + \frac{1}{RC}\right)S + \left(\frac{r}{LCR} + \frac{1}{LC}\right)} \tag{1.1}$$

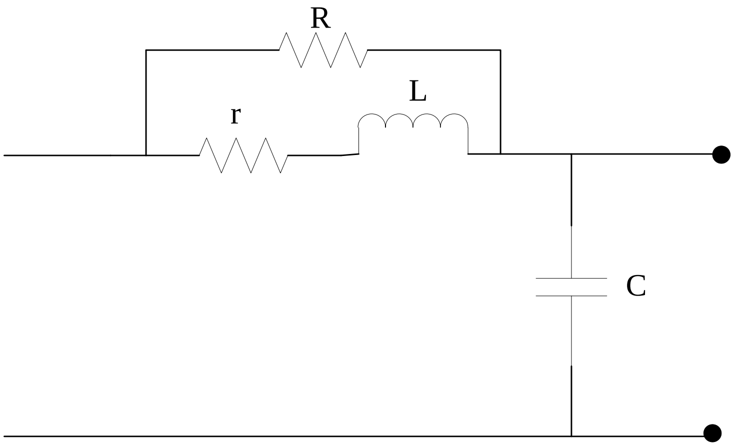


Figure 4: Input Filter of Matrix Converter (Single Phase)

1.3.1.2 Output filter

For the purpose of attenuating voltage ripples produced by the converter switching, Matrix Converter requires an output filter i-e LC filter (low pass). Matrix Converters are mostly used for power supply applications, where the converters output impedance should be close to zero so that its operation is as an ideal voltage source. For this purpose, output filter is designed so that the value of capacitor is maximized and value of inductor is kept close to zero in order to achieve a specific cut off frequency. However, very high value of capacitor may induce inrush currents to the system. Therefore, the value of capacitor must be optimized in order to get a satisfactory performance.

Figure below shows single phase circuit of the output filter. In this figure, L is the inductance, C is the capacitance and r is the internal resistance of inductance. Output filter's transfer function can be calculated from the circuit diagram of the filter. Furthermore for reducing ripples from switching frequency, a neutral inductor Ln which has a value smaller than the output inductor is used [10].

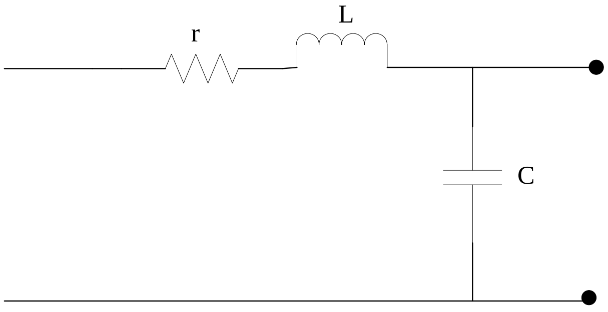


Figure 5: Output Filter of Matrix Converter (Single Phase)

Output filter's transfer function is shown below:

$$TF = \frac{V_{out}}{V_{in}} = \frac{\left(\frac{1}{LC}\right)}{S^2 + \left(\frac{r}{L}\right)S + \left(\frac{1}{LC}\right)} \tag{1.2}$$

1.3.1.3 Bidirectional switches

Working of Matrix Converter involves switches which are capable of conducting current and blocking voltage both ways. A switch with such capabilities is however still not available [5]. Thus, discrete devices combination made switches are used in Matrix Converter. Some of the bidirectional switches arrangement are discussed below with their advantages and disadvantages, which are commonly used in Matrix Converter and are proposed in literature [11] [12].

Diode bridge arrangement

This topology is the simplest structure of bidirectional switch arrangement. Structure of bidirectional switch is shown below in the figure, which shows an arrangement of diodes with IGBT at the center. A single active device is needed in this arrangement thereby reducing cost and complexity. On the other hand there are high conduction losses as there devices will be conducting simultaneously.

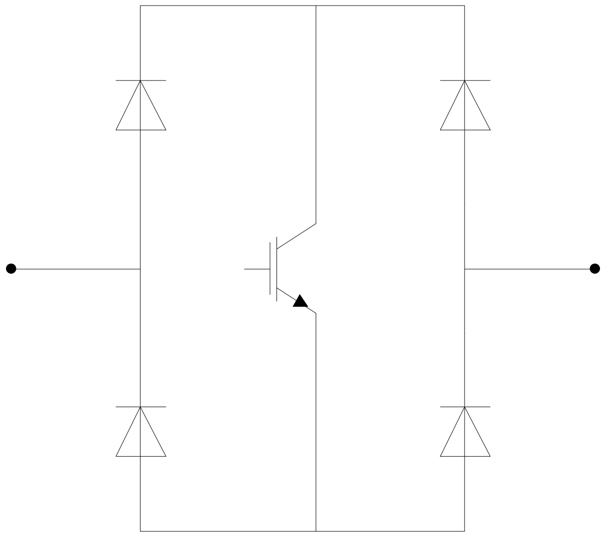


Figure 6: Diode Bridge Arrangement

Common emitter configuration

Common emitter arrangement is shown in the figure below. It is an anti-parallel arrangement of two IGBT's and two diodes. Reverse blocking capabilities are provided by diodes and at any time only one diode and one IGBT is conducting. Advantages of this arrangement include lower losses in conduction and control of current direction.

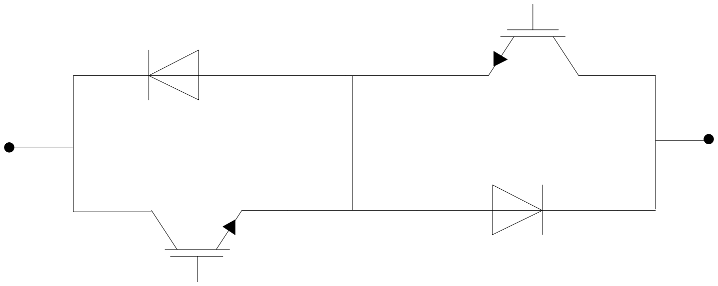


Figure 7: Common Emitter Configuration

Common Collector Configuration

Figure 8 shows Common Collector Configuration. The configuration is however not suitable for using in larger systems because of inductance problem within the commutation cells. Moreover, this arrangement also offers lower losses in conduction [5].

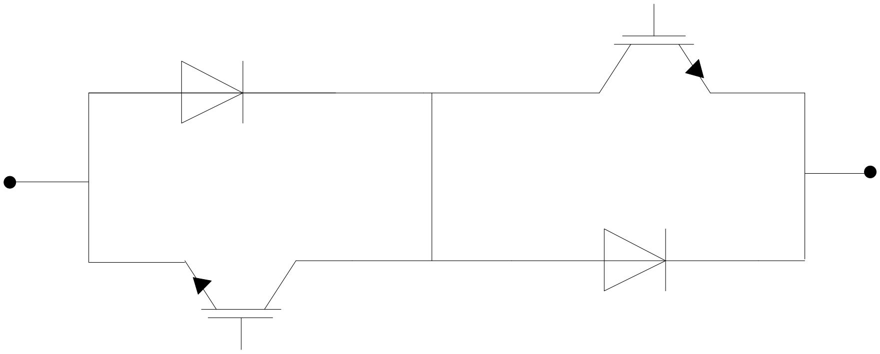


Figure 8: Common Collector Configuration

Anti-parallel reverse blocking IGBTs

Figure below shows the structure of this arrangement which is anti-parallel arrangement of two reverse blocking devices. Advantages of this configuration include higher efficiency and reduced size. But the blocking ability of IGBT's is not very effective, which makes this arrangement a bad choice for matrix converter.

Thus the configuration most suitable for use in matrix converter appears to be common emitter configuration because of lower losses in conduction and its ability to provide control over current direction [5].

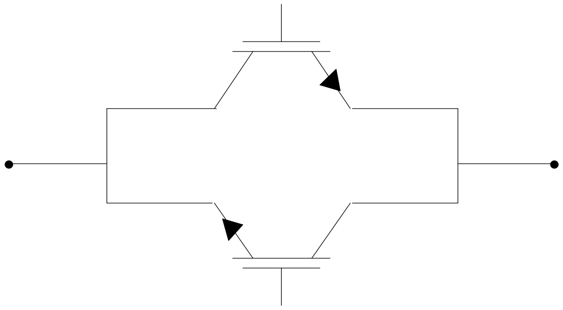


Figure 9: Anti-parallel Reverse Blocking IGBTs

1.3.3 Matrix Converter Current Commutation

Matrix Converter offers difficulty in Current Commutation because there exist no freewheeling paths for current to flow. For current commutation two rules are needed to be considered:

- Two switches of any output phase if switched on together will result in producing a short circuit, destroying the system.
- Two switches of any output phase if switched off together will result in producing an over voltage.

Simple commutation methods proposed in literature are discussed below. [13] [14]

Simple Commutation Method

There are two simple commutation methods discussed here namely dead time and overlap commutation methods.

Dead Time Commutation Method

In this method, a dead time is introduced where the inductive load current has no path, thus the snubber circuit provides an alternative path to the current. This is done by switching off the outgoing switch before the incoming switch is turned on [15].

Overlap Commutation Method

In this method of commutation, incoming switch is switched on before outgoing one is switched off resulting in short circuit between supply phases. For the purpose of limiting the current an extra line inductance is needed. Conduction losses are increased in this method as the inductors are in the conduction path [15].

1.3.4 Matrix Converter Modulation Strategies

An effective modulation strategy should minimize the harmonic distortion in the output voltage and input current, and also the power losses in the device. A number of modulation strategies are proposed for Matrix Converter in literature some of which are discussed here [16].

Methods of modulation developed for Matrix Converter which are most relevant are space vector modulation scheme, Venturini modulation scheme and the scalar modulation scheme [4][5][6].

Scalar Modulation scheme presented by Roy involves the generation of zero and active switching states of the converter. While the Venturini modulation scheme involves the generation of output voltages by the product of transfer matrix and the input voltages. Venturini modulation scheme also provides with lower harmonics for input current and output voltages. On the other hand SVM provides with lower switching losses. However, Venturini method is used in this work as it uses scaler quantities.

1.3.4.1 Space Vector Modulation (SVM)

Space Vector Modulation scheme in case of Matrix Converter is the representation of output voltages and input currents as space vectors at any time. This modulation strategy was first proposed by Huber and Borojevic in 1989 and in year 2002 Casadei presented a modulation strategy based on Space Vector representation which provided control over both input power factor and output voltage. Matrix Converter produces a set of switching states which in turn produces vectors involved in this modulation strategy. In case of basic configuration of Matrix Converter i-e 3 x 3, there exists 27 switching states [7] [17]. Representation of three phase line to neural voltages are given as:

$$V_o(t) = \frac{2}{3}(V_{oa} + aV_{ob} + a^2 V_{oc}) \tag{1.2}$$

$$i_i(t) = \frac{2}{3}(i_{1i} + ai_{2i} + a^2 i_{3i}) \tag{1.3}$$

Value of $a = e^{j\frac{2\pi}{3}}$, output phase voltages are represented by V_oa, V_ob, V_oc and input currents are represented by i_1, i_2, i_3 . The three vectors shown in the diagram below are plotted using Argand diagram. There are three vectors having a spacing of 120 degrees. Angle is represented by a_o and rotating frequency by ω_o. By producing a value that is time averaged over the switching period and by switching between adjacent space vectors, an output space vector is generated, that is required.

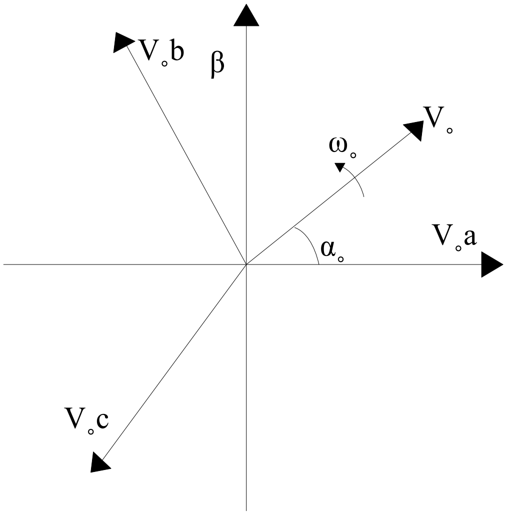


Figure 10: Balanced Three Phase SVM

1.3.4.2 Venturini's Modulation Scheme

Venturini modulation scheme was proposed by Alessina and Venturini for Matrix Converter [3] [18] [19]. The basic working of modulation is to control the bidirectional switches of matrix converter by producing train of pulses so that the input voltage with fixed frequency and amplitude can be changed into an output voltage with variable frequency and amplitude. Ratio of voltage transfer in basic Venturini modulation, was limited to 0.5 [18].

