Design of a Controller for Three Phase Four Leg Matrix Converter

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Abstract

Matrix converter is the direct AC-AC power conversion technique. There are two types of matrix converters, direct matrix converter having no storage elements or DC components and indirect matrix converter having stages and DC link components. To design a controller for direct matrix converter is the main concern of my research work here. For the classification upon working there are two types of matrix converters 3-Phase 3-leg matrix converters and 3–phase 4-leg matrix converter. 3-Phase 4-leg matrix converter has 4th leg as a path for the flow of zero sequence current in the case when it feeds un-balance load. Here as the main topic of concentration is 3-Phase 4-leg matrix converter. The control of 3-Phase 4-leg matrix converter is different and complicated as compared to the controller design for 3-phase 3-leg matrix converter. In case of 3-Phase matrix converter system there are different control techniques previously used among which are various types of repetitive controllers, model predictive controllers and sliding mode controllers.

In this work a proportional resonant controller is used for the control of 3-Phase 4-leg matrix converter system considering the un-balance load. The main advantage of this controller as compared to other controller is selection harmonic control as well as to satisfy the required delay margin. The loop to be tracked is considered the output voltage loop as the main controllable entity as compared to inner current loop to guarantee the desired stability in the amplitude and frequency to feed the sensitive un-balance load. As in these types of applications the inner current is not considered due to faster rate and bandwidth limitation. The system is consisting of a matrix converter, an output filter and un-balance load for this purpose. The general scenario for the designing of a controller for any system is based on the worst condition that a system can face so that practical response of controller is enough strong to reject all the unwanted changes in the system. The software to be considered for this simulation is Matlab Simulink. On the basis of Bode diagrams and reference voltage tracking the system performance fulfills the stability criterion which shows the correctness of simulation.

Key Words: *Matrix converters, PID controller, Bode diagram, Proportional resonant controller, high gain peak, switching frequency.*

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List of Journals/Conference Papers

- Muhammad 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.

- Gussan Mufti, Adeel Waqas, Muhammad Arifeen Ali, Raheel Afzal "Design and Analysis of Optimal Controllers for Grid Connected Inverters for Photo Voltaic Applications" International Conference on Recent Trends in Computer Science and Electronics (RTCSE) Malaysia, 2-3 January 2016.

- Asad Nawaz, Mohsin Jamil, Raheel Afzal, Muhammad Zubair, Muhammad 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, Muhammad 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).

List of Abbreviations

List of Abbreviations	
K_C	Inner-loop gain
MC	Matrix Converter
K_I	Integral Gain
GHG	Green House gases
C	Capacitance
GCC	Grid-Connected Converter
PCC	Point of Common Coupling
L	Inductance
DC	Direct Current
PI	Proportional Integral
MT	Million Tones
THD	Total Harmonic Distortion
PCC	Point of Common Coupling
PLL	Phase Locked Loop
GCI	Grid Connected Inverter
LC	Inductor Capacitor
LCL	Inductor Capacitor Inductor Filter
K_C	Inner-loop gain
K_P	Proportional Gain
K_P	Proportional Gain
DFT	Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
K_P	Proportional Gain
PR	Proportional Resonant
AC	Alternative Current
IEC	International Electro Technical Commission
Sec	Seconds
PID	Proportional integral derivative
Q	Quality Factor

Chapter 1

Introduction

1.1 Back ground, Scope and Motivation of the research

Power electronics converters are extensively used now a day for the achievement of desired power quality and the desired level of current and voltages for commercial and domestic purposes. There are basically 4 type of power electronics converter.

- **Rectifiers, which converter the AC power into the desired DC power.**
- **Inverters, which converters the DC power into the desired AC power.**
- **Choppers, which converts the DC power into desired level of DC power.**
- **Cyclo converters, which converters AC power into the desired AC power.**

Depending upon the requirement of power, it is converted from one level to another level through these power electronics converters. Cyclo converters are further divided into two main categories which are naturally commutated cyclo converters and forced commutated cyclo converters. Matrix converters are actually forced commutated type of cyclo converters. Matrix converter is a technique to achieve AC-AC conversion with the flexibility in variation of both voltage and frequency. It is a light weight and a static solution for AC-AC conversion. It has no bulky components, due to which it can be called as light solution as compared to inverter/rectifier setup. Also due to the absence of DC link component it is compact and simple. The absence of these heavy components inherits the converter comparatively longer life than other similar converters; it has the characteristics to give output voltage within a pre-defined range having arbitrary values of amplitude and frequency. Also due to bi-directional flow of power it has many advantages. For the 3-Phase matrix converter the switching pattern is arranged so that in each phase there are 3 switches. For a single Phase matrix converter there is combination of 4 switches with each two switches parallel. Switching frequency varies for application to application. Matrix converter is very sensitive to the input side system's voltage [1]. The first matrix converter originally arises from a cyclo converter initially named it as forced commutated cyclo converter [2]. As in 3-Phase 3-leg converters there is no path for the flow of zero sequence current.

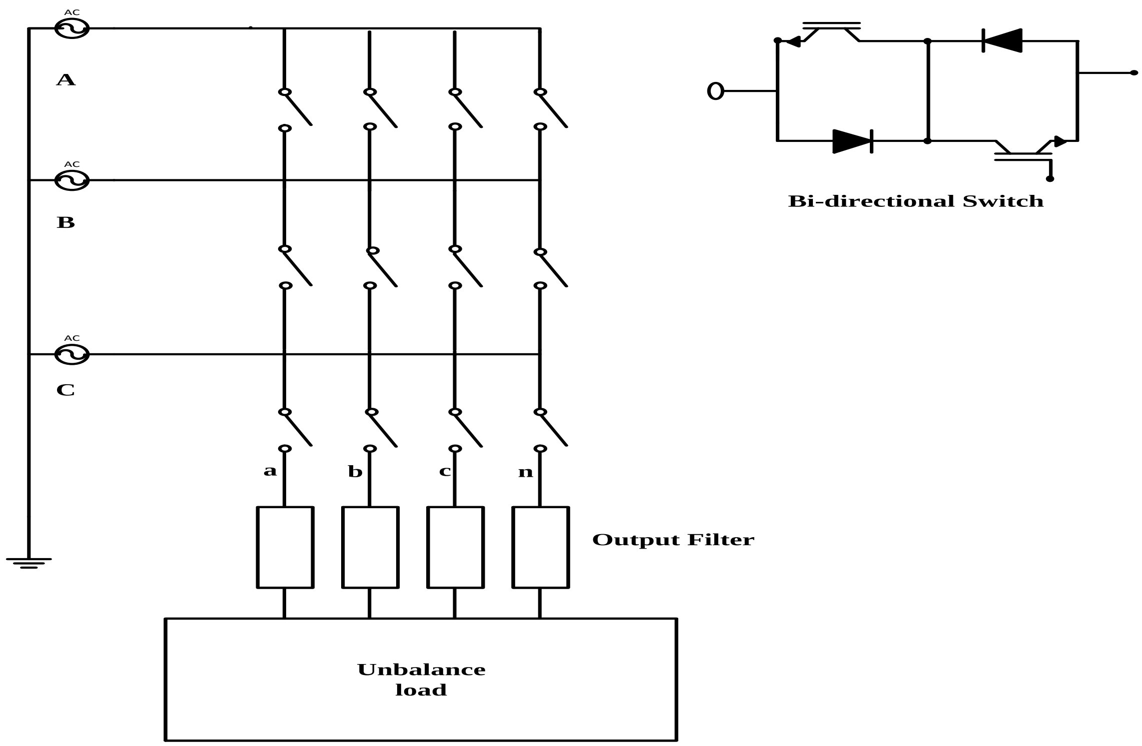

Figure 1 Schematic Diagram of 3 Phase 4 Leg Matrix Converter

This zero sequence in the case of power supply application arises because the load is not balanced every time. 3-phase 4-leg matrix converter is the solution here.

1.2 Matrix Converter

A sinusoidal input current waveform makes it equally advantageous over classical inverter rectifier system [3]. The input displacement factor in case of matrix converter is also controllable. The very practical modulation techniques for used in the case of matrix converter are Venturini modulation technique and space vector modulation technique. Venturini modulation was developed by Venturini in 1989 [1]. The incoming voltage and the transfer matrix give us the desired output voltage through product. The converter's zero and ON state of switches are produced through the ratio of phase voltages from input side in Roy scalar modulation [5] [4]. Taking the switching losses in account for the difference amidst Venturini modulation and SVM assures that Venturini modulation has greater losses. Considering the harmonics in output voltage and input current the Veturini modulation technique has advantage over the state vector modulation technique [2]. As here it is considered as unbalance or non-linear load for the control technique it is easy to deal with scalar quantities rather than to deal with vector quantities, due to this reason here Venturini modulation is preferred as compared to SVM technique [6][7]. Similarly SVM for the first used by Huber and Borojevic in 1989 for the matrix converter, before that SVM was normally limited for the case of inverters more commonly. To control both the input power control and the output voltage control was covered by full Space Vector Modulation technique presented in 2002 [8]. For the matrix converter SVM is based on any time's input currents and output voltages space vectors representation. The switching states that are produced by matrix converter results in these vectors. Considering a ground power unit(400 Hz, 100V) for an aero plane as the case of un-balance load we have two options to feed the load, first one is a delta star transformer feed by 3-phase 3-leg converter and the second option is the load feed directly by 3-phase 4-leg converter. Using transformer with converter gives us better isolation but the size and weight of transformer is the main issue here. The less weight and comparatively lower size make the second choice most feasible here.