Modulation method:

Considering the modulation problem the input voltage is given as:

$$Vi(t) = \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix} = \begin{bmatrix} V_{im}\cos(\omega_i t) \\ V_{im}\cos(\omega_i t + \frac{2\pi}{3}) \\ V_{im}\cos(\omega_i t + \frac{4\pi}{3}) \end{bmatrix} \tag{1.4}$$

Whereas output current is represented as:

$$I_o(t) = I_{om}\begin{bmatrix} \cos(\omega_i t + \varnothing_o) \\ \cos(\omega_i t + \varnothing_o + \frac{2\pi}{3}) \\ \cos(\omega_i t + \varnothing_o + \frac{4\pi}{3}) \end{bmatrix} \tag{1.5}$$

Equations below shows sinusoidal input currents and output voltages, assumed considering the modulation problem

$$V_o N(t) = q.V_{im} \begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t + \frac{2\pi}{3}) \\ \cos(\omega_o t + \frac{4\pi}{3}) \end{bmatrix} \tag{1.6}$$

$$I_i(t) = q.\frac{\cos\varnothing_o}{\cos\varnothing_i} I_{om} \begin{bmatrix} \cos(\omega_i t + \varnothing_o) \\ \cos(\omega_i t + \varnothing_o + \frac{2\pi}{3}) \\ \cos(\omega_i t + \varnothing_o + \frac{4\pi}{3}) \end{bmatrix} \tag{1.7}$$

Displacements angles of output and input are represented by Ǿo and Ǿ$_i$, frequencies of the input and output are given by ω_i and ω_o respectively, whereas q represents the voltage transfer ratio. Modulation matrix M(t) is to found which appears to be foremost objective of this modulation problem.

Main objective here is to determine modulation matrix M(t). Venturini proposed two solutions for this modulation problem which are given below:

For

$$\omega_m = \omega_o - \omega_i$$

$$[M1(t)] = \frac{1}{3} \begin{bmatrix} 1+2q\cos(\omega_m t) & 1+2q\cos(\omega_m t - \frac{2\pi}{3}) & 1+2q\cos(\omega_m t - \frac{4\pi}{3}) \\ 1+2q\cos(\omega_m t - \frac{4\pi}{3}) & 1+2q\cos(\omega_m t) & 1+2q\cos(\omega_m t - \frac{2\pi}{3}) \\ 1+2q\cos(\omega_m t - \frac{2\pi}{3}) & 1+2q\cos(\omega_m t - \frac{4\pi}{3}) & 1+2q\cos(\omega_m t) \end{bmatrix} \tag{1.8}$$

For

$$\omega_m = \omega_o + \omega_i$$

$$[M1(t)] = \frac{1}{3}\begin{bmatrix} 1+2q\cos(\omega_m t) & 1+2q\cos(\omega_m t-\frac{2\pi}{3}) & 1+2q\cos(\omega_m t-\frac{4\pi}{3}) \\ 1+2q\cos(\omega_m t-\frac{2\pi}{3}) & 1+2q\cos(\omega_m t-\frac{4\pi}{3}) & 1+2q\cos(\omega_m t) \\ 1+2q\cos(\omega_m t-\frac{4\pi}{3}) & 1+2q\cos(\omega_m t) & 1+2q\cos(\omega_m t-\frac{2\pi}{e}) \end{bmatrix} \quad (1.9)$$

For the first solution the Φi and Φo are same so the input and output has same phase displacement. For the later solution as given above as both Φi= -Φo thus giving the input phase a reverse order. Combination of both solutions gives us the control of input displacement exact means.

Here $\alpha 1 + \alpha 2 = 1,$

$$[M(\mathrm{t})] = \alpha_1[M1(t) + \alpha_2[M2(t)] \quad (1.10)$$

By putting the α1 and α2 equal, the convert’s input displacement factor is 1 at its terminals. By putting α1 and α2 of any combination of leading or lagging will have similar impacts at the output power factor.

$$mkj = \frac{tkj}{T_{sequence}} = \frac{1}{3}(1+\frac{2VkVj}{V^{2}{}_{im}}) \quad (1.11)$$

k= A, B, C and j= a,b,c.

The average of input voltage is represented in the equation Vim as shown above.

The targeted voltage for the output side is achieved by taking the sequence of switching so as to achieve the average output voltage. The hypothetical envelop of voltage at input side is the guide to achieve the output voltage so as to fit into that envelop. This gives the ration of 0.5 for input over output in this condition which is increased in the optimum Venturini modulation technique. The purpose behind the development of this technique into optimum Venturini was actually the low transfer ratio between the output and input voltages magnitude represented by Q here.

Venturini Optimum Solution

In this method basically the targeted output voltage is achieved by the inclusion of third harmonics that are presented in the frequencies of both output and input sides. This technique is called common mode addition technique as explained. The equation previously described is given as below which is modified by inclusion of third harmonics.

$$V_o(t) = QV_{im} \begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t + \frac{2\pi}{3}) \\ \cos(\omega_o t + \frac{4\pi}{3}) \end{bmatrix} \tag{1.12}$$

By this inclusion and changes involved the 0.866 is maximum value of the ratio between output and input voltages magnitude that can be achieved.

1.3.5 Control of Matrix Converter

Digital controllers offer certain advantages over analogue controllers when implemented in the field of power supplies with switch mode. Some of those advantages are mentioned below:

- Implementation of highly complex control structures and the ability to reprogram the control structure, which is a difficult task in case of analogue controllers.
- Digital controllers provide attractive features such as variations in parameters, signal handling and dealing with nonlinearities.
- Cost of digital controllers is experiencing reduction continuously and on the other hand computation power of digital circuits is on a rapid increase.
- Digital controllers do not have any ageing effects.

CHAPTER 2

CONTROL OF MATRIX CONVERTER

2.1 Introduction

This chapter aims to present design of a control system for Matrix Converter for the purpose of regulating the output voltage. Firstly this chapter describes design of a second order linear controller which acts as a basis for repetitive controller and also provides stability to the output voltage. Secondly repetitive control and its implementation in plug-in mode is discussed in detail.

2.2 Repetitive Control

Advancement in electronic systems require more efficient and effective control methods to fulfill certain requirements and specifications, which cannot be fulfilled by previously used classical control approaches. Thus new control structures have been proposed in order to enhance performance of systems and to achieve a stable control quality and accurate tracking. For the purpose of removing periodic disturbances, repetitive control structure proves to be highly effective. Wonham and Francis presented internal model principle in 1976 which later became an integral part of repetitive control. Internal model principle states that a controller can track any periodic signal which has a time period T, if the controller contains the structure of disturbance within itself. In year 1980, Inoue proposed repetitive control for the purpose of tracking a repetitive periodic signal with a specific time period, in continuous domain for Single Input and Single Output plants. In year 1981, this proposed concept got practical implementation in proton synchrotron magnet power supply [20] [21]. Main objective of a repetitive control structure is to track a periodic signal in stable closed loop by generating an extraordinary gain on periodic signal’s fundamental frequency its multiples. Applications of repetitive controllers include PWM rectifiers[26][27][28] and inverters[22][23][24] 25], Disk Drive Systems[29][31], Robotic manipulators[32].

Repetitive Control Structure consists of three major components i-e Periodic Signal Generator (Internal Model), Delay Compensator and Low Pass Filter. Periodic signal generator reduces steady state error, compensator ensures better performance during transient state while low pass filter increases robustness of the system. Literature suggests that repetitive controller has three different types i-e Ordinary Repetitive Controller, Plug-in Repetitive Controller and Parallel Repetitive Controller.

Repetitive controller functions by discarding errors signals that are periodic in nature. Steady state performance of repetitive controllers is excellent however they provide a poor transient performance. To achieve an overall better performance repetitive controller is used in combination with a second order linear controller.

2.3 Fundamental Components of Repetitive Controller

2.3.1 Internal Model Principle/Periodic Signal Generator

Internal model principle states that a controller can track any periodic signal which has a time period T, if the controller contains the structure of disturbance within itself. Figure below shows structure of disturbance added to a controlled system [33].

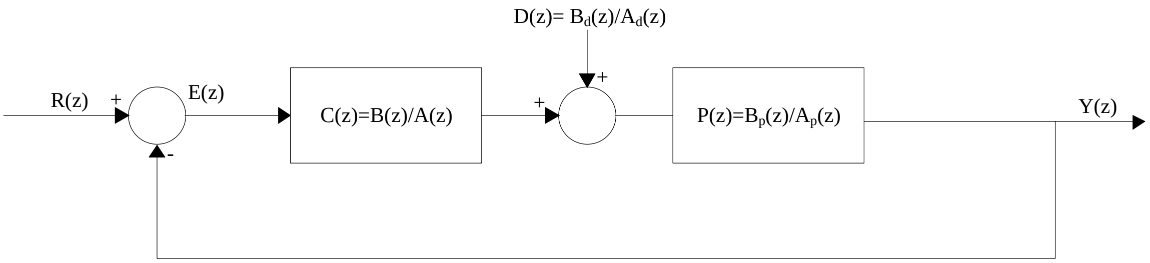


Figure 11: Incorporating of Disturbance into a Controlled System

Where R(z) is the reference signal, E(z) is the error signal, C(z) is the controller, D(z) is the disturbance, P(z) is the plant and Y(z) is the output signal.

1. Conditions of Internal Model Principle to achieve stability:

- The controller C(z) has to contain mod of disturbance D(z).
- Numerator of plant Bp(z) and denominator of disturbance Ap(z) should not have common roots.

Basic repetitive controller consists of a periodic signal generator, which uses a positive feedback loop and is a forward time delay chain [34].

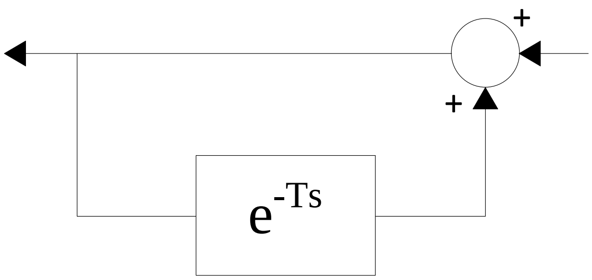


Figure 12: Counter Disturbance Generator Continuous Time

Basic periodic signal generator’s transfer function and block diagram in discrete time is given below:

$$G_R(z) = \frac{z^{-N}}{1 - z^{-N}} \tag{2.1}$$

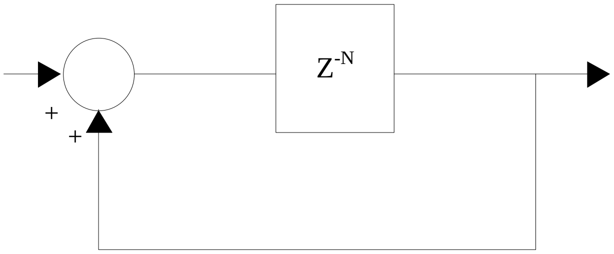


Figure 13: Counter Disturbance Generator Discrete Time

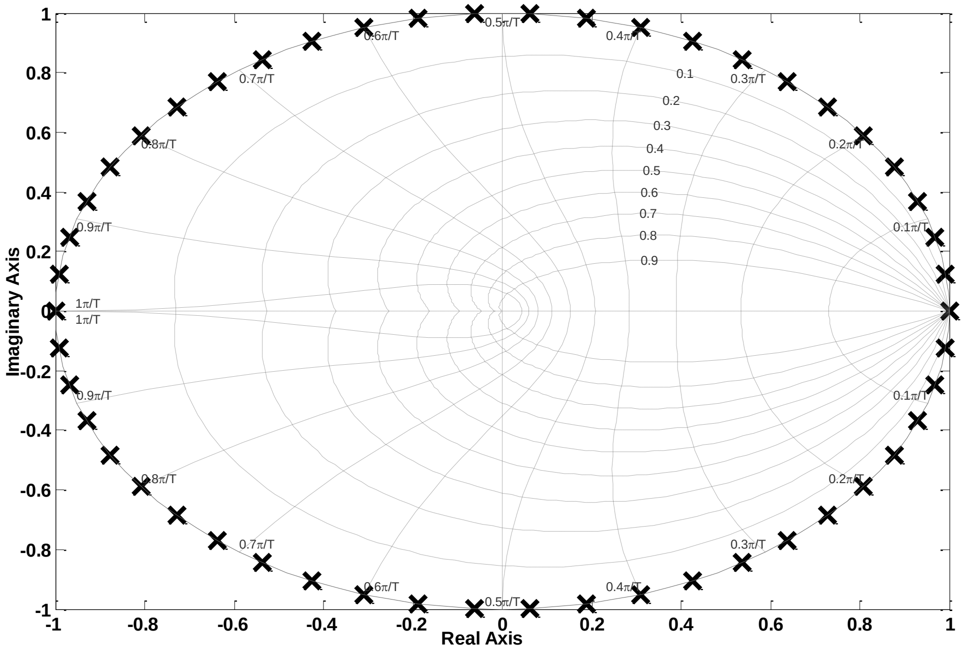


Figure 14: Pole Zero Map of an Internal model with N=50

N represents the ratio of fundamental and sampling frequency. For example if sampling frequency is 5 kHz and fundamental frequency is 50 Hz then

$$N = \frac{Sampling\ Freq}{Fundamental\ Freq} = \frac{5000}{50} = 100 \tag{2.2}$$

System's frequency response when Sampling frequency = 5000 and Fundamental frequency =50 Hz is shown in Figure 19.

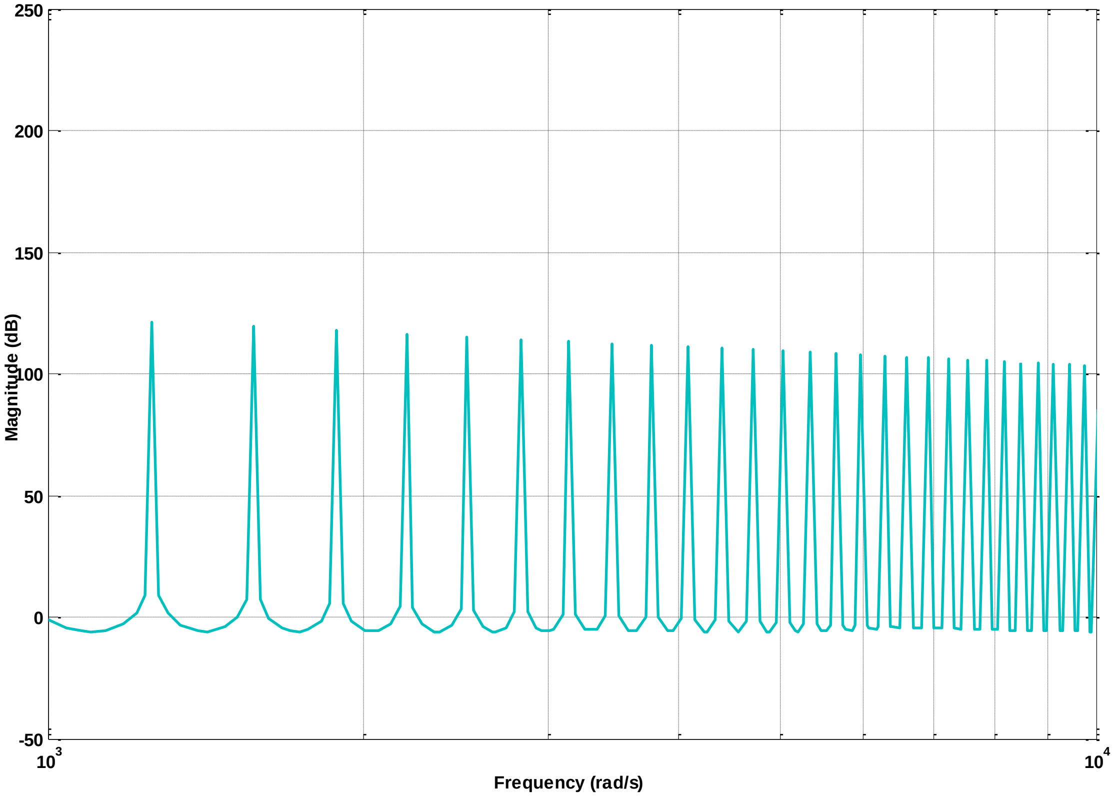


Figure 15: Frequency Response of a Counter Disturbance Generator.

Figure 15 shows that a high gain is produced by periodic signal generator on fundamental and harmonic frequencies, thereby reducing the error in output voltage to zero when operating in steady state conditions.

Structure of Disturbance

Here in this work we are rejecting only periodic disturbances with the help of Repetitive control technique, therefore structure of periodic disturbance should be known and is given as $1 - z^{-N}$.

Counter Disturbance

- If basic structure of controller is C(z)=Bc(z)/Ac(z), then it should create a counter disturbance C(z)=Bc(z)/Ac(z)Ad'(z) for cancelling disturbance which is illustrated in Figure 13 [34].

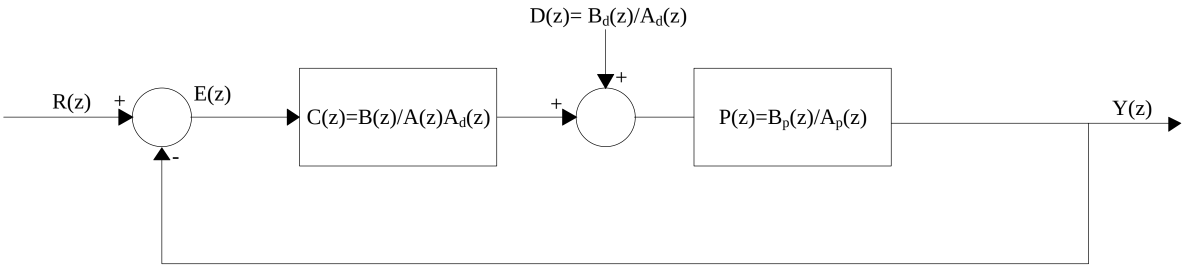


Figure 16: Creation of Counter Disturbance in Controller

2.3.2 Delay Compensator

Delay compensator is introduced in repetitive control structure in order to eliminate phase error. System losses stability if there exists a phase lag of 180 degree between the converters output voltage signal and the controllers signal. Thus to avoid instability we introduce a delay compensator such that it compensates for the phase lag. A simple delay compensators value is calculated through experiments which consist of lead step Z^D. Number of samples of delay compensator is represented by D, which can be calculated as:

$$D = \text{Phase difference} * \frac{\text{Delay points in a cycle}}{360^o} \tag{2.3}$$

2.3.3 Digital Low Pass Filter

Digital Low pass filter is an integral part of repetitive control providing stability to the control structure. Main function of the filter is to extinguish higher order harmonics ensuring stability to the controller. General form of a first order filter is represented as:

$$Q(z) = a_1 z^{-1} + a_0 + a_1 z^1 \tag{2.4}$$

For improving the overall performance of system, a low pass filter is equipped with Repetitive Controller. During the stability analysis it was seen that the proposed converter is very sensitive, due to the fact that the poles of plant are on the margin of unit circle. Thus different internal models conventionally used in literature were analyzed below [35].

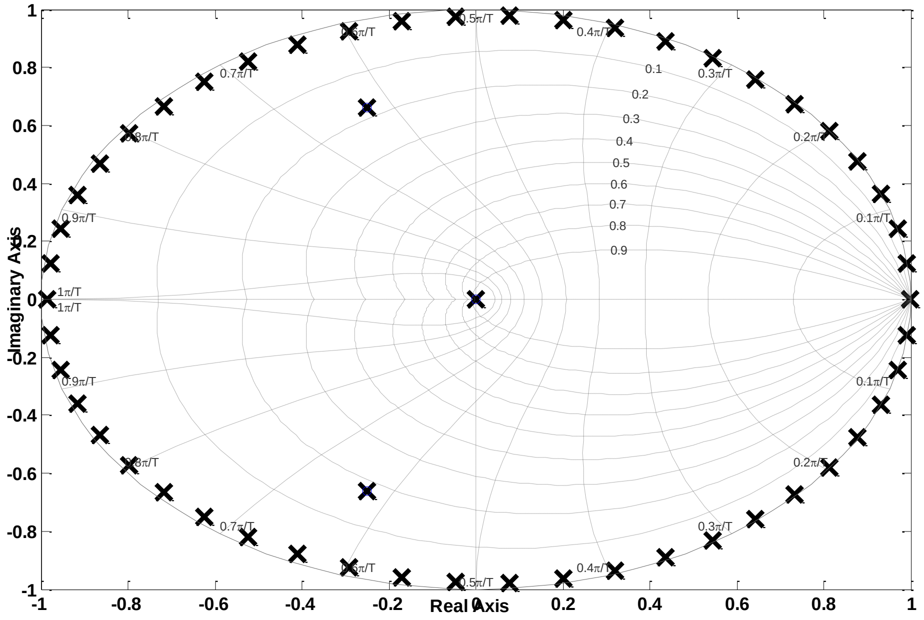


Figure 17: Pole Zero Map of an Internal model with N=50 using digital filter $F(z) = 1/4z^{-1} + 1.2 + 1/4z^{1}$

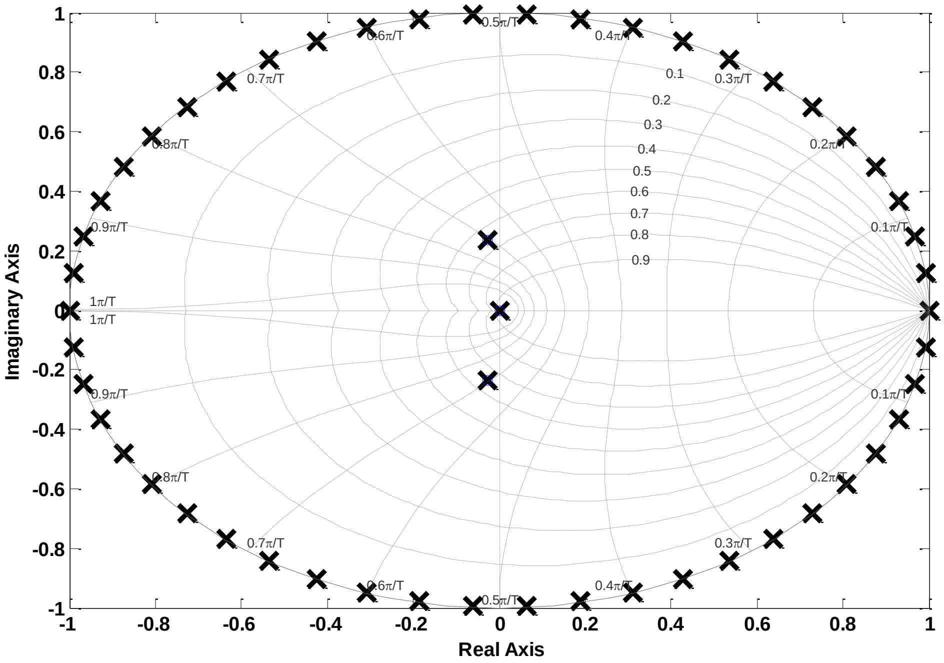


Figure 18: Pole Zero Map of an Internal model with N=50 using digital filter $F(z) = 0.9+0.05z^{-1} + 0.05z^{1}$

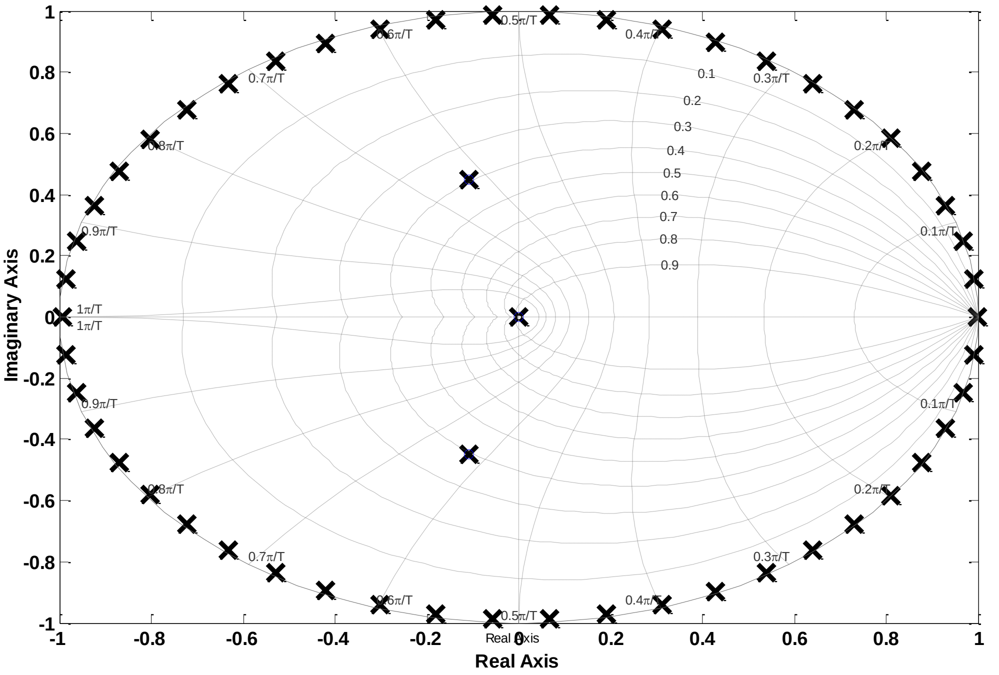


Figure 19: Pole Zero Map of an Internal model with N=50 using digital filter $F(z) = 0.7+0.15z^{-1}+ 0.15z^{1}$

2.4 Classification of Repetitive Control

There are three types of repetitive controllers namely parallel, plug in and ordinary repetitive control structure. All structures are shown below such that Gc(z) is the classical controller, Gp(z) is the plant, R(z) represents reference signal, E(z) represents error signal and the output signal is represented by Y(z).

2.4.1 Parallel Structure

In this type, repetitive controller is installed with classical controller in parallel as shown in Figure 20. Classical controllers can be PI or PID which provide the required dynamic performance whereas parallel repetitive control enhances steady state response of the system [36].