1.3 Literature Review

1.3.1 Details of Matrix Converter

As the power supplies feed un-balance load, it is more feasible to apply digital controller for such system in switch mode. As compare to analogue controllers the digital controller has the advantage to be modified or reprogram and also implementation of complicated and sophisticated control techniques. Also digital controller can handle non-linearites and signal manipulation, a very appealing feature of digital controller. The lower cost and high computational power increases the importance of digital controllers as compared to analogue controllers. The problem of aging in analogue controllers is overcome by digital controllers as well as advantage of less thermal drifts. Due to the above mentioned reasons here the work is first in frequency domain and then in digital time domain [9].

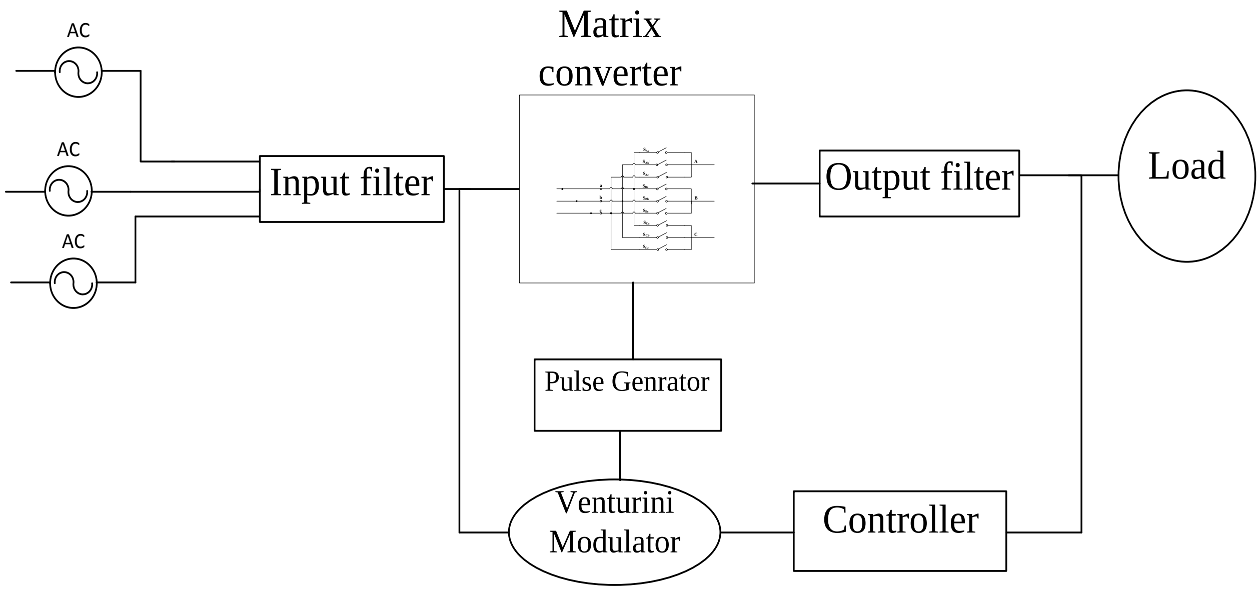

Figure 2 Overall System's flowchart

1.3.2 Resonant Controllers:

Resonant controllers are more effective than conventional PI or PID controllers. In alpha-beta stationary frame as abc frame is changed into the mentioned frame for the prevention of phase locked loop (PLL). The conventional controllers cannot be employed to obtain zero steady state error. Normally a high gain introduced at fundamental frequency which is needed to increase the band width. The conventional PI and PID controllers have limited bandwidth so they cannot provide the desired high gain [10]. The resonant controllers have inherited advantage of providing high gain at the specific frequency known as resonant frequency and no gain at any other frequency. This property of PR controller enables it to use in active power filter for notching to remove unwanted harmonics in the system [11]. Ideally this gain has infinite value but practically it is impossible. The integral portion in classical converters performed same action as resonant controller, the integrator integrates all other frequencies near resonant frequency but unlike normal PI or PID controller PR controller does not introduces steady state error or phase shift[12]. The PR controller is in fact a set of sub block or sub controllers arranged in series or parallel. The controller is highly selective as the each sub block deals with the perspective harmonic and provides high gain at certain frequency. To deal with the individual harmonics and to remover state errors made the resonant controllers more suitable for utility converters. The basic resonant controller is identical to an integrator that has infinite DC gain at the particular frequency known as resonant frequency. Theoretically the gain is introduced at each individual harmonic and has infinite value. For practical resonant controller its value is not infinite but still enough to handle steady state error [12]. The controller's bandwidth is also controlled by cutting frequency unlike PI or PID controller [13]. The high gain provided by resonant controllers in the form of peak gains at the selected frequency and at selected harmonics provides it an efficient disturbance rejection property which the classical PI and PID controllers cannot perform although stability margins show not a big difference between PR and classical controllers [13]. To control the number of harmonics totally depends upon the system's designer and for each harmonic rejection there is a separate sub controller. Hence the size of controller increases as the selection of harmonics order increases. For high order harmonics with the increase number of sub controllers make the system more complicated and these results in the overall complication of the system. Stability limits in the PR controllers however reduces the systems stability at that time [14][15]. This in turn results in the implementation of a digital hardware for the desired PR controller to avoid this instability. Usually passive damping is use to stabilize the system but this increase the losses in the system and also the performance of the filter is not same as earlier. Active damping can also be used by introducing a current loop through installation of an extra inductor but here again this will affect the system's memory and sensors. [16].

1.3.3 Aero plane Power Supplies Ground Unite

Normally aircraft electrical equipment can run both by DC and AC power systems. Self-excited generators are used as DC power systems. Three phase AC converters are an AC power supplies. The standard requirement is 100 or 115 volts with the frequency of 400 Hz, in the case of DC power it is 28 volts. Ground power unites as the name show supplies power to the aero plane during its ground operations such as mobility and loading of passengers and cargo. These supplies are mainly provided at airport. The noticeable features are low weight and less space requirements for a 400 Hz system. As the system frequency decreases, passive elements increases and decreases for a high frequency systems. This means for a 400 Hz system the number passive elements are much lower than that of 50 Hz system. Controller's bandwidth is has a limited range due to relation between fundamental and switching frequencies in the converters. According to power supplies standards voltage unbalance is 3 Vrms, maximum voltage distortion must be unto 5 percent and steady state frequency 393 to 407 Hz. Due to unbalance loading conditions, the three phases load feeding is different. The unequal phase shift and unbalance output voltages are caused due to zero and negative components of the phases. In the matrix converter having 4th leg is actually a path for the flow of these zero sequence components. Thus each output phase voltage can be controlled independently.

Chapter 2

System Background and Components Details

The system is composed of input filter, output filter and matrix converter. How the concept of matrix converter was introduced and which parts of the system must be considered during the designing of a matrix converter's controller, are described here. The basic parts of a matrix converter to design a controller for the converter must be specified as the controller is system specific.

2.1 Detail Introduction to Matrix converter:

The progress in PE technology was the main mile stone for the idea of matrix converter. In 1976 the idea of matrix converter was firstly proposed [17]. Nonlinear magnetic or other circuitries having switches controlled by different techniques and rotatory electrical systems are the ways through which we can an input frequency into the desired output frequency. There two concepts of AC-AC power conversion are mainly direct AC-AC conversion and indirect AC-AC power conversion based on PE techniques. Indirectly it means there are some sort of DC liked elements in the circuits which store energy and convert first the AC power into DC power and then DC power into AC power. Diode rectifier/inverter bridge circuit is actually the described type of circuit in which AC power is first rectified into DC power and then DC power is converted into variable AC frequency power. This is called a two stages indirect AC/AC power converter. Direct AC/AC power conversion without intermediate DC conversion is known as direct AC converters. This process is also known as single stage direct AC-AC power converter [2].

2.1.1 Indirect AC-AC Power Converters:

Two indirect AC-AC patterns are show in the figure. For lower and medium range power converters topology is diode bridge voltage source converter. This technology in used intensively in AC drives. AC power is rectified into DC power by diodes. Voltage amplitude and frequency is changed by the voltage source inverter circuit. This pattern of conversion is very basic and popular. It has high performance with PWM and SVM modulation techniques. The cost is comparatively low and easy to implement. For the sensitive electrical devices and loads, it is not such efficient because the harmonics are produced in the input line voltages and finally causing impacts the other sources which are feed by same power supply.