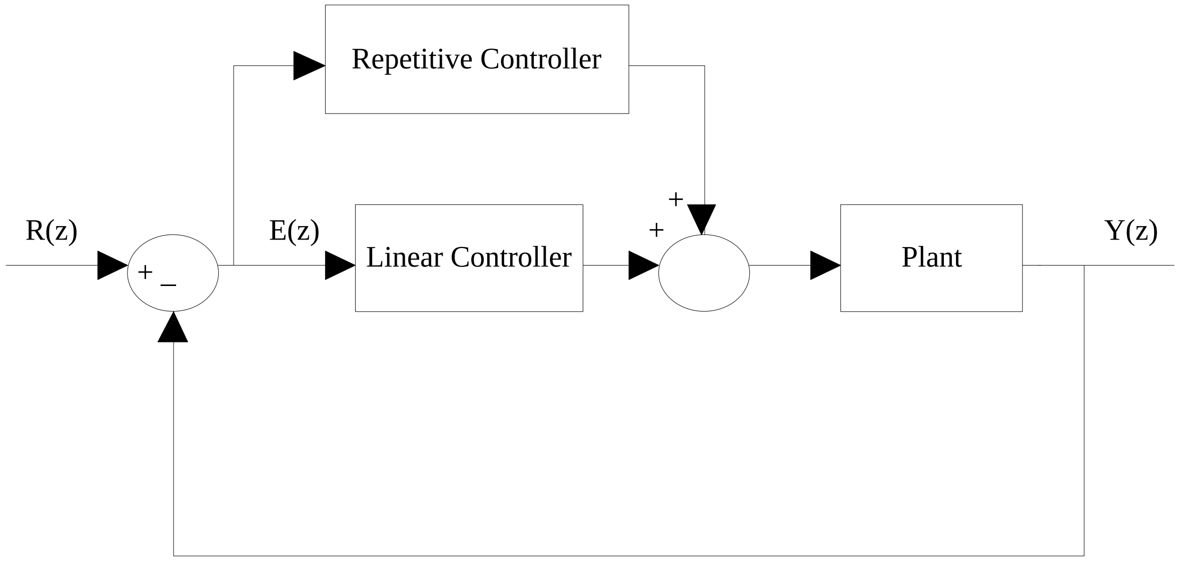


Figure 20: Parallel Structure

2.4.2 Plug in Structure

Plug in repetitive controller is easy to apply as it implemented without disturbing the existing controller. Repetitive controller is placed such that its output and error signal sum up to constitute input of classical controller. Plug-in Repetitive Control provides direct alteration on the error signal thus it has proven to be more effective than other types of repetitive controller. Therefore due to these attractive features Plug in Repetitive Control is preferred for use in this work.

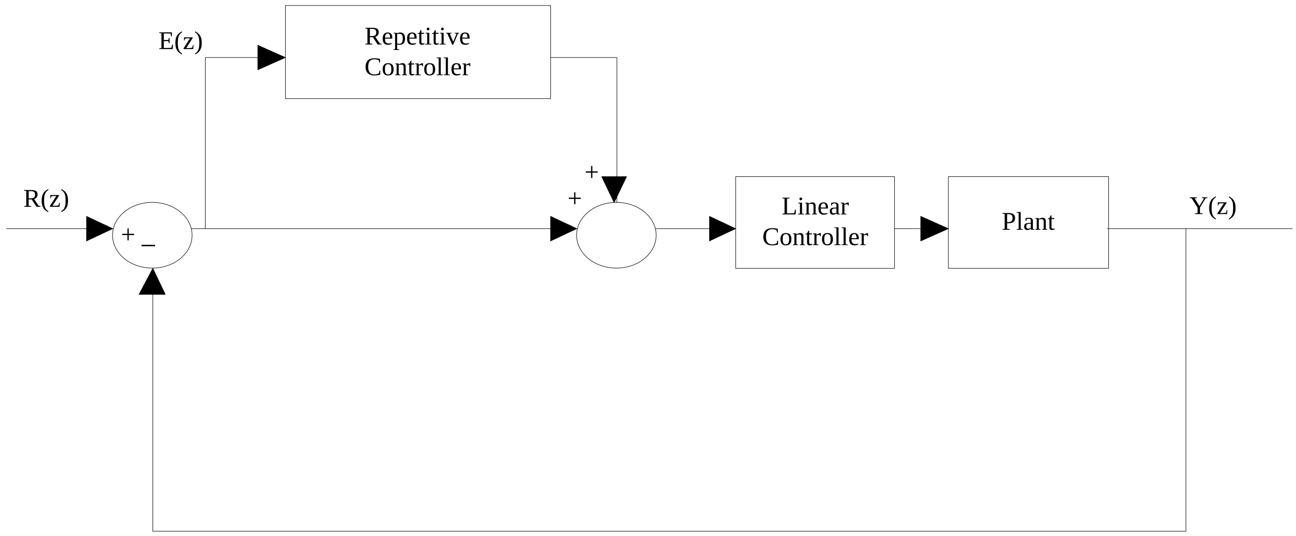


Figure 21: Plug in Structure

2.4.3 Ordinary Structure

Ordinary structure consists of a repetitive controller connected directly to the plant and it requires the plant to be non-minimum phase and stable [37].

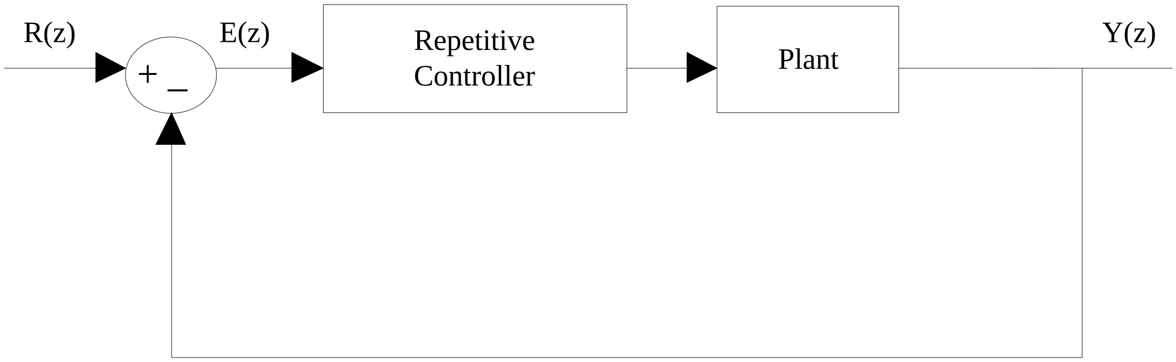


Figure 22: Ordinary Structure

2.5 Modeling of Matrix Converter

For the selection of appropriate control approach, modeling of system is an important step. In case of Matrix Converter, the plant which needs to be controlled is load and output filter. When designing control, one must try to satisfy the worst case scenario, thus in this case worst case scenario appears to be no load condition. Therefore output filter can be considered as the plant to be controlled, as it virtually will have no damping. Equivalent circuit of single phase output filter and transfer function of output filter is given below:

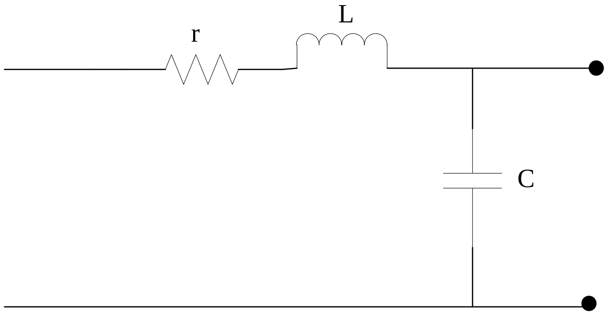


Figure 23: Equivalent Circuit of Single Phase Output Filter

$$TF = \frac{V_{out}}{V_{in}} = \frac{\left(\frac{1}{LC}\right)}{S^2 + \left(\frac{r}{L}\right)S + \left(\frac{1}{LC}\right)} \tag{2.5}$$

Output voltage of Matrix Converter contains a lot of harmonics. For the removal of harmonics and to obtain a sinusoidal waveform, an output filter (low pass) is required to remove high frequency components. The output filter is modeled such that its cut off frequency is kept considerably lower than switching frequency of Matrix Converter.

Output filters inductor, capacitor have internal resistances. Moreover bidirectional switches of Matrix Converter possess conduction losses. These losses mentioned above are all represented by a resistance installed in series with output filter inductor.

2.6 Tracking Controller Design for Matrix Converter

For an initial stability analysis of system a second order linear controller is designed in Matlab.

Considering the output filter of Matrix Converter as the plant, design of controller is done using root locus method. Analysis of output filter shows that there exists two oscillatory poles, and these poles need to be replaced by desired poles for the purpose of suppressing resonant peak. Hence to cancel these undesired poles, pole zero cancellation method used. Matlab simulations and stability analysis is also provided. Plant parameters and transfer function in z-domain is shown below. Transfer function was converted into discrete form, using zero order hold method.

Table 1: Plant Parameters

Resistance (Ω)	0.2
Capacitance (μF)	35
Inductance (μH)	583

$$TF = \frac{V_{out}}{V_{in}} = \frac{\left(\frac{1}{LC}\right)}{S^2 + \left(\frac{R}{L}\right)S + \left(\frac{1}{LC}\right)} \tag{2.6}$$

$$Gp(z) = \frac{0.06029z + 0.05995}{z^2 - 1.863343z + 0.983} \tag{2.7}$$

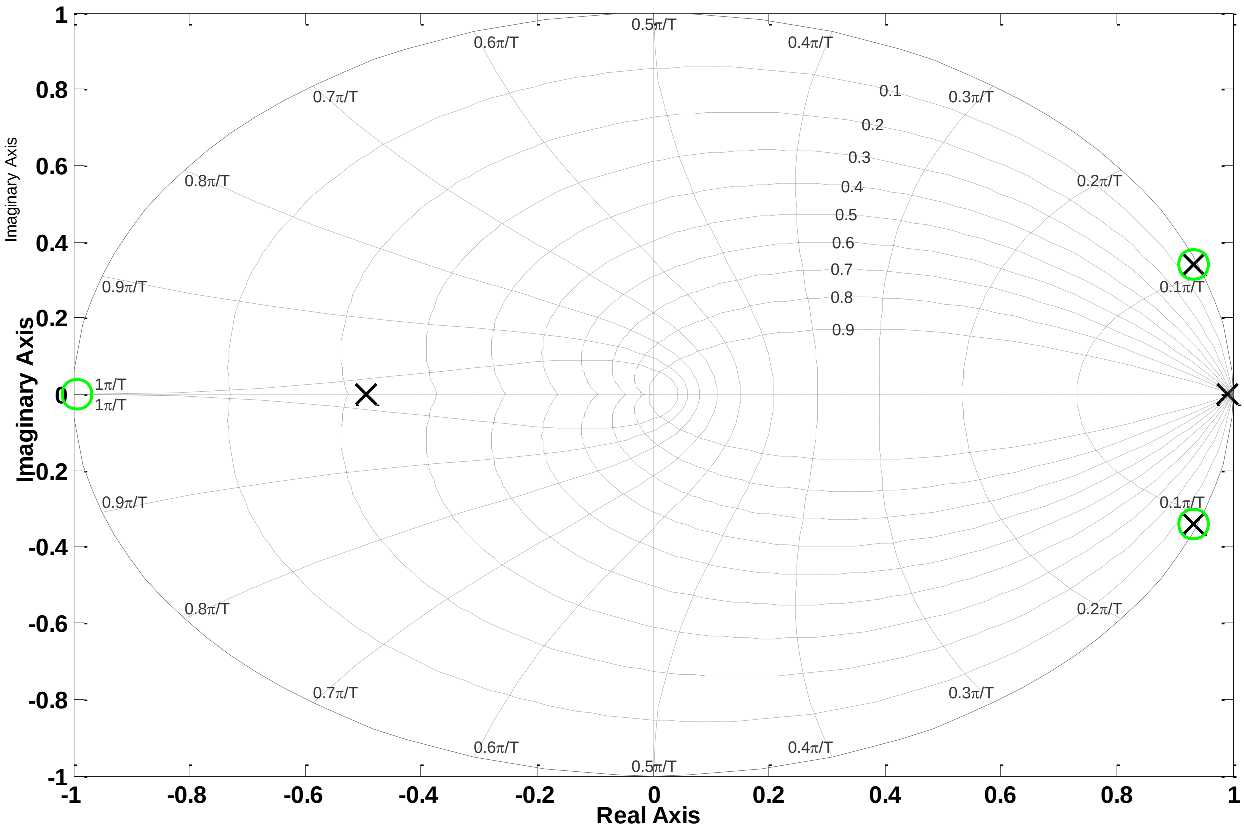


Figure 24: Open Loop System Root Locus

Desired poles shown in the figure are found using Matlab Sisotool found. Pole locations are P1= -0.51 and P2 = 0.998. Value of Kp is selected as 0.13. Tracking controller Gc(z) is therefore calculated to be:

$$Gc(z) = 0.13 * \frac{z^2 - 1.863z + 0.983}{z^2 - 0.495z - 0.49} \qquad (2.8)$$

Single phase closed loop system is shown below in Figure 25 which incorporates the tracking controller Gc(z) found above and Figure 26 shows the tracking of reference signal by output voltage signal.

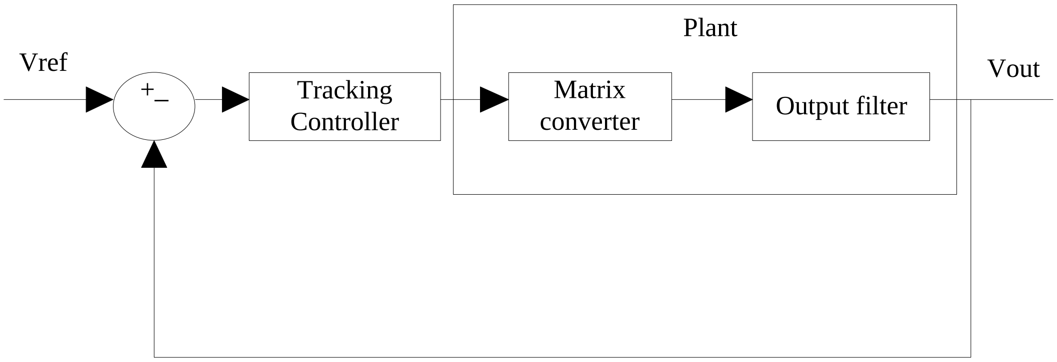


Figure 25: Simplified Diagram of Single Phase Closed Loop System

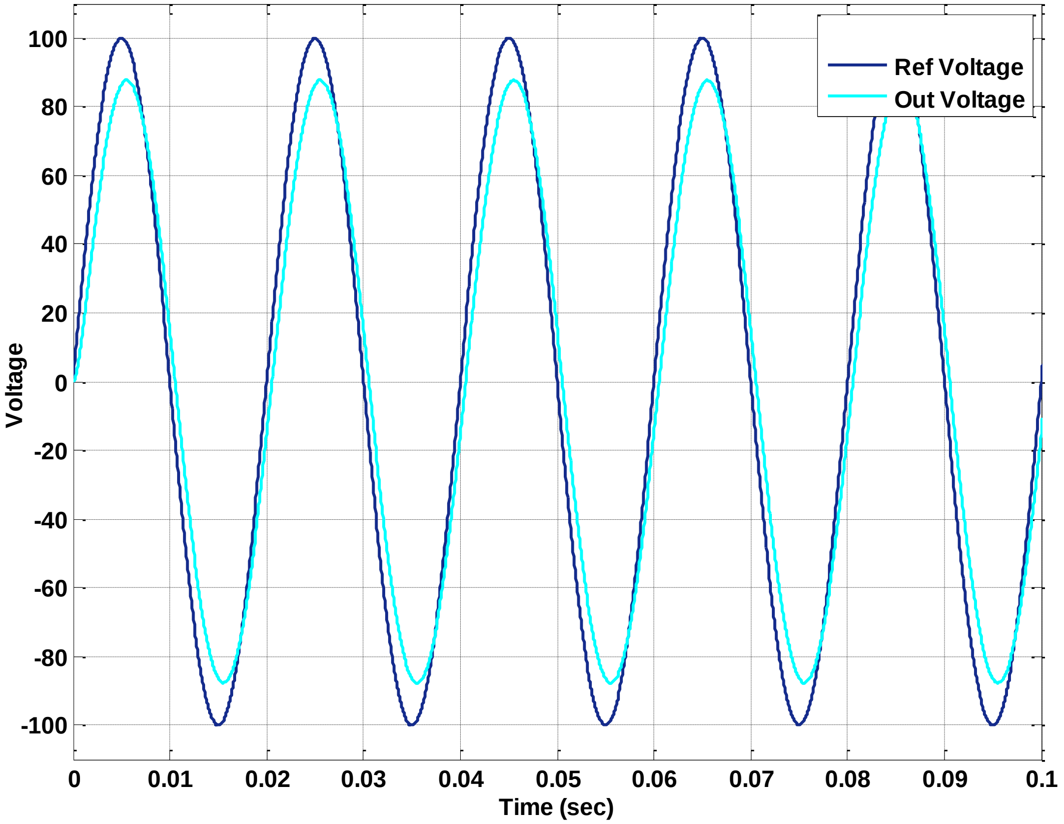


Figure 26: Comparison of Output Voltage Response Vs Reference Voltage Signal

The bode plots of plant with the controller and without it are shown below.

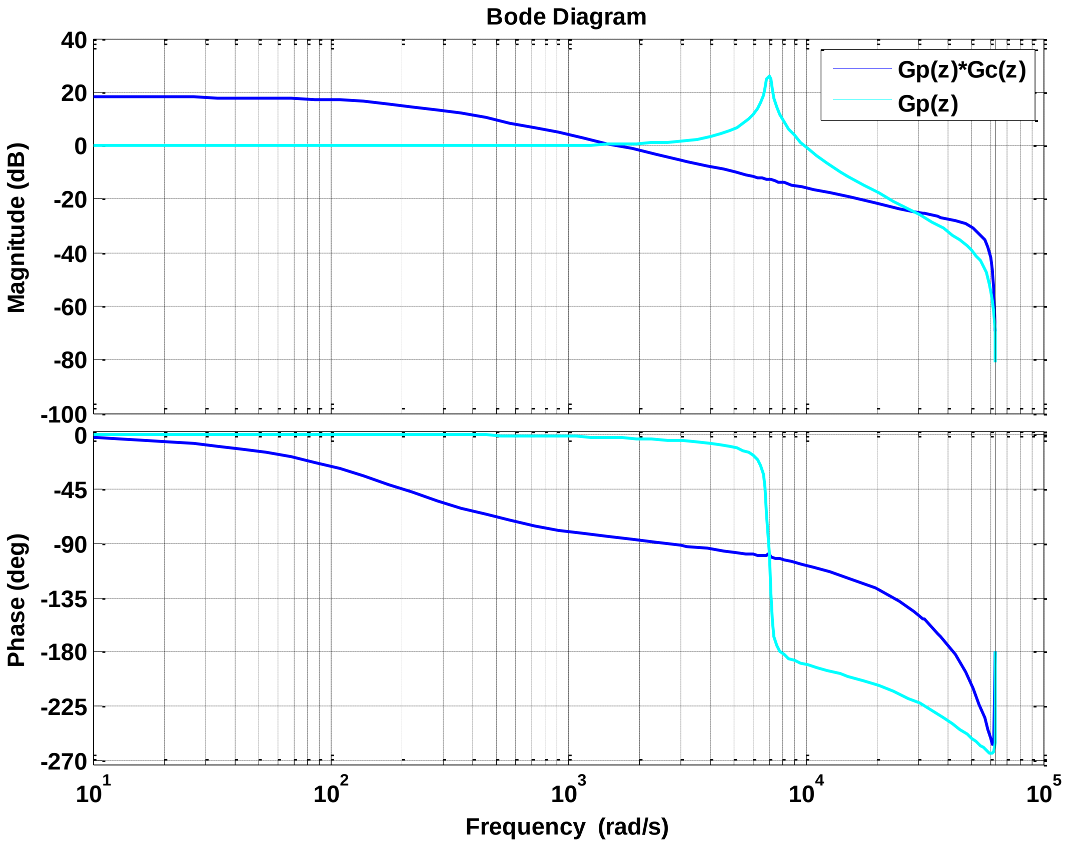


Figure 27: Bode Plot of Open Loop Response Vs Plant Response

Analysis of bode plots suggest that system is stable but there exists a 95º phase shift between signal of output voltage and reference signal. Furthermore phase and amplitude error are detected when reference signal is compared to voltage signal of phase A, which is shown in figure 14. For the purpose of overcoming the problems mentioned above, a repetitive controller can be used.

2.7 Transfer Function of Overall System

For the purpose of reducing periodic error and enhancing systems performance, a repetitive controller is proposed here in plug in mode. Figure 28 shows Repetitive Controllers block diagram.

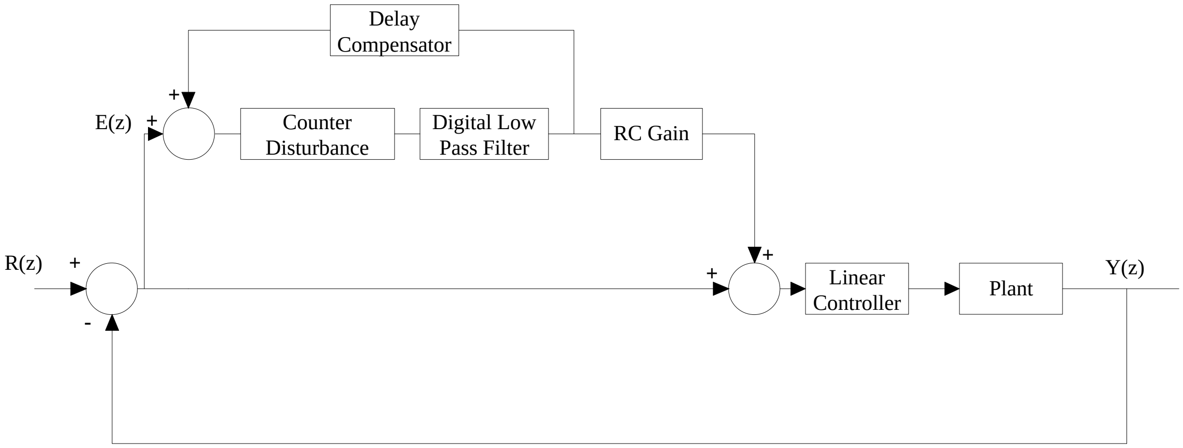


Figure 28: Structure of Plug-in Repetitive Control Integrated with Conventional Controller and System

Where E(z) is the error signal, R(z) is the reference signal and Y(z) is output voltage signal. Transfer function of prototype repetitive controller[38]:

$$G_R = \frac{K.z^{-N}}{(1-z^{-N})} \tag{2.9}$$

G_R is Repetitive Controller, K is RC Gain and z^{-N} is delay compensator.

Transfer function of repetitive controller in plug-in mode is given below:

$$G_R(z) = \frac{Z^{-N}.F(z).K}{1-Z^{-W}.F(z)} \tag{2.10}$$

Where F(z) is the digital filter. Furthermore transfer function of complete closed loop system is given below:

$$TF = \frac{G_C(z)G_P(z)(1+G_R(z))}{1+G_C(z)G_P(z)(1+G_R(z))} \tag{2.11}$$

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Design of Repetitive Control

Finally repetitive control structure proposed, is implemented using MATLAB Simulink.

3.1.1 System Parameters

Simulations were performed using the following parameters[39]:

Table 2: System Parameters

Input Amplitude	100
Switching Frequency	20 KHz
Sampling Time	50×10^{-6}
Input Voltage Frequency	50 Hz
Output Filter Inductor	583 μH
Output Filter Capacitor	35 μF
Output Amplitude	100
Fundamental Frequency	400 Hz

3.1.2 Periodic Signal Generator

Periodic signal generator is added for the purpose of countering the periodic disturbance present in the system. It is a forward time delay chain as discussed earlier. Periodic signal generator's inclusion in the loop ensures exact tracking of the reference signal by rejecting disturbances. Its transfer function is given below:

$$G_R(z) = \frac{z^{-N}}{1 - z^{-N}} \tag{3.1}$$

N represents the ratio of fundamental and sampling frequency.

$$N = \frac{Sampling\ Freq}{Fundamental\ Freq} = \frac{20000}{400} = 50 \tag{3.2}$$

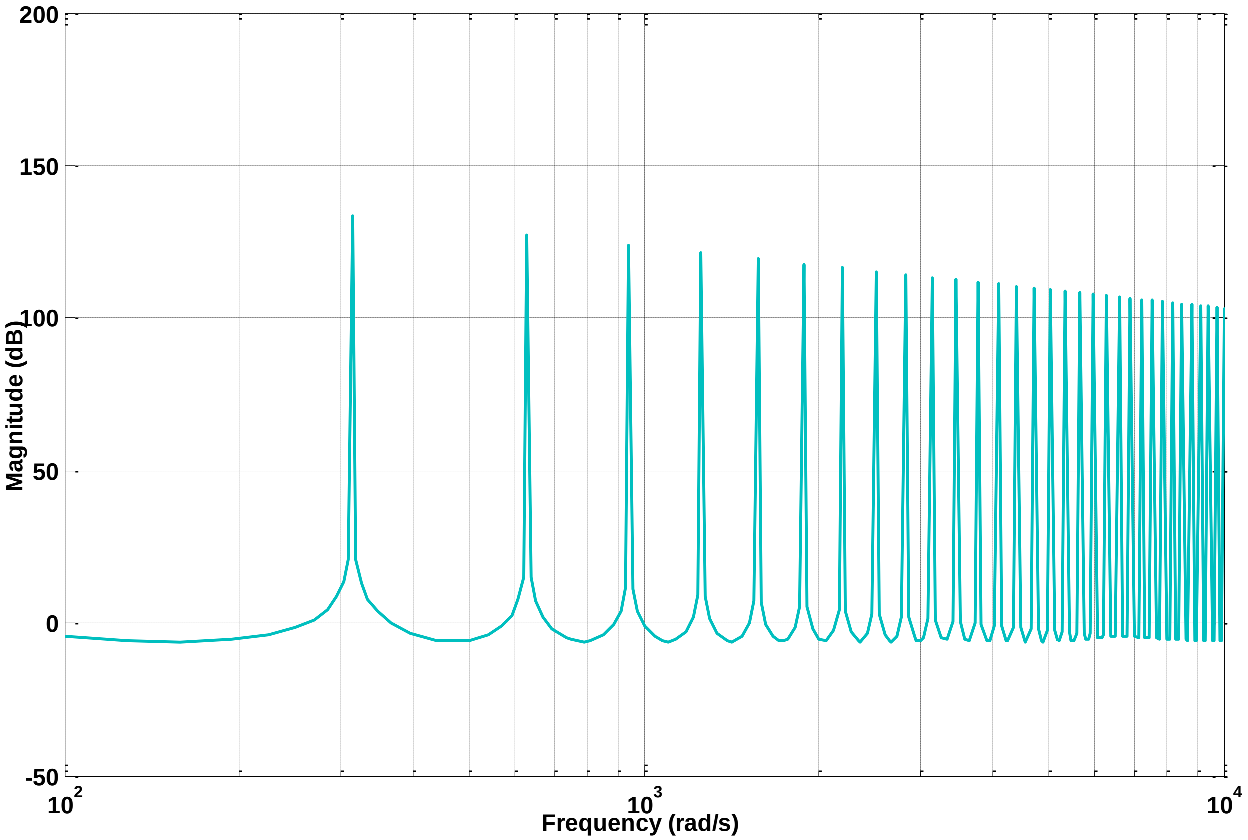


Figure 29: Frequency Response of the Periodic Signal Generator with N=50

Figure 22 shows bode plot of periodic signal generator which demonstrates gain being is introduced at fundamental frequency and integer multiples of fundamental frequency.