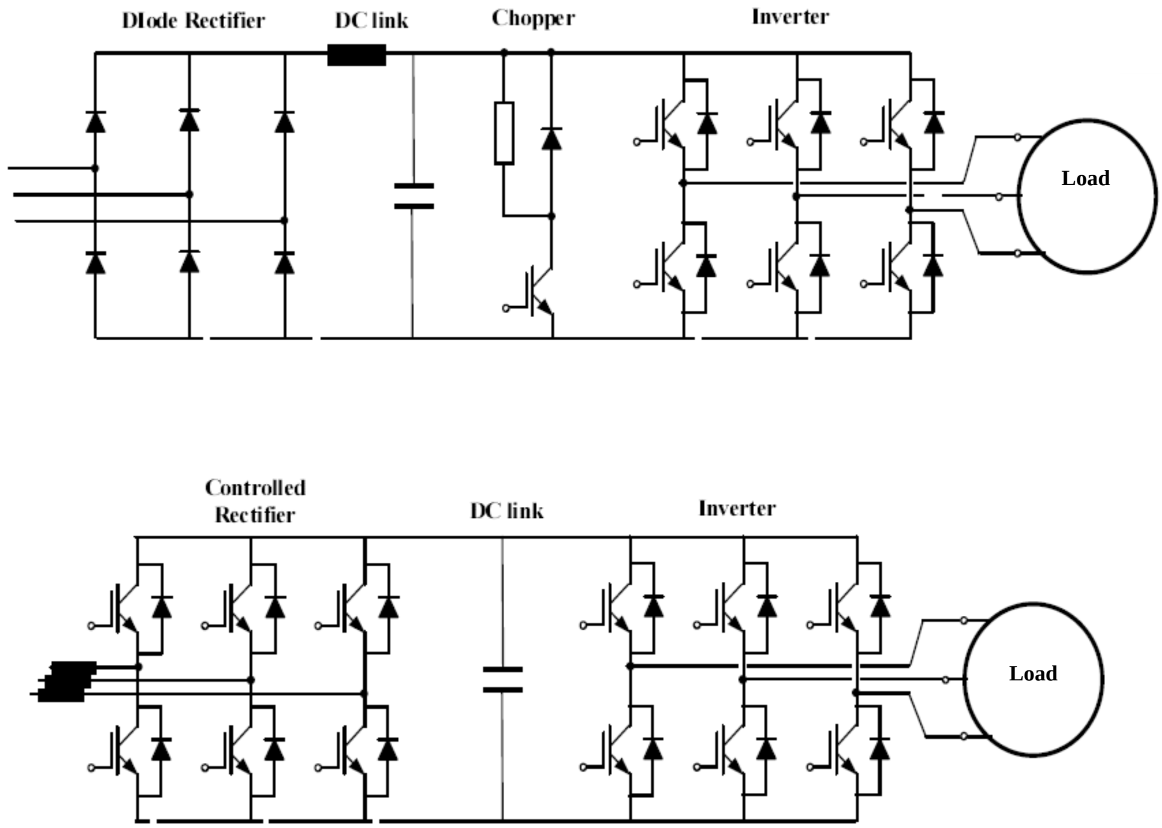

Figure 3 Two Indirect AC/AC Converters

Large over voltages caused by excitation of electrical resonance are produced as a result of current harmonics that results in extra losses at utility side. Serious concerns regarding utility side power quality are raised due the use of this type of power electronics converters. Due to lack of mechanism for the reversal of current direction in the diode rectifier and also due to electromagnetic breaking the DC bus voltage can reach destructive limits. Energy loss is the main problem in Diode Bridge and they can use efficiently only when their energy losses are controlled [18].One of the main thing that capture our attention regarding the losses is DC link, it grabs the attention particularly if DC link is composed of electrolyte capacitor. They have short life due to sensitivity to high temperature but their storage capability is good.

The 2nd conversion scheme is show here as well. In this circuit PWM removes the diode bridge rectifier stage. For high and medium ranged applications for example for elevators and cranes this technique is use due to possible conversion of bidirectional power flow. There is notable decrease in the input current harmonics due to PWM controlled rectification and the reason is high switching frequency. Thus the requirement for filtering elements reduced very much. The numbers of semiconductor devices are large in the scheme b, also the complicated control plan of combined PWM controlled rectifier and inverter is the main reason behind this scheme disadvantages. Just like scheme of DC link here is the similar problem of short capacitor's life.

2.1.2 Direct AC/AC Power Converters:

There is direct connection between input phases and output phases in direct AC-AC converters having static switches arrays. The segmentation of input waveform into the desired output wave form is the basic principle for these types of converters; the outer waveform is obtained through piecing and the combination of segments from input waveforms. The cyclo converters are one of the most earlier developed of these types of waveform developed between 1930 and 1940 initially [17]. Here it is discussed only the direct power frequency converter. Forced commutated cyclo converters and naturally commutated cyclo converter are the two types of converter discussed here.

AC supply voltage is responsible the switching of naturally commutated cyclo converters, AC supply voltage turned off the switches. The thyristors are used as switches due to this reason for switching. One third or one half frequency of the original frequency is the limiting range for this type of technique. In motor driven applications where they need high frequency the problem is solved by high frequency engine driven generator feeding the load through cyclo converter [19].

The output frequency can be higher than the input frequency due to comparatively good switching methods in force commutated converters allow them to be used for various loads independent of the source. Due to absence of self-turning OFF and turning ON feature in force commutated converter the thyristor cannot be used for switching. Some other components and auxiliary commutating circuits are used for this purpose. Many phase controlled circuits when connects with an AC supply system together can be termed as a cyclo converter. The input phase's voltages are segmented to generate the waveform of output voltages with a different frequency through each controlled converter technique. Half wave controlled three phase cyclo converter is shown here. The thyrister firing angle is modulated, thus the frequency and voltage at output side is controlled in natural commutated converter. The maximum output/input voltage transfer ratio in naturally commutated cyclo converters is given as.

$$\frac{Vout(max)}{Vin(max)} = r(max) = \frac{m}{\pi}\sin(\frac{\pi}{m}) \tag{2.1}$$

The m=3 as it shows the number of incoming phases and r maximum value is approximately equal to 0.827 [17]. The cycle converters feed the load with non-sinusoidal current and also at the input the current supplied to it is also non sinusoidal due to phase controlled operating mode. There is reactive power transfer passing through cyclo converter when it feeds a reactive load and the reason is the direct connection of input and output phases. For all direct power frequency converters due to this reason it is consider a must sacrifice in power factor, harmonics distortion and input displacement angle. Not due to load but due to phase delay the input current is always leading and supply voltage is lagging. The reason due to which input displacement factor cannot be unity. The total harmonics distortion in this case will be considerable. There is inherent bidirection power flow in naturally commutated converters and also have comparatively lower losses of commutation and conduction, thus overall make the design of converter more compact. Among the disadvantages of naturally commutated cyclo converters the complex control circuitry for large number of thyristers control, comparatively lower voltage transfer ratio and the output frequency is limited to a low values. Thus high power reversible AC drives having lower speed are its visible applications. Forced commutated cyclo converters have the advantage over naturally commutated cyclo converter due to these disadvantages. For higher output frequency, input power factor control and a good transfer ration between input and output voltages the forced commutated cyclo converters have higher switching frequency and this is ensured by complex control algorithms used for this purpose.

2.2 System's Components

Matrix converter is composed of the following components.

2.2.1 Matrix Converter

Structure wise matrix converter is just a forced commutated cyclo converter. For a single phase, matrix converter is composed of 4 switches [20] and for the case of three phase it has nine switches, for each phase we have three switches as shown in the figure.

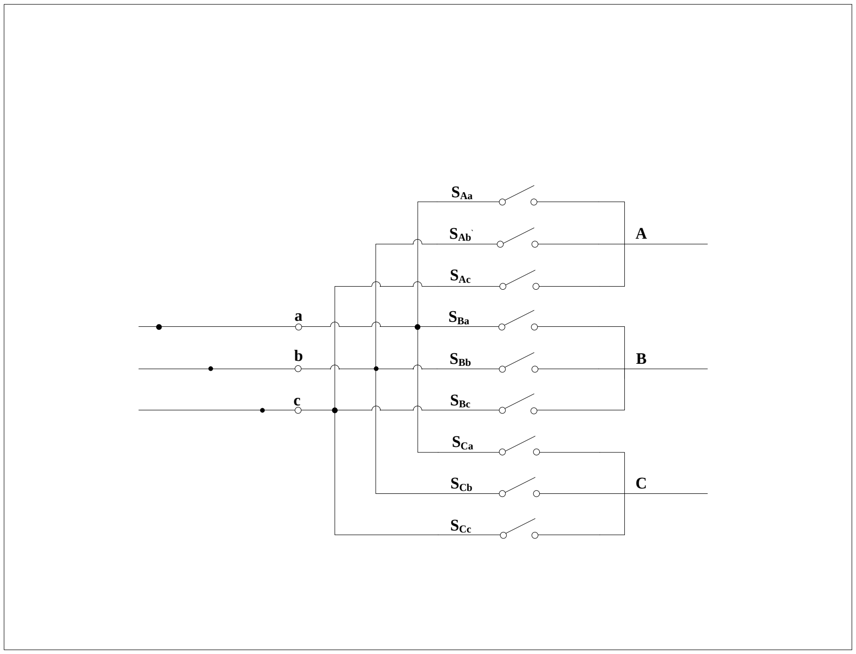

Figure 4 Simple Three Phase Matrix diagram

Venturini in 1980 was the first to perform basic calculations and control techniques for three phase matrix converter but the idea and topology of matrix converter was presented by Gyugi Pelly in 1960’s. Generalized transformers, forced commutated cyclo converter, direct frequency changer and unrestricted frequency changers are some of the names used for matrix converter initially [21][22][23]. As it is forced commuted cyclo converter and works better comparatively than the naturally commutated cyclo converter. The distortion of output waveforms of voltage and input current is still a problem here along with the some limitations at output voltage. The ouput voltage limitation was the main problem although even in 1980 Venturini suggested a new high switching frequency control based on algorithm that was much effective than the previous control algorithms [19]. The other shortcoming of this control algorithm is the control of input power factor and also the output voltage magnitude was limited about to the half of the input voltage. Classical rectifier and inverter based methods were proposed in 1980’s [21][22][24]. To use matrix converter practically after the mentioned methods were not yet achieved, although the maximum output voltage and distortion problems were reduced up to a level. The maximum transfer to voltage at output side was improved in the next level of control strategy from 0.5 to 0.866 and the input, output theoretical limits. Space vector modulation technique in 1990s and late 1980s were introduced for matrix converter [4][23][25]. In space vector modulation there is more flexibility as it allows sinusoidal input current and sinusoidal output waveform of voltage along with the advantages of full transfer ratio theoretically between input/output voltages and also the control of power factor at input side of converter [26]. The applications of matrix converter are very limited despite the recent research activities but now it is attracting the AC drives industry. The main problems in the matrix converter implementation are to develop some resistible control strategies which can deal with problems present in its modulation methods.

Here the complete structure matrix converter includes input filter, output filter and matrix converter, which are discussed here one by one.

2.2.2 Input Filter

The reduction of ripples and distortion in the current wave and to reduce the impact of matrix converter on the input supply are the main functions of input filter. There are many topologies for input filters design of matrix converter [27]. The features of input filters are many and basically it interfaces the converter and the power supply at input side. Some of its mains features are here and the filter must satisfy the following needs of converter.