3.1.3 Design of Delay Compensator

As discussed earlier while observing the action of classical controller Gc(z) on the plant, we see that output voltage waveform and reference voltage experience a phase difference. Thus to avoid instability we introduce a delay compensator such that it compensates for the phase lag. Phase shift of 95 degree is seen when reference is compared to output voltage as shown in figure below. Thus for the purpose of compensating this phase difference and to achieve exact tracking of reference signal we introduce a delay compensator. Delay compensator not only removes the phase difference but also increases phase margin of the system. Number of samples of delay compensator is represented by D, which can be calculated as:

$$D = \text{Phase difference} * \frac{\text{Delay points in a cycle}}{360^{o}} \tag{3.3}$$

In our case phase difference is 95 degree and delay points in a cycle are 50 for 20,000 Hz switching frequency.

$$= 95^{\circ} * \frac{50}{360} = 13.19 \tag{3.4}$$

Thus delay samples are calculated to be 13.19, which are rounded to 13.

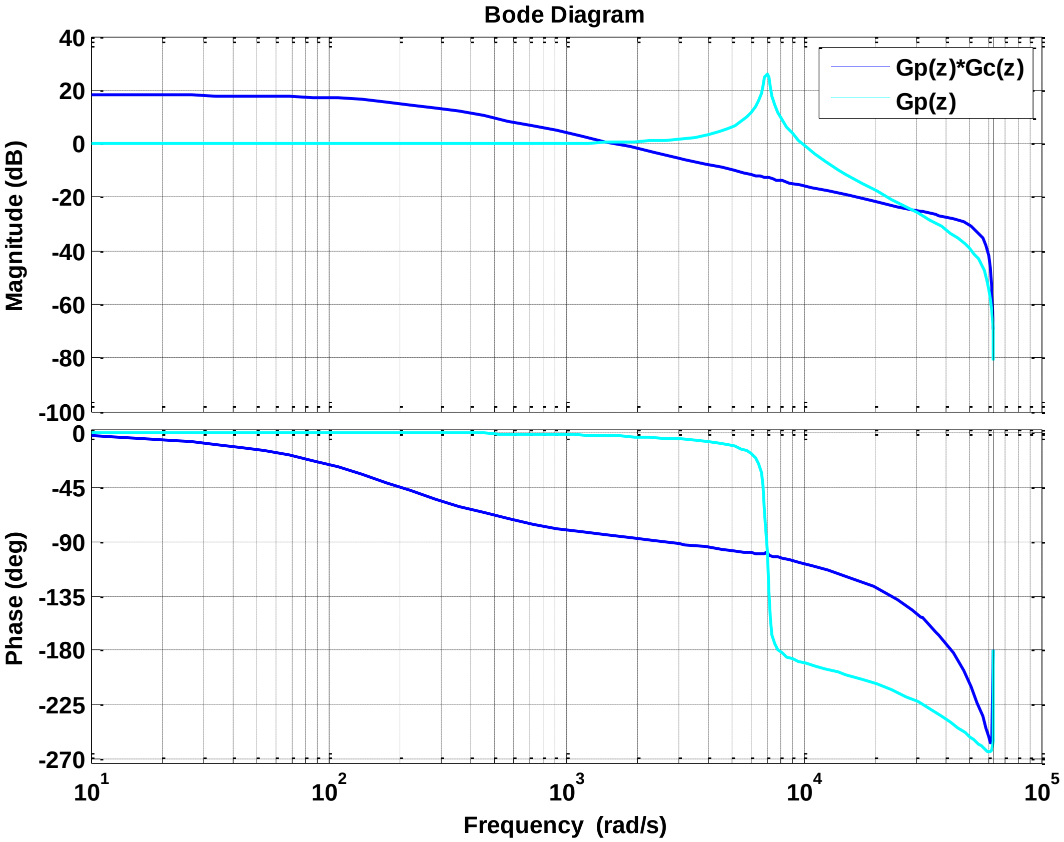


Figure 30: Bode plot of Open Loop Response Vs Plant Response

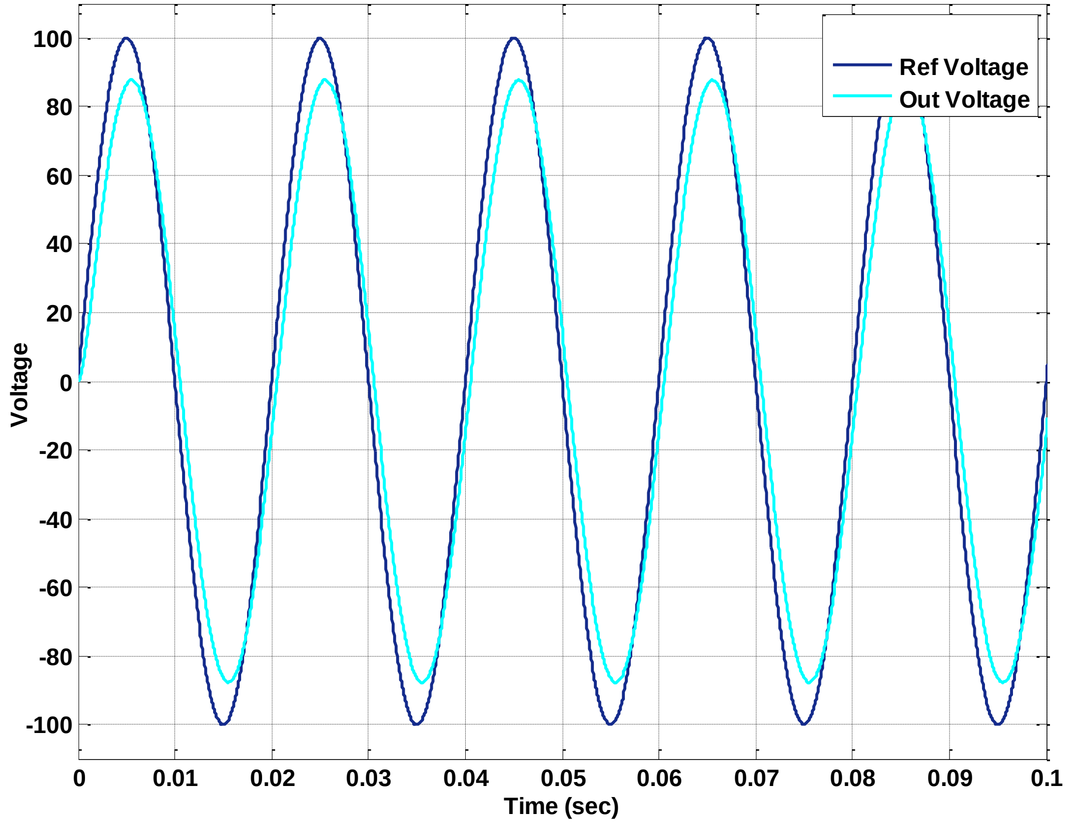


Figure 31: Comparison of Output Voltage Response Vs Reference Voltage Signal

3.1.5 Digital Filter F(z)

For improving the overall performance of system, a low pass filter is equipped with the repetitive controller. During the stability analysis it was seen that the proposed converter is very sensitive, due to the fact that the poles of plant are on the margin of unit circle. Thus for such a sensitive system, a low pass filter was a requirement.

$$F(z) = 1/4z^{1} + 1/2 + 1/4z^{-1} \tag{3.5}$$

$$G_R(z) = \frac{Z^{-W}.K.F(z)}{1-(Z^{-N}.F(z))} \tag{3.6}$$

Whereas Z^{-W} is part of delay line. Thus by incorporating value of digital filter in the overall transfer function of repetitive controller is represented as:

$$G_R(z) = \frac{0.2.\left(0.25z^{-1} + 0.5 + 0.25z^{1}\right).Z^{-39}}{1-\left(0.25z^{-1} + 0.5 + 0.25z^{1}\right).Z^{-50}} \tag{3.7}$$

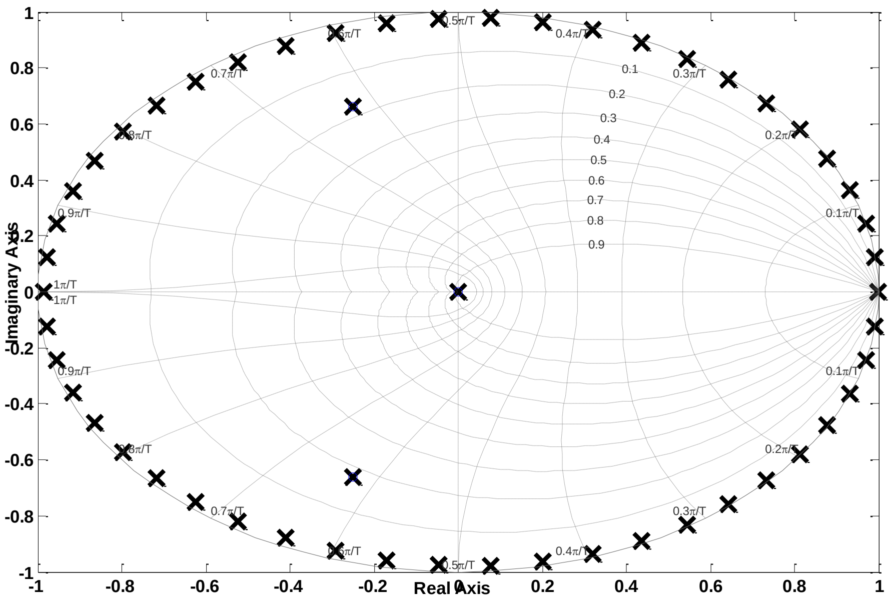


Figure 32: Pole Zero Map of an Internal model with N=50 using digital filter F(z) = 1/4z^{-1} + 1/2 + 1/4z^{1}

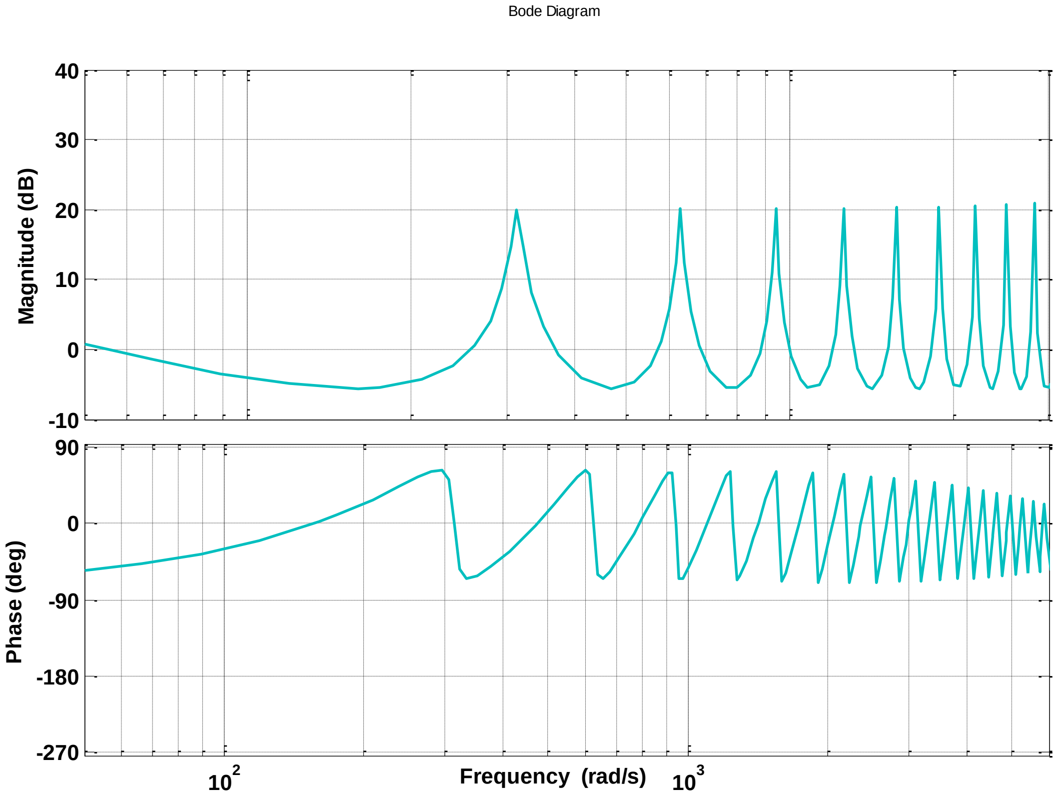


Figure 33: Bode plot of digital Filter F(z)

Pole zero map of Repetitive controller using digital filter shows that the poles of repetitive controller are pushed slightly inward the unit circle improving the overall stability of the system.