- The requirements of electromagnetic interference must be fulfill.
- To stop the disadvantageous harmonics flow towards the power supply at input side.
- Sometime transients are produced in supply from input side, to protect the matrix converter from such type of transients.
- During PWM cycle it must protect the system from significant changes.
- The switching frequency and cutting frequencies are deciding criteria in input filter so the to select the value of cut off frequency will have to one decade less than the switching frequency and one decade more than input frequency of supply.
- To achieve high voltage transfer ratio at converter, it must ensure to have less voltage drop at filter inductor.
- The losses due to resistance of damping resister must be controlled up to desired level.
- The ripples must be low, as low as possible both in capacitor voltage and in current waveform of supply side.
- The displacement factor between the input of filter and voltage applied to the converter must be minimized to a level.

For PE converter there are huge range of input filters topology and similar is the case of matrix converter. The selected topology is second order filter having LC components and the frequency response is good. It is show here in the figure below as,

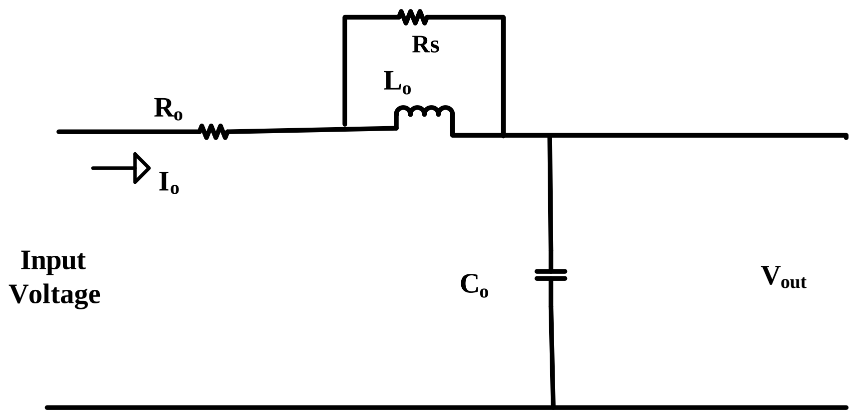

Figure 5 Input Filter's Circuit Diagram

The filter’s cutoff frequency is dependent upon the values of capacitor and inductors.

$$f_{resonant} = \frac{1}{2\pi\sqrt{L*C}} \tag{2.2}$$

To use this matrix ac voltage source converter usually the value of capacitor is chosen as a lower value. The important thing is to balance the value of capacitor. The value of inductance is chosen as larger as possible in the input filter with an internal resistance.

To keep the cutoff frequency same as recommended the value of capacitor and inductor both are inversely proportional to each other, the need of high input power factor is fulfilled by high value of inductor while scarifying the value of capacitor to be lower so as to reduce the chances of high current flow. This increased the voltage drop in the system. The transfer function of input filter is given below. The value of capacitor is chosen as according to availability. The input capacitor setting along with the converter is shown in the diagram given

$$TF = \frac{V_{out}}{V_{in}} = \frac{\left(\frac{1}{R_s C_0}\right) S + \left(\frac{R_o}{R_s L_o C_o} + \frac{1}{L_o C_o}\right)}{S^2 + \left(\frac{R_o}{L_o} + \frac{1}{R_s C_o}\right) S + \left(\frac{R_o}{L_o C_o R_s} + \frac{1}{L_o C_o}\right)} \tag{2.3}$$

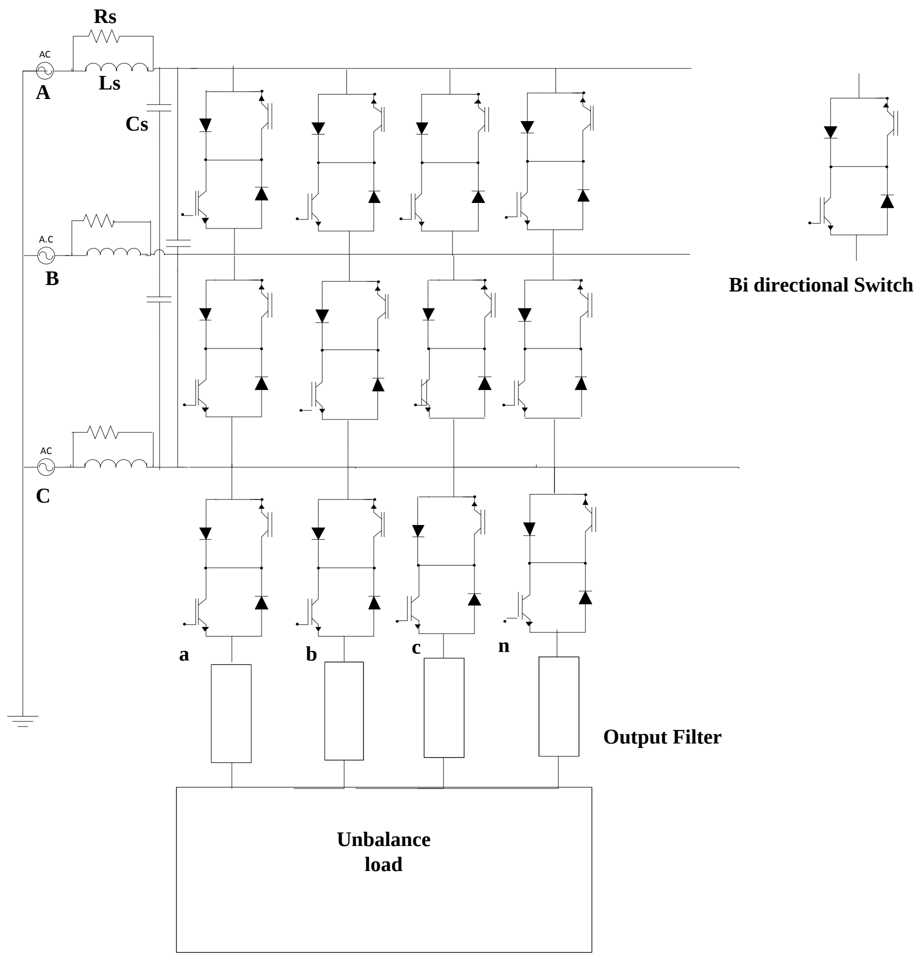

Figure 6 Schematic Diagram of Three Phase 4 Leg Matrix Converter with Un-balance Load

To achieve appropriate the damping a parallel resistor Rs is provided with the inductor as shown in the filter's diagram. This parallel resistor has a disadvantage of energy losses [28]. The higher value of parallel resistor ensures low damping rate as required but high losses as well while its lower values have high damping and lower losses. For a described 7.5 KW system for a resister of 500 Ohms its damping provided is 0.01 damping and for a 10 Ohms resistor the damping is 0.5. The power loss in 500 Ohms resistor is approximately equals to 48mW. The value selection process is a careful process here. The final value of this resistor selected is 56 Ohms which has losses of 428 mW and damping is 0.089 provided. As the cutoff frequency is 2.45 kHz so according to the needs the values for inductor is 600 µH and capacitor's value is 2µF. The cutoff frequency of the filter is lower than the switching frequency which ensures that the high frequency components are being blocked and the phase shift is near to zero degrees. Thus the input filter described here is the best solution for the discussed problems and its use will get rid the related problems. The main problems are the switching harmonics entrance into the systems which are also controlled through the filter. Low number of the components in this filter makes this filter's topology as good for matrix converter and specifically for the purpose of aero plane power supply purpose. The reason is the system needed here is a low cost, less losses and to be low weighted. The desired result is to achieve a good quality current waveform and less distortion in the voltage in the waveform.

2.2.3 Output Filter:

To handle the output voltage waveform ripples that are produced as a result of switching normally a filter at the output of matrix converter is installed. The filter is a low pass filter according to the needs. To work like an ideal voltage source converter the matrix converter is must have very low impedance. In other words the inductor value is keep as minimum s possible while the value of capacitor is keep as larger as possible, but due to large size of capacitor may be more energy is stored leading to the conditions of high inrush current flow. Thus it is recommended to use capacitor of high value but not extra high as the problem of high inrush current may be arise. The component to lower the power rating of filter according to the system requirement is the inductor here and it must a small value of inductance [29][30].

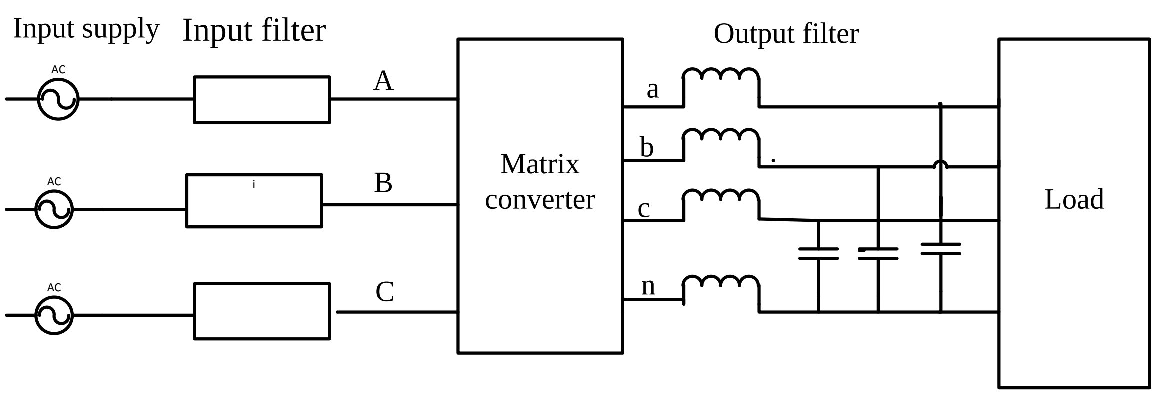

Figure 7 Output Filter's Diagram along with the Overall System

The selection of L and C values are therefore strongly dependent on the value of cutting frequency. The cutoff frequency of output filter is 1100 Hz as it chosen less than the switching frequency in the same way as input filter. The equivalent circuit of output filter is shown in the diagram below.