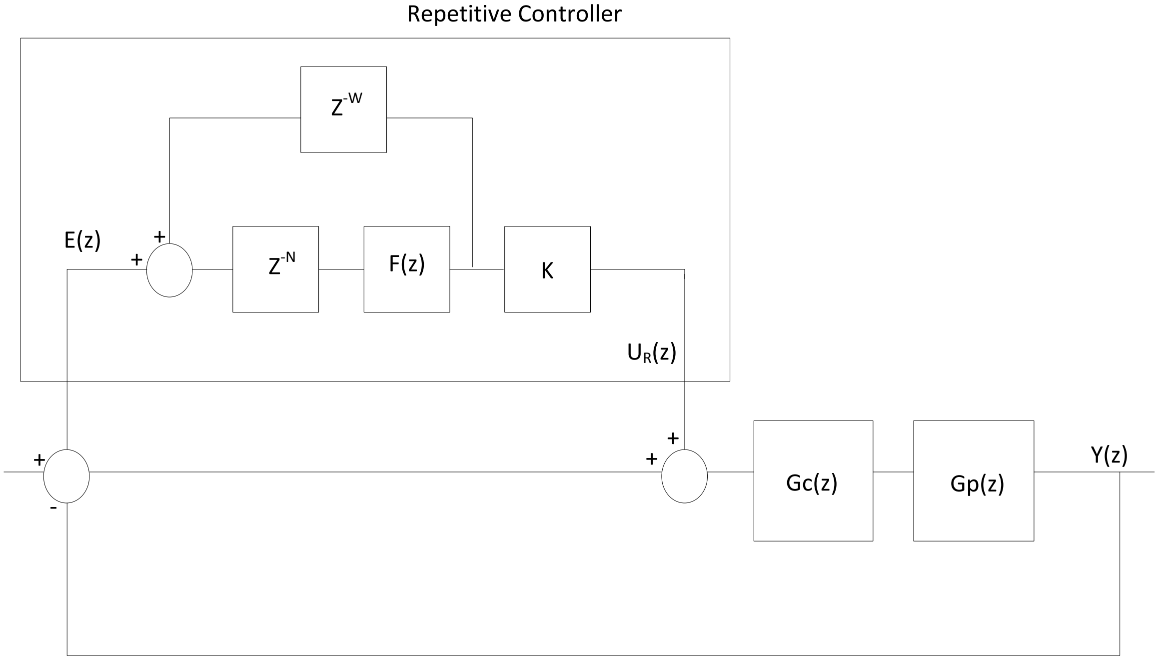


Figure 34: Overall System With Plug-in Mode Repetitive Controller

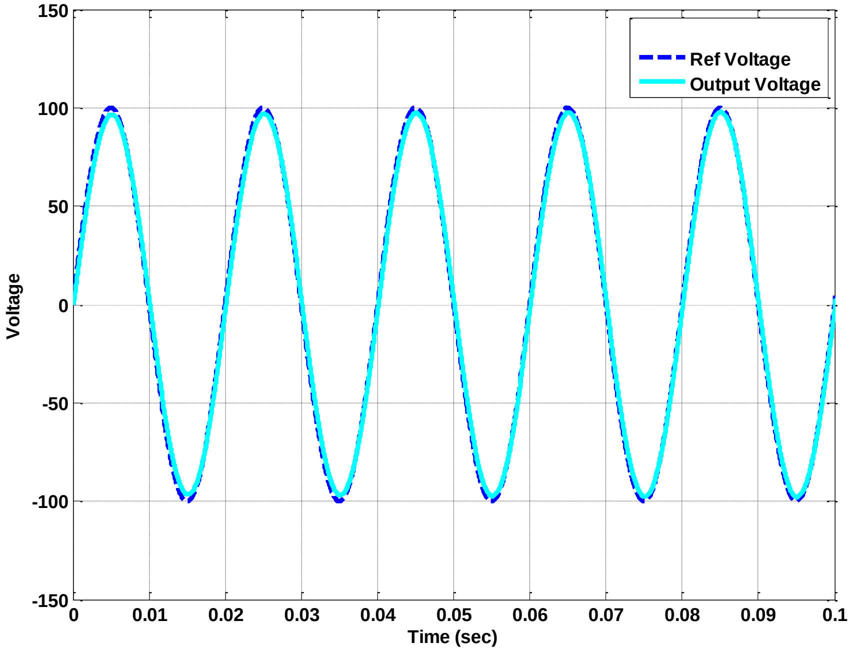


Figure 35: Exact Tracking of Reference Signal by Voltage Output Signal

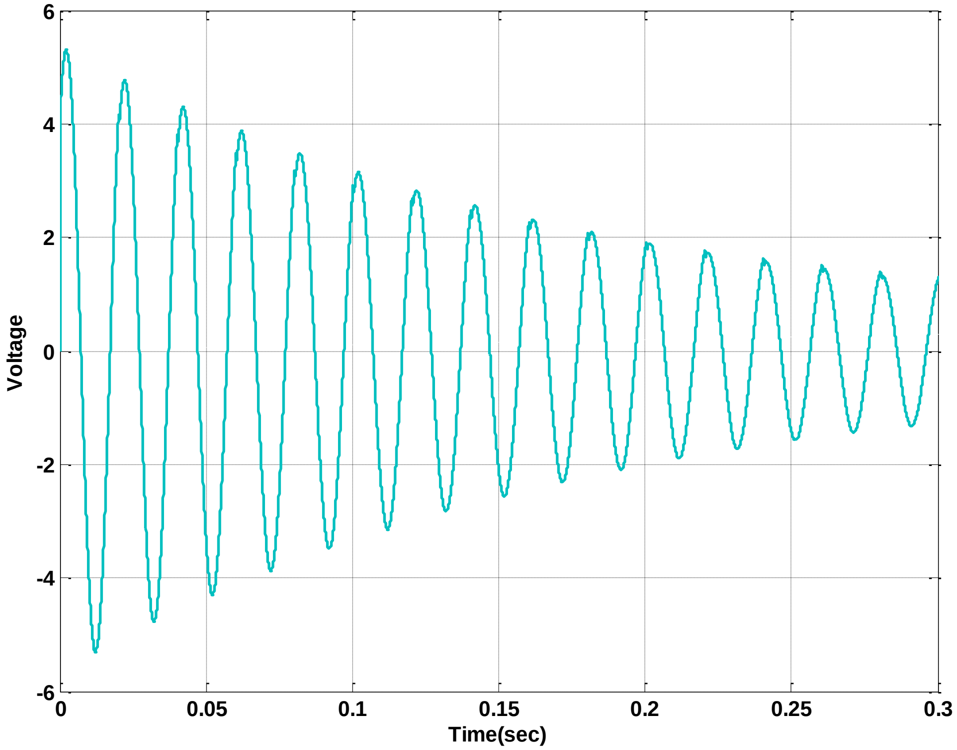


Figure 36: Error Signal E(z)

Hence the overall objective of achieving absolute tracking of reference signal is achieved as shown in the results above

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Annexure I

Design of an Input Filter for Matrix Converter for the purpose of Harmonics Reduction

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Abstract

Matrix converters having wide variety of applications are an emerging technology in the industry. Matrix converter converts AC supply voltages into varying magnitude and frequency output voltages. Thus matrix converter has proven to be a good alternative to Voltage Source Inverters. However, matrix converters are open to an instability i-e harmonic distortion in the input currents, which is examined here. In this paper an input filter for matrix converter is designed for the purpose of reducing total harmonic distortion and smoothen the input currents in order to satisfy EMI requirements.

Keywords: *Matrix converter, harmonics, input filter, modulation.*

1. Introduction

For high power conversion applications AC to AC converters are extensively used in industry. Different converter topologies lacking a DC-link structure have been suggested in literature. Matrix converter provides AC power with desired variable frequency and magnitude without any intermediate DC-link. It uses bi-directional switches array for the purpose of conversion and no energy storage links are used. Matrix converters can be used in many applications such as variable frequency applications, aircraft power supply applications, induction motors, uninterrupted power supplies etc. [1]

There are many advantages of Matrix converter over traditional AC-AC converters which include capability of bi-directional energy flow, full control over input power factor, sinusoidal inputs and outputs and its energy requirements are extremely low thus allowing to discard costly and limited lifetime energy storage elements. There are also some limitations with Matrix converter which include transfer ratio limited to 87% of input and output voltage in case of sinusoidal waveforms, when compared to indirect AC-AC frequency converters matrix converter requires more semiconductor devices and furthermore matrix converter is sensitive to input voltage changes producing higher order harmonics. [2] Matrix converter possesses 9 bi-directional switches in its basic structure which connects the input to output. Figure 1 shows basic structure of matrix converter.

After years of dedicated continuous efforts there now exists several control and modulation strategies for matrix converter. Moreover after intensive research matrix converter is also now used in industries. Yaskawa which produces power converters on large scales now offers matrix converter units for medium voltage (200-6000 KVA) and low voltage (9-114 KVA).[1]

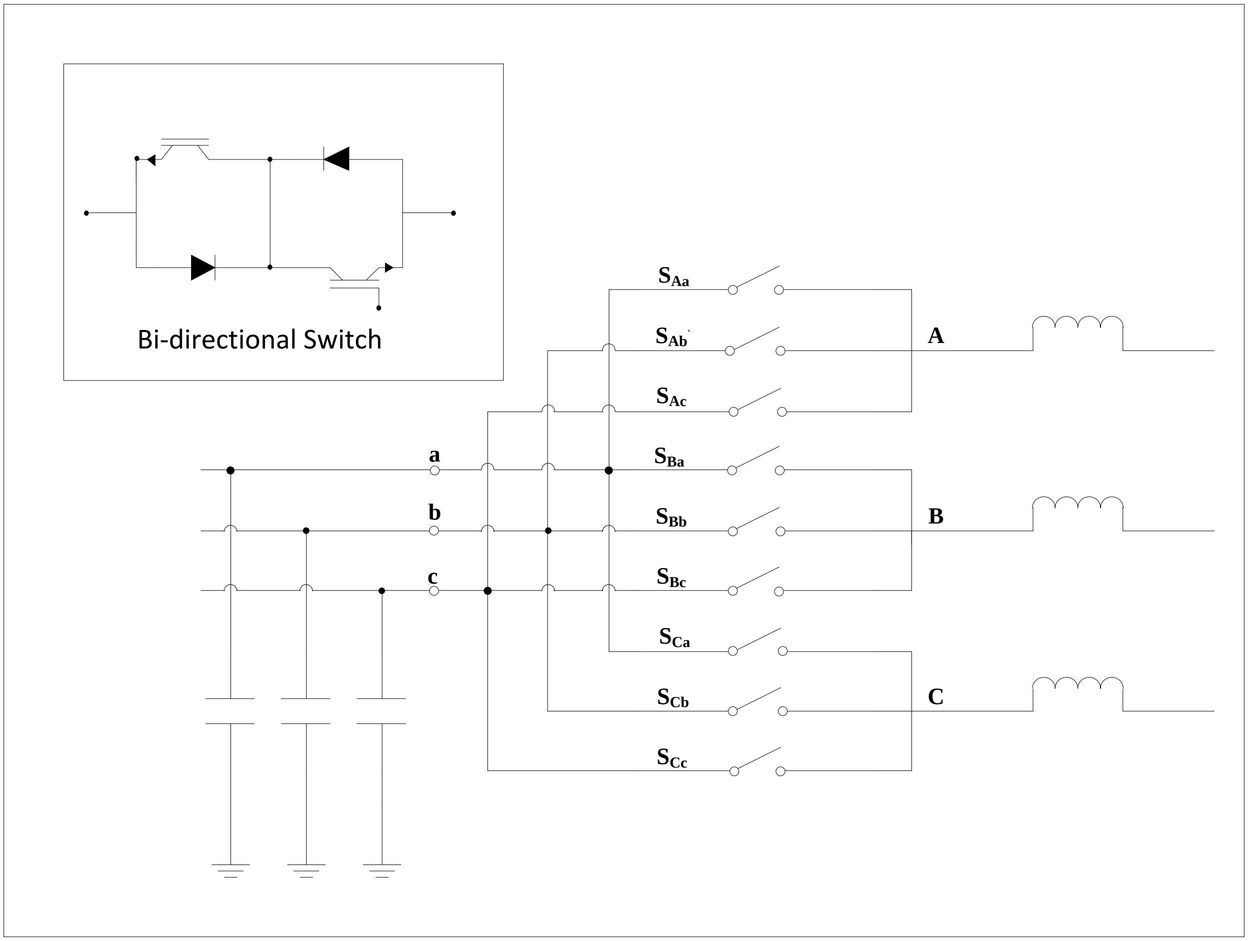


Figure-1 Matrix Converter Basic Configuration

2. Space Vector Modulation Strategy

Space vector modulation strategy scheme is proposed in 2002 Casadei at al [3] at provides with full control over factor input power factor as well as output voltages. For Matrix converter Space vector modulation scheme involves illustration of output and input voltages at any time as space vectors. These output voltage vectors and input current vectors are produced as a result of switching states of matrix converter. A standard three phase to three phase matrix converter has 27 switching states. The space vectors are defined as follows:

$$\bar{V}_1 = \frac{2}{3}(V_{ab} + \bar{a}V_{bc} + \bar{a}^2 V_{ca}) = V_i(t)e^{j\alpha_i(t)} \tag{1}$$

$$\bar{V}_o = \frac{2}{3}(V_{AB} + \bar{a}V_{BC} + \bar{a}^2 V_{CA}) = V_o(t)e^{j\alpha_o(t)} \tag{2}$$

$$\bar{i}_1 = \frac{2}{3}(\mathrm{i}_a + \bar{a}i_b + \bar{a}^2 i_c) = i_i(t)e^{j\beta_i(t)} \tag{3}$$

$$\bar{i}_o = \frac{2}{3}(\mathrm{i}_A + \bar{a}i_B + \bar{a}^2 i_C) = i_o(t)e^{j\beta_o(t)} \tag{4}$$