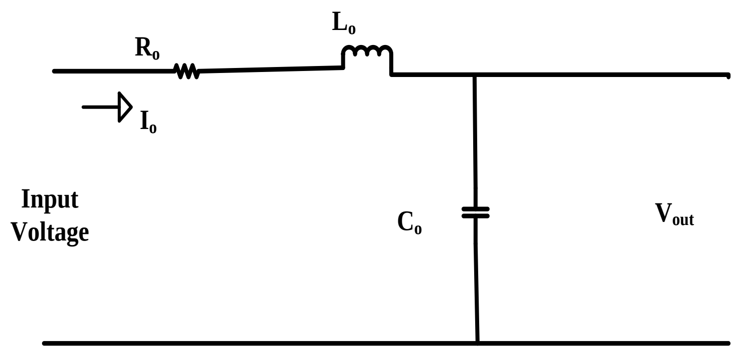

Figure 8 Output Filter's Circuit diagram

The total harmonics distortion in the voltage waveform must be less than 5 percent and maximum ripples range is ±3V. The basic formula for the selection of L and C values in the output filter is as given below,

$$f_{resonant} = \frac{1}{2\pi\sqrt{L*C}} \tag{2.4}$$

The value of inductor is 0.588mH and the value of its internal resistance is as 0.8 Ohms approximately. The capacitor value is selected according per mathematical equations given below.

$$C = \frac{1}{\omega^2 * L} \tag{2.5}$$

The angular frequency is given as

ω =2*π*f and L=0.58mH.

The cutoff frequency value here represents the value of f and is 1.1 KHz or 1100 Hz, putting all the values,

$$C = \frac{1}{(2*\pi*1100)^2*(0.00058)} \tag{2.6}$$

The capacitor value finally selected is $35*10^{-6}$ Farads as according to market size availability near to the closest calculated size. The transfer function of the output filter is given as,

$$. \; Tf = \frac{1/L_oC_0}{S^2 + r_0/L \, S + 1/L_0C_0} \tag{2.7}$$

The final step in this case is to take the transfer function of the output filter. This transfer function shown is in frequency domain as it is the first mile stone to represent any system in frequency domain involving control systems analysis.

2.4 Parts of the Matrix Converter

The matrix converter is composing of the following parts.

2.4.1 Types of Bidirectional Switches:

As recent studies reveals that there are many topologies used for the set of sub components to be used as bidirectional switches. Although the true bidirectional switches are also available but due to the extra benefits the non-monolithic bidirectional switches are used extensively in PE converters. The patterns for various bidirectional arrangements are described as below.

2.4.1.1 Common Emitter Configuration:

The properties of this configuration are excellent voltage, current, power gains and are most practically used configuration in the real life. Collector emitter ends provides the output and the input is provided at base emitter side. Here the common terminal to the both is the emitter and that is the reason behinds it names. In term of amplifying circuits it is mostly used one and results a phase reversal between the input and output waveforms. The setup is comprised of two diodes and anti-parallel connected two IGBTs. Reverse signals are blocked by diode due to its inherent feature to block the reverse signal. Its gives freedom for both positive and negative currents and has less conduction losses. These two features are its advantages over others configurations. The diagram is show as below. This configuration is useful against other to be selected for practical use as it has lower losses as any two devices at a time are conducting. Moreover the current direction can also be control although the disadvantage is the requirement of two gate driving circuits at a time [31]. Thus the requirement of an extra power supply in this type of configuration is the main bottle neck but still advantages are more as compared to its disadvantages.

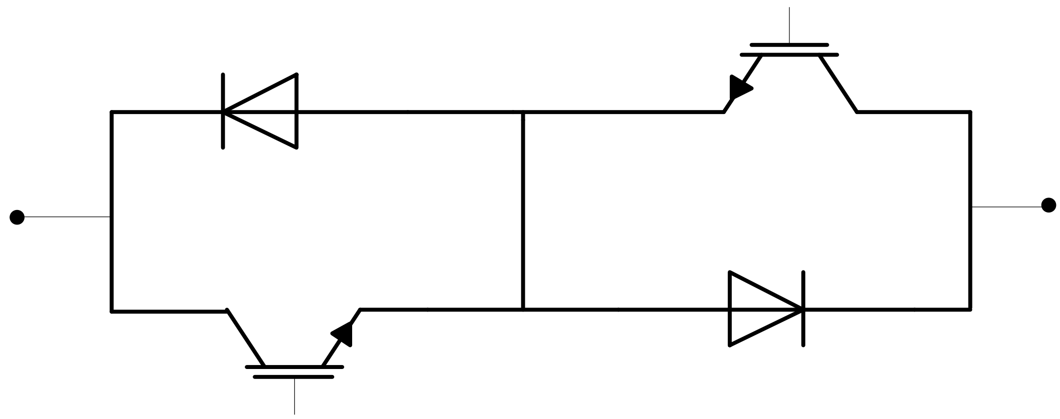

Figure 9 Common Emitter type Bidirectional Switch

2.4.1.2 A Set of Two Anti-parallel Reverse Blocking IGBTs:

The two IGBts are arranged in anti-parallel pattern to make a bidirectional switch**.** The size of converter is small and compact in this type of system and losses are less due to fewer components used. The main problem in this type of switches is that the IGBTs have poor property to block reverse signal which limited it uses.

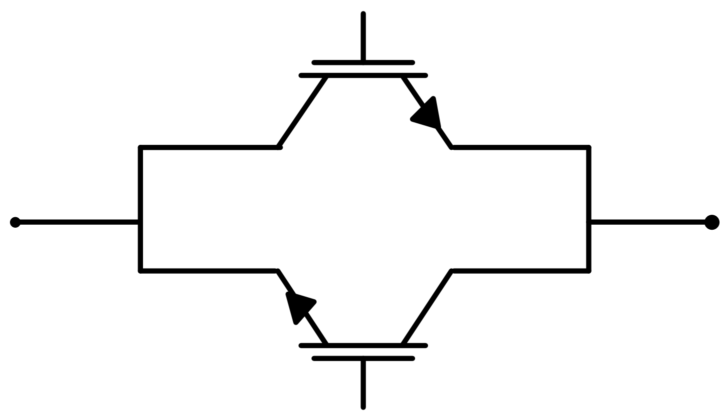

Figure 10 A Set of Two Anti-parallel IGBTS Bidirectional Switch

2.4.1.3 Common Collector Configuration:

This configuration is much similar to common emitter configuration. The losses in term of components are same but it has more losses in sense that at large scale it may cause problem of high induction losses due to the high inductance between the cells commutated. The diagram is shown as below. The common terminal in this type of configuration is collector for the input and output both signals. The voltage of emitter follows the voltage at the base and due to this reason it is also called as emitter follower configuration. The region where input is supplied is base-collector and from the emitter collector region the output is received. The output impedance is less and the input impedance is very high. Unlike common emitter configuration, in this type of configuration the output and input applied signal both are in phase to each other. The summation of collector and base currents results in emitter current [2].

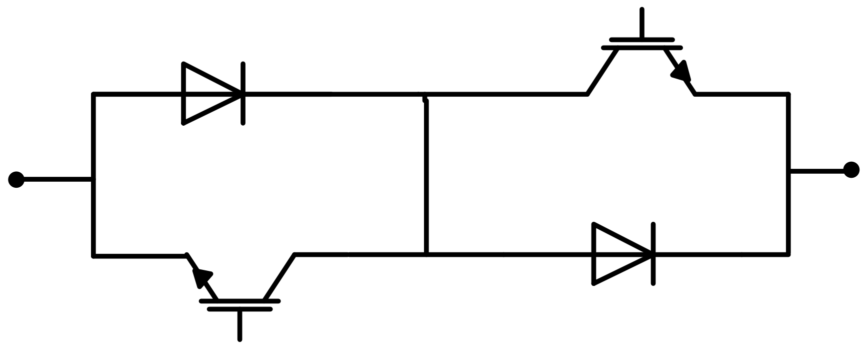

Figure 11 Common Collector type Bidirectional Switch

2.4.1.4 Diode Bridge:

This is basically an arrangement of four diodes and an IGBT. The four diodes are arranged so in a bridge and the polarity of output is same as that of input. This type of arrangement with some changes is also used to rectify AC signals into DC signal. As there is only one IGBT used per switch in this type of pattern so only one driving circuit is needed and this is the main advantage of this type of configuration. The conduction pattern is so that three devices at a time conducts the signals and this is the main disadvantages which leads to higher losses as compared to other configurations. The figure is shown here.

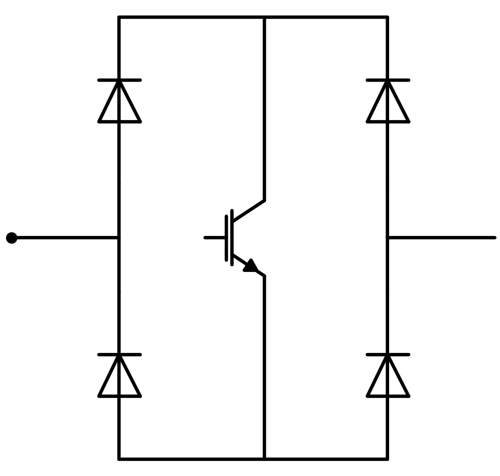

Figure 12 Diode Bridge type Bidirectional Switch

2.1.2 Commutation Techniques for Matrix Converter

The transfer of current and to change it with the change of phase is a big problem in matrix converters. The reason behind this problem is the lack of natural path for freewheeling of the current. The main thing is the commutation between the described bidirectional switches. High short circuit may results when more than one switch is in the output phase are ON at the same time.

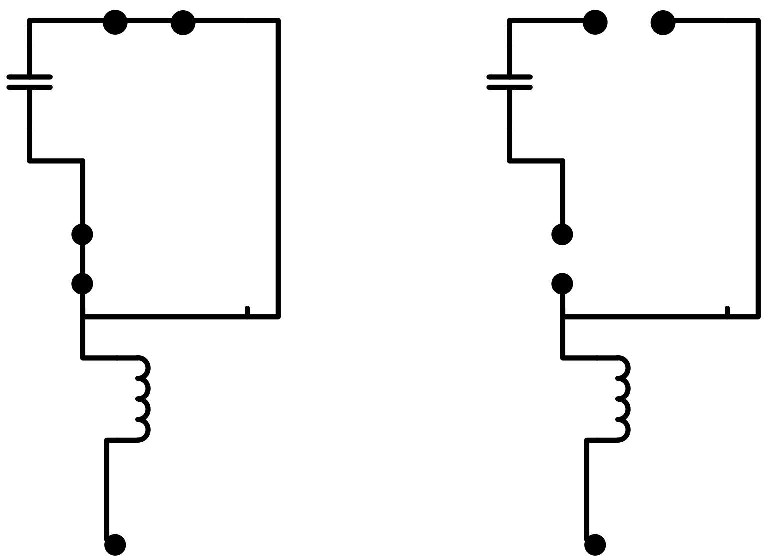

Figure 13 Two Avoiding Conditions in Commutation

The conditions shown in the diagram are actually not good for the system and must be avoided. The opposite condition is when more than one switch are OFF at the same time as this may results in the over voltage condition. The inductive load current must not be disconnected any time. These are some conditions to be must consider while commutating one phase to another phase in matrix converter. Without the described rules current commutation will not be performed but will results in the system's failure. The suggested techniques for the commutation of current in matrix converter are described as below along with merits and demerits.

2.1.2.1 Basic Commutation Methods:

The very basic current commutation methods are semi soft commutation, overlap and dead time commutation techniques.

In overlap current technique there is overlapping of two switches. The switch next to be opened is ON in advance before the last switched is turned OFF. As the two phase's shorts circuits due this condition, so this leads in slight shirt circuiting of the phases. This is the main disadvantage of this type of commutation, as addition of an extra inductor to provide extra supply inductance is needed. This disadvantage limits the use of the described commutation method [4].

The dead time commutation method for current in matrix converter is exactly opposite to the overlap current commutation method. In this type of method the incoming switched is remained OFF until the previous switch is completely turned OFF. The reason behind its name is actually at that time when both the switches are OFF, there is dead time at which the inductive load is feed through some other active or passive sources. Normally this setup for feeding load in case of passive circuit is called snubber circuit. Although this method is safer one than the earlier described due to no short circuiting of phases but the main problem in this type of commutation method is installment of snubber circuit and definitely the losses increased due to the components of the snubber circuit.

2.1.2.2 Soft Switching Techniques:

There are many techniques of soft switching for example auxiliary resonant circuits and resonant switch circuits. Their main goal is to improve the efficiency of PE converter and reduce losses. The basic concept of soft switching is the product of V and I equals to zero at any instant due to which power losses reduces considerably. Thus unlike other switching methods it needs high level of control algorithms and techniques for its operation. In the case of matrix converter the type of soft switching suggested is resonant techniques have the advantages along with the other advantages it provides better commutation. The demerits are very low losses but as described it needs installment of some extra components in hardware and this leads to the complication of overall system. Although this reduces the switching and commutation losses but the losses in the other components increased due to increase in the number of components [32, 33].

2.1.2.3 Advance Commutation Methods:

In these type commutation methods the basic principle is the input voltage magnitude or the exact measurement of direction of load current. As the previous three rules which are the main rules to obeyed and to not break the load current and to avoid short circuiting of any two phases which may lead to short circuit conditions that is difficult to handle. The most favorable advance commutation that obeys the above rules accurately is a semi soft commutation method also termed as four-step commutation method [34][35]. The first step and fourth steps are the short steps as compared to the second and third steps. The second and third steps are long as they are basically the ON, OFF currents duration steps. The first step in which a special flip flop in designed to achieve the input signals in the sectors form, in second step the decision of switching is decided as the realization of allowed switching pattern occurs in this step. In third the decision whether it is right time for a switch to be ON or OFF in accordance to the commutation method is taken. In fourth step there is a proposal of sequenced switching. The output current direction method is the base in this type of commutation method to be use in the matrix converter case.

2.1.2.4 Commutation Method Based on Output Current Direction:

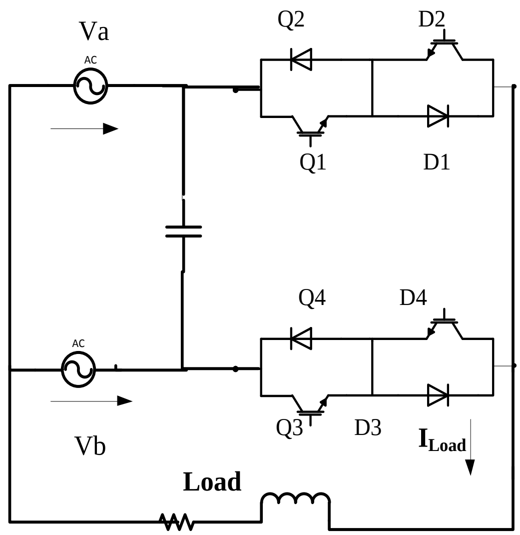

Figure 14 Single Phase Matrix Converter Circuit

In the figure shown above, the matrix converter having two phases at input and basically single phase to feed the load. The flow of current is from both sides in steady state conditions when the upper switched is close the load current is in the direction shown in the figure. To find out which component of an active switch is not conducting the signal the direction of current gives that hint and this is use for the commutation of lower switch. Q2 then switches OFF and the upper switch is turned OFF. The next switch then gated as the current from the previous device passes. It depends upon the polarity of supply voltage as the transfer of the load current to the next coming device or Q1 which was the previous device is turned OFF. The reverse current is allowed by Q4 as its turn ON in the lower switch. The device characteristics tells about the delay to be given between the two consecutive switching's. Due to uncertainty at lower currents or due to other errors in the circuits will mislead the controller about the load current direction which will result in cutting OFF the load current. Therefore a recommended protection technique is required to avoid problems due to such conditions. To gate the conducting devices can create a change in four step current commutation method and will results in only a two-step commutation method. The least pulse width is decreased as the commutation time decreases. The maximum voltage transfer is insured by the minimum width of the pulse [36]. To know the load current direction is the basic principle behind all the current commutation methods. The current drops to low levels in the high power devices due to which it is difficult to know exactly the direction of current. A new method based on the voltage passing through the bidirectional switch to is developed to find out the exact direction of the current [37]. Within the bidirectional switch when the flow of current occurs the direction is determined through a control switching of IGBTs by an intelligent gate drive circuit. The other gate drivers at same output phase switch the switches in the presence of information about the load current direction which they are supplied by FPGA drivers. The safe operation of all switches switching is possible due to proper communication present in this type of commutation. In the case when the load current is small there is lot of harmonics in the output voltage waveform as all the two steps methods use for commutation performs poor in such conditions. The end step of the four step commutation ends on the non-conductive device which gives the advantage to solve this problem.

Here the main feature which based this commutation method is direction of load current. The commutation of current from one switch to another occurs in a definite pattern. In the active switch the load current signal's direction find out the not operating device. Now the switch which is next that is considered to be ON in operated at this instant or when the previous switch completely gets OFF. This all is predicted by the direction of load current. Now the switch conducted the current at the reverse as it gets ON and the process repeats for the next switch.

2.1.2.5 Commutation Method Based on the Voltage Magnitude:

To find out the pattern of switch input voltage magnitude is used in this type of commutation method. The D3 is reverse bias when Q3 is turn ON and commutation from the upper switch to the lower occurs only when potential difference developed at the upper switch is greater than the potential difference developed at the lower switch. The commutation will occurs as Q4 turn ON or commutation to Q3 occurs as the current flow in the shown direction of the previous figure. Line to line short circuit fault occurs at supply side in this type of commutation when any errors occurs in sensing the direction of input voltage. Matrix converter as well as the supply will be in danger during such error. The device which must be used to handle the shoot through situation in this method is different from the described two step voltage magnitude based commutation. To measure the input voltage exactly plays an important role in this method implementation. Commutation sequence will be disturb when the input voltage measurement is not done correctly and this will leads to the errors in the zero at the crossing points of the voltage between two lines. There is a path for the current when the zero crossing point of line to line voltage occurs in the improved version of this method. The inhabited commutation between some phases creates problem in this method and this method is not a complete solution as a result. The critical situation occurs when the two voltages become equal and this situation is handled by the next method. The needed end phase commutation follows the commutation of the third phase at the input and the introduction of two un-critical phases instead of two critical phases occurred in this method. The insertion of another sequence in this method can cause problem which increases the switching losses and this basic disadvantage of this type of commutation method [38][39].

2.1.2.6 The Commutation Method Based on Current Direction and Magnitude of the Voltage:

The magnitude of the voltage and the direction of load current is the base for this method. The direction of load is the guide for conducting all the switches devices. It depends upon the relation between the input voltages magnitude and switching the state to turn OFF two or one device at the same time for the commutation between the three phases. Due to this reason only one step is involved in this type of commutation method. The demerits of this method are many. Due to the crossing of the zero line to line currents, commutation to the mistaken input phase occurs which creates the distortion in the input currents waveforms. The distortion in the output waveform of the load current is present of the crossing point of the zero.