3. Indirect space vector modulation strategy

Through the following transformations, a space vector is obtained from three phase quantities i-e

$$\bar{X} = \frac{2}{3}(X_a + \alpha X_b + \bar{\alpha}^2 X_c) \tag{5}$$

$$\bar{\alpha} = e^{j(\frac{2\pi}{3})} = \cos(\frac{2\pi}{3}) + j\sin(\frac{2\pi}{3}) \tag{6}$$

Huber and Borojevic first proposed Indirect Space Vector Modulation Strategy[4,5]. In this modulation strategy matrix converter is considered as an equivalent circuit consisting of a virtual DC link through which voltage source inverter and current source rectifier are connected. Separation of output voltage and input current is the basic idea of this modulation strategy. In case of matrix converter, Switching scheme of conventional VSI is followed exactly. Due to the presence of a virtual link, VDC is obtained as following

$$V_{DC} = \frac{3}{2} V_{in} . m_C . \cos(\theta_{in}) \tag{7}$$

θin is the input displacement angle and Vin is the peak value of input voltage.

$$V_{ref} = \frac{2}{3}(V_a + \bar{\alpha} V_b + \bar{\alpha}^2 V_c) \tag{8}$$

Eight inverter switching combinations can be utilized in order to avoid short circuit. Three zero and six non zero input currents constitute these combinations. Hence the reference output voltage vector is produced with the help of adjacent vectors Vα and Vβ having duty cycles dα and dβ,

$$V_{ref} = d_\alpha . V_\alpha + d_\beta . V_\beta \tag{9}$$

Duty cycles dα,dβ and dov are given as:

$$d_\alpha = \frac{T_\alpha}{T_S} = m_V \sin(\frac{\pi}{3} - \theta_V) \tag{10}$$

$$d_\beta = \frac{T_\beta}{T_S} = m_V \sin(\theta_V) \tag{11}$$

$$d_{OV} = \frac{T_{OV}}{T_S} = 1 - d_\alpha - d_\beta \tag{12}$$

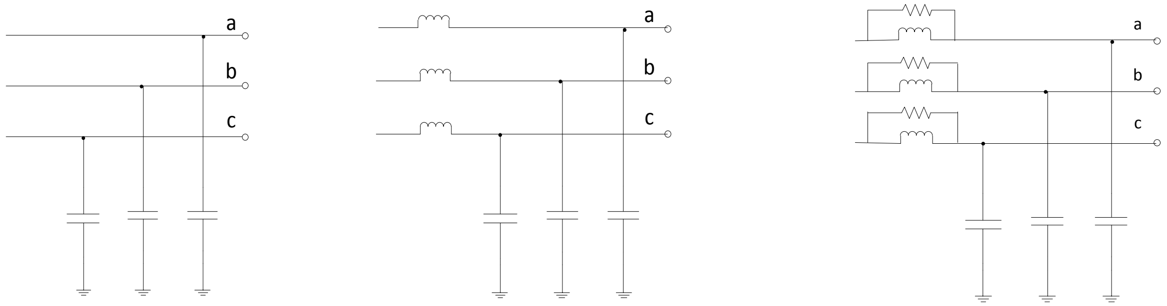
θv is the angle of reference voltage vector while mv represents voltage modulation index[6,7,8].

5. Input Filter

Although matrix converter does not possess any energy storage elements and is sometimes referred to as silicon solution but it still has some reactive components comprising of input and output filters. Input filter in an interface between the converter and the input power supply. Purpose of input filter in power converters is to reduce voltage distortion at input and to improve the quality of input current. In case of matrix converter, the input filter should possess following features:

- During each PWM cycle, input filter should oppose any significant changes in the input supply.
- Undesirable harmonics should not be allowed to flow back to input power supply.
- Filter should satisfy the requirements of electromagnetic interference.
- Filter should be able to protect the converter in case transients appearing at the input side[9,10].

For Matrix converter different topologies for input filter can be used and are shown in fig 2



a) Capacitors star or delta connected.

b) Second order L-C Filter.

c) L-C Filter with parallel damping resistor.

Figure-2 Input Filter Basic Configurations for Matrix Converter.

Different factors influence the choice of input filter topology that include cost, number of components and the frequency response to be achieved.

6. The Effect of Switching Frequency on the Size of the Input Filters

The frequency components near the multiples of switching frequency are to be eliminated thus design of input is filter is based on the converters switching frequency. The cut off frequency is kept lower than the switching frequency. The input filter components are selected according to the cut off frequency. Moreover, size of input filter also depends on the switching frequency of the converter i-e if switching frequency is increased, the size of input filter will decrease.[11]

7. Design of input filter

Design of input filter should be based on following criteria's:

- Cut off frequency should be one decade higher then the supply frequency at least and one decade lower than the converters switching frequency.

- Power losses should be controlled in the damping resistor.
- Ripples in the supply current be reduced.
- The displacement factor be reduced between voltages of supply and those applied to converter.
- Voltage drop on the input filter inductance should kept be low for the purpose of providing maximum voltage transfer ratio.[10]

This work includes the compensation of current harmonics using LC filter for matrix converter. The supply voltage is 141Vrms and frequency is 60Hz. The simulation is carried out in Matlab Simulink in discrete form and the simulated results without filter and with filter are shown separately. Moreover the total harmonic distortion for both cases (with & without filter is also shown below).

By observing the output wave forms, we see that there are significant amount of harmonics in the load. These harmonics are produced because of highly sensitive behavior of matrix converter to disturbance in the input voltages and the range of voltage for output is less than the input in case of matrix converter. An inductive-capacitive input filter was designed for the purpose of reducing total harmonic distortion. The filter designed is a low pass filter which does not allow higher order harmonics to pass through. Harmonics are viewed by using FFT transformation, which shows a considerable reduction in harmonics after filter is installed.

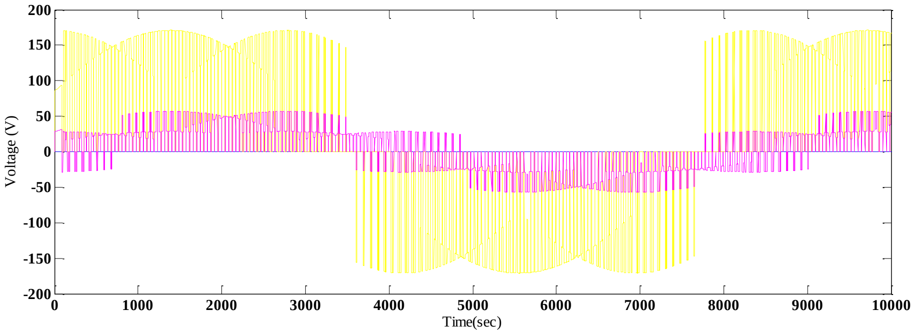


Figure-3 Waveforms of voltage and current without filter.

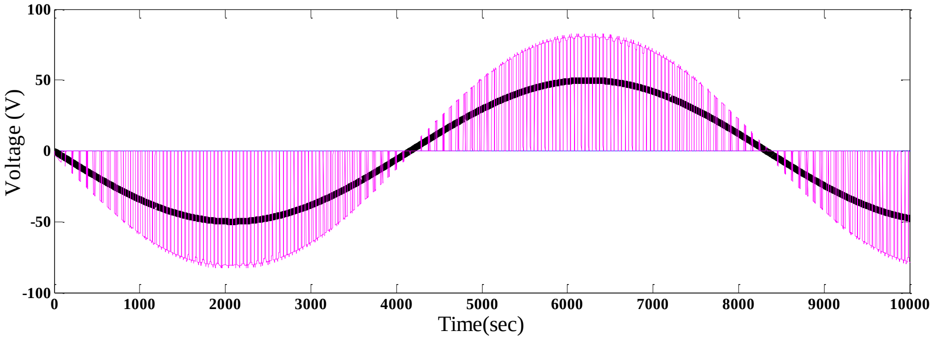
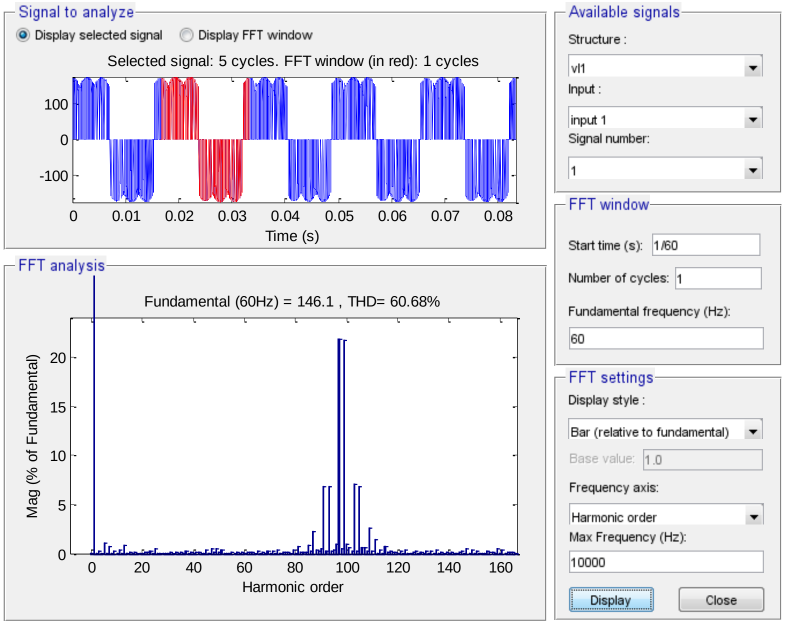


Figure-4 Waveforms of voltage and current with filter.



● Display selected signal ○ Display FFT window

Selected signal: 5 cycles. FFT window (in red): 1 cycles

Fundamental (60Hz) = 146.1 , THD= 60.68%

Structure : vl1

Input : input 1

Signal number: 1

Start time (s): 1/60

Number of cycles: 1

Fundamental frequency (Hz): 60

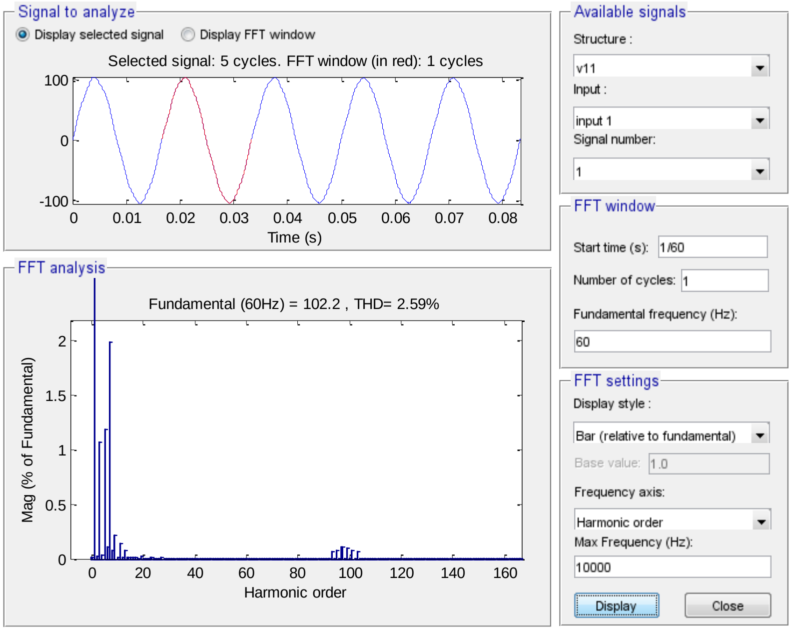
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 10000

Figure-5 Toltal Harmonic distortion without filter



Selected signal: 5 cycles. FFT window (in red): 1 cycles

Fundamental (60Hz) = 102.2 , THD= 2.59%

Structure : v11

Input : input 1

Signal number: 1

Start time (s): 1/60

Number of cycles: 1

Fundamental frequency (Hz): 60

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 10000

Figure-6 Total Harmonic distortion with filter

8. Conclusion

Results of simulations when analyzed show that behavior of matrix converters in terms of harmonics is more suitable than inverter converters. The results reported in this paper show a considerable reduction in harmonic distortion with the implementation of newly designed LC filter. Thus the results suggest that use of matrix converter is more secure in terms of practical usage such as motor-driven systems, which appears to be a serious problems of conventional drives.

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