2.1.3 Modulation Strategies of Matrix Converter:

Pulse width modulation was proposed by Stemmler and Schaunung in 1964. This technique was based on the triangular carried sinusoidal pulse width modulation. Later on in three phase converters the described technique was used as a basic modulation technique. Both voltage control loop and current control loop can perform pulse width modulation for the three phase converters case. In the case of inverters however mostly current control loop performance is better as compared to voltage control loop. They respond very fast as compared to voltage control loop and current control loop is the inner while voltage control loop is the outer [40].

Cascade control structure is use for most AC drives for industrial use up till now having the inner faster current loop and outer speed and position loops. To control the current loop is the basic implementation technique for cascade control systems in this case. Faster dynamic response, good tracking, less harmonics, negligible steady state error and very less ripples in the current waveform can only be achieved through a proper current control method. It is recommended that as fast as possible the disturbances must be taken into the account and this can be done when the response of the current or voltage loop is speedy. For example in servo motor drives the most important thing is the control of high current flow in the case when the load increases than the rated. The high load demand is fulfilled by high torque for which the operation of the loop is continuous. To decrease the dependency on the parameters of the stator and to permit the instant response on the flux and the torque of the motor, the current controlled systems are connected with AC motors. To obtain the required reactive and active components of power the current regulation is very must. The harmonics in the current waveform and the power factor of the line are also brought to the desired level through proper current control. For the control of three phase PE converters the control structure is composed of internal feedback loop of the current. The required reference waveform is in ampere-second or voltage-second average just same as a train of switched current or voltage pulses that are created in all modulation methods basically. The power quality of the system is disturbed by the presence of harmonic in the trains of switched pulses although these harmonics are unwanted and need to be minimized. The disturbed power's quality basically impacts the other devices presence in the system and their proper functions are disturbed. To control the matrix converter switching pattern and to modulate the signals there are many methods previously used. The main difference in the choice is the type of load and the rating level for this converter. For the reduction of distortions in the output voltage waveform and also in the input current waveform it is convenient to use an optimal modulation technique. Thus a modulation strategy over all decreases or increases the losses depending upon the application use. For the matrix converters the mostly used modulation techniques are Venturni modulation technique and state vector space modulation techniques. These techniques are sub divided into other modulation techniques but due to their main difference of vector and scalar quantities, they are classified as two large classes to be opted for modulation[41][42].

In Venturini modulation technique the basic background for the calculation of output voltage is product of input voltage and the transfer matrix. The converter's active and zero states are produced through the ratio of instantaneous voltage ratio of particular phase voltages. The main advantage of state vector space modulation technique over the Venturini modulation techniques in matrix converter case is its lower losses. The input current waveform and the output voltage waveform must have fewer harmonic in this application case. The other thing to compare it is easy to deal with scaler quantities than to deal with vector quantities. In state vector space modulation technique as the controller has to deal with vector quantities so it has disadvantageous and in Venturini modulation method as the controller has to deal with scalar quantities so in this case it has advantage to use easily for the controller design purpose. To deal with the vectors in the case of nonlinear loads is much difficult and as a result there are a lot of complications created as well. Overall in the case of nonlinear load for three phase four leg matrix converter the Venturini modulation is recommended [43].

2.1.4 Modulation Techniques for Three Phase Three Leg Matrix Converter:

Initially Venturini modulation method was mostly used for the control of inverters. In the case of matrix converter Borojevic and Hubar for the first used it in 1989. Casadie brought an improvement in SVM technique by controlling the input power factor and output voltage in 2002 [8]. The new strategy was named as full vector space modulation method. In this method as described earlier the quantities are represented as vectors and the vector quantities are input current and output voltages here. The switching states of the matrix converter basically produce that the vectors. Here for example to create a level +1, the other phases at output voltage (b, c, n) must be connect to phase B at input side and the output phase a must be connect to the phase A of the input side. For 3 phase four leg system the available switching states are 3^4 states, that are 81 and in the case of three phase three legs matrix converter 27 [44]. The potential difference between phase line and neutral are given below

$$Vo(t) = \tfrac{2}{3}(Voa + aVob + a^2Voc) \tag{2.8}$$

$$\mathrm{I}_i(t) = \tfrac{2}{3}(\mathrm{I}_i + aI_{2i} + a^2\,\mathrm{I}_{3i}) \tag{2.9}$$

The a is represented by $a = e^{j\frac{2\pi}{3}}$ and the phase voltages at output side are as Voa, Vob, Voc, similarly the currents at input side are represented by I2i, I3i and I1i. Omega is the angular frequency by which the three vectors of output voltage rotate and their length is the magnitude of their length. These voltage vectors are displaced from each other at angle of 120 degree. The output vectors are produced as shown in the voltage equation above is the adjacent space vectors that are switched and gives a time averaged value for a switching duration which intern produces the net output voltage.

2.1.4.1 State Vector Space Modulation for Matrix Converter:

In the case of matrix converter the state vector modulation strategy all switching positions cannot be used. The values that have specific magnitude and some direction which have the properties of a vector can be used as switching conditions. The stationary vectors are actually these vectors. These vectors are shown here in the table.

Table 1 Venturini Modulation states of Matrix Converter

Switching pattern	Converter's state	V_{out}	Displacement angle of voltages	Ii	Displacement angle of currents
+1	S122	2/3 V_{12i}	0	$\frac{\pi}{\sqrt{3}} I_{1o}$	$-\frac{\pi}{6}$
-1	S211	-2/3 V_{12i}	0	$-\frac{\pi}{\sqrt{3}} I_{1o}$	$-\frac{\pi}{6}$
+2	S233	2/3 V_{23i}	0	$\frac{\pi}{\sqrt{3}} I_{1o}$	$\frac{\pi}{2}$
-2	S322	-2/3 V_{23i}	0	$-\frac{\pi}{\sqrt{3}} I_{1o}$	$\frac{\pi}{2}$
+3	S311	2/3 V_{31i}	0	$\frac{\pi}{\sqrt{3}} I_{1o}$	$\frac{7\pi}{6}$
-3	S133	-2/3V_{31i}	0	$-\frac{\pi}{\sqrt{3}} I_{1o}$	$\frac{7\pi}{6}$
+4	S212	2/3 V_{12i}	$2\frac{\pi}{3}$	$\frac{\pi}{\sqrt{3}} I_{2o}$	$-\frac{\pi}{6}$
-4	S121	-2/3 V_{12i}	$2\frac{\pi}{3}$	$-\frac{\pi}{\sqrt{3}} I_{2o}$	$-\frac{\pi}{6}$
+5	S323	2/3 V_{23i}	$2\frac{\pi}{3}$	$\frac{\pi}{\sqrt{3}} I_{2o}$	$\frac{\pi}{2}$
-5	S232	-2/3 V_{23i}	$2\frac{\pi}{3}$	$-\frac{\pi}{\sqrt{3}} I_{2o}$	$\frac{\pi}{2}$
+6	S131	2/3 V_{31i}	$2\frac{\pi}{3}$	$\frac{\pi}{\sqrt{3}} I_{2o}$	$\frac{7\pi}{6}$

-6	S313	-2/2V_{31i}	$2\frac{\pi}{3}$	$-\frac{\pi}{\sqrt{3}}I_{2o}$	$\frac{7\pi}{6}$
+7	S221	2/3 V_{12i}	$4\frac{\pi}{3}$	$\frac{\pi}{\sqrt{3}}I_{3o}$	$\frac{-\pi}{6}$
-7	S112	-2/3V_{12i}	$4\frac{\pi}{3}$	$-\frac{\pi}{\sqrt{3}}I_{3o}$	$-\frac{\pi}{6}$
+8	S332	2/3V23i	$4\frac{\pi}{3}$	$\frac{\pi}{\sqrt{3}}I_{3o}$	$\frac{\pi}{2}$
-8	S223	-2/3V23i	$4\frac{\pi}{3}$	$-\frac{\pi}{\sqrt{3}}I_{3o}$	$\frac{\pi}{2}$
+9	S113	2/3V31i	$4\frac{\pi}{3}$	$\frac{\pi}{\sqrt{3}}I_{3o}$	$\frac{7\pi}{6}$
-9	S331	-2/3V31i	$4\frac{\pi}{3}$	$-\frac{\pi}{\sqrt{3}}I_{3o}$	$\frac{7\pi}{6}$
0_1	S111	0	-	0	0
0_2	S222	0	-	0	0
0_3	S333	0	-	0	0
FR1	S123	Variable	Variable	Variable	Variable
FR2	S231	Variable	Variable	Variable	Variable
FR3	S312	Variable	Variable	Variable	Variable
BR1	S132	Variable	Variable	Variable	Variable
BR2	S213	Variable	Variable	Variable	Variable
BR3	S321	Variable	Variable	Variable	Variable

As visible in the table three sub groups can be form from the first group vectors. The direction of these six vectors is the direction of vectors which are decided by the described states. There is 120^o displacement between each of the three sub groups. The needed input current vectors and vectors of output voltage are generated by using the three null vector and eighteen fixed direction vectors [45]. The output voltage and input current vectors lying adjacent to the vectors needed that are produce by four different configurations for any voltage and current vectors.

2.1.4.2 Venturini Modulation Technique:

This was the first modulation technique developed for matrix converter. Transfer ratio of output to input voltage was initially 0.5. The output desired voltage is obtained at the price of injection of third harmonic in both input and output voltages. 0.866 is the maximum output voltage ratio that can be achieve through this type of modulation technique. The output and input designation is considered as arbitrary due to symmetrical nature of matrix converter as the analysis of three phase input and output converter is taken. Current and voltage "stiff" situation is present at the two ports respectively in the case of matrix converter's sensible mode. As the current and voltage waveforms are constant without certain interruptions or sudden changes so the term stiff is used here. Output current and input voltage ports are stiff after the analysis. The feature of stiff voltage at the output voltage or current has no variations etc. stiff voltage or stiff current feature is generated by circulating high harmonics (produced due to switching) by the input filter in a matrix converter. The stiff feature in the current is basically generated by the output inductive part of the load. Mathematical modeling of matrix converter is done through considering the switching functions as the basic concept. S_{kj} is the general representation of any definite switch here it means that an input line represented by K is connected to the j line of the output phase. The switching function has two values 0 and 1, 0 for the OFF condition and 1 for the ON condition of switch [46]. Using that assumption the relations of currents and voltages are given as below.

$$\begin{pmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{pmatrix} = \begin{pmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{AC}(t) & S_{Bc}(t) & S_{Cc}(t) \end{pmatrix} \begin{pmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{pmatrix} \tag{2.10}$$

$$\begin{pmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{pmatrix} = \begin{pmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{AC}(t) & S_{Bc}(t) & S_{Cc}(t) \end{pmatrix} \begin{pmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{pmatrix} \tag{2.11}$$

The following equation is the must obey rule in the case of every matrix converter.

$$\sum_{K=A,B,\mathrm{C}} m_{Ka}(t) = \sum_{K=A,B,\mathrm{C}} m_{Kb}(t) = \sum_{K=A,B,\mathrm{C}} m_{Kc}(t) \tag{2.12}$$

The main purpose of this equation as a rule is that one switch in any phase can be ON to allow conduction through it. As there are not freewheeling diodes of the basic matrix converter as clears from the diagram of matrix converter so the short circuit and open circuit conditions must be avoided during the operation of a matrix converter. To determine the behavior of output voltage's average of a matrix converter the definition of duty cycle of the modulation must be properly defined. The modulation function is here defined by a mathematical expression which is given as below.

$$m_{Aa} = \frac{t_{Aa}(t)}{T_{sequence}} \tag{2.13}$$

The denominator in the upper modulation equation is the time actually needed to complete one full PWM in the sequence and the numerator is the time when the switch is at ON condition. The time functions are taken then actually the modulation functions. For the case of three phase matrix converter the equations are given as.

$$\begin{pmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{pmatrix} = \begin{pmatrix} m_{Aa}(t) & m_{Ba}(t) & S_{Ca}(t) \\ m_{Ab}(t) & m_{Bb}(t) & S_{Cb}(t) \\ m_{AC}(t) & m_{Bc}(t) & S_{Cc}(t) \end{pmatrix} \begin{pmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{pmatrix} \tag{2.14}$$

$$\begin{pmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{pmatrix} = \begin{pmatrix} m_{Aa}(t) & m_{Ba}(t) & m_{Ca}(t) \\ m_{Ab}(t) & m_{Bb}(t) & m_{Cb}(t) \\ m_{AC}(t) & m_{Bc}(t) & m_{Cc}(t) \end{pmatrix} \begin{pmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{pmatrix} \tag{2.15}$$

The voltage and currents at the left hand sides of the both above equations over the sequenced time are averaged for the ease. The large matrices at the right hand sides of the above equations shows the modulation matrix and more compactly it is written as M(t). So in term of this short term representation the output voltage and the input voltage are represented are below.

$$[V_o(t)] = [\mathrm{M(t)}][\mathrm{V}_i(t)] \tag{2.16}$$

$$[\mathrm{i}_i(t)] = [\mathrm{M(t)}]^T [\mathrm{i}_o(t)] \tag{2.17}$$

2.1.4.2.1 Modulation Method's Solution:

Sinusoidal waveform of both input current and output voltage is required in the modulation technique. Representing these two quantities as a function of time and along with the perspective angle can be expressed easily. For this purpose the equation can be written as below.

$$V_{input}(t) = \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix} = \begin{bmatrix} V_{im}\cos(\omega_i t) \\ V_{im}\cos(\omega_i t + \frac{2\pi}{3}) \\ V_{im}\cos(\omega_i t + \frac{4\pi}{3}) \end{bmatrix} \tag{2.18}$$

For the current the expression set can be written as,

$$I_{output}(t) = I_{om}\begin{bmatrix} \cos(\omega_i t + \varnothing_o) \\ \cos(\omega_i t + \varnothing_o + \frac{2\pi}{3}) \\ \cos(\omega_i t + \varnothing_o + \frac{4\pi}{3}) \end{bmatrix} \tag{2.19}$$

M(t) is the desired matrix of modulation which can be find when the system obeys the desired equations given as below[3]

$$V_o(t) = QV_{im}\begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t + \frac{2\pi}{3}) \\ \cos(\omega_o t + \frac{4\pi}{3}) \end{bmatrix} \tag{2.20}$$

$$I_i(t) = Q\frac{\cos\varnothing_o}{\cos\varnothing_i} I_{om}\begin{bmatrix} \cos(\omega_i t + \varnothing_o) \\ \cos(\omega_i t + \varnothing_o + \frac{2\pi}{3}) \\ \cos(\omega_i t + \varnothing_o + \frac{4\pi}{3}) \end{bmatrix} \tag{2.21}$$

The voltage transfer ratio is represented by Q. In the above equations ωi and ωo are the input side frequency and the output side frequencies are given in the equation for both current and voltage equations. Similarly ∅o and ∅I are the phase displacement angles of both input and output sides. The modulation matrices found by Venturini are given as below.

The modulation frequency is given as $\omega_m = \omega_o - \omega_i$

$$[M1(t)] = \frac{1}{3}\begin{bmatrix} 1+2Q\cos(\omega_m t) & 1+2Q\cos(\omega_m t-\frac{2\pi}{3}) & 1+2Q\cos(\omega_m t-\frac{4\pi}{3}) \\ 1+2Q\cos(\omega_m t-\frac{4\pi}{3}) & 1+2Q\cos(\omega_m t) & 1+2Q\cos(\omega_m t-\frac{2\pi}{3}) \\ 1+2Q\cos(\omega_m t-\frac{2\pi}{3}) & 1+2Q\cos(\omega_m t-\frac{4\pi}{3}) & 1+2Q\cos(\omega_m t) \end{bmatrix} \quad (2.22)$$

Where in the other case it is given as, $\omega_m = \omega_o + \omega_i$.

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

(2.23)

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 $\alpha 1 + \alpha 2 = 1$, (2.24)

$$[M(\mathrm{t})] = \alpha_1 [M1(t) + \alpha_2 [M2(t)] \quad (2.25)$$

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

$$mkj = \frac{tkj}{T_{sequence}} = \frac{1}{3}(1 + \frac{2VkVj}{V^2{}_{im}}) \quad (2.26)$$

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

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

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 [47]. The equation previously described is given as below which is modified by inclusion of third harmonics.

$$V_o(t) = QV_{im}\begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t + \frac{2\pi}{3}) \\ \cos(\omega_o t + \frac{4\pi}{3}) \end{bmatrix} \quad (2.27)$$

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.

$$V_o(t) = QV_{im}\begin{bmatrix} \cos(\omega_o t) & -\frac{1}{6}\cos(3\omega_o t) & +\frac{1}{2\sqrt{3}}\cos(3\omega_i t) \\ \cos(\omega_o t + \frac{2\pi}{3}) & -\frac{1}{6}\cos(3\omega_o t) & +\frac{1}{2\sqrt{3}}\cos(3\omega_i t) \\ \cos(\omega_o t + \frac{4\pi}{3}) & -\frac{1}{6}\cos(3\omega_o t) & +\frac{1}{2\sqrt{3}}\cos(3\omega_i t) \end{bmatrix} \quad (2.28)$$

The unity displacement which is needed can be obtain when the input satisfied by the equation given as below moreover in the both output and input frequencies the third harmonic inclusion is the necessary condition.

$$mkj = \frac{1}{3}[1 + \frac{2V_k V_j}{V^2_{im}} + \frac{4Q}{3\sqrt{3}}\sin(3\omega_i t + \beta k)\sin(\omega_i t)] \quad (2.29)$$

K= A, B, C and j=a,b,c

$\beta k = 0, \frac{2\pi}{3}, \frac{4\pi}{3}$ For k=A, B, C.

Any reduction in the displacement factor of input will result in the reduction of voltage transfer ratio from the maximum 0.866 to other value depending upon the value to reduction in the input displacement factor. There is the inclusion of phase shift between both input voltages (actual and the theoretical) Vk in order to achieve maximum ratio of 0.866, which is the actual targeted value [1].

Chapter 3

Technique for the Controller Design of 3 Phase 4 Leg Matrix Converter

The control of system plays important role in the working of any system. The control system details and controllers design techniques for matrix converter are described in detail in this chapter.

3.1 System's Modeling Technique for the Controller Design

To model a system is important to design an appropriate controller for the specific system. An appropriate controller gives overall system the essential support for its desired performance. Mathematical modeling tells about system's performance in various conditions and normally a controller is designed for the worst conditions of that system. The converter's performance is described by the average model of that system and the modulating signal here explains the converters dynamics. The detailed knowledge regarding the high frequency components of system is not a must part for dynamic analysis of the system and for the design of a controller for that system. The compensators and the filters in the system do not respond to the high frequency components as they are low pass here. Thus in close loop system it deals with the desired low frequency only and for the discrete time system we discretize the system in accordance to the switching frequency. Instantaneous switching values and there conditions are not taken into account while controller design is the only area of interest which is limited to the average values of the variables [48]. Pulse train with the repeating frequency is the normal output voltage waveform of any matrix converter. This pulse train has normally a lot of harmonics especially when the modulation technique is Venturini but also in state vector space type of modulation has also enough harmonics in the output voltage waveform but comparatively less than the Venturini modulation. There to reduce these harmonics a low pass filter at the output of matrix converter is normally implemented. The switching frequency is many times high than the cutting frequency of the low pass output frequency which ensures the reduction of the desired harmonics only. As the converter in the case of 4th leg is composed of 12 switches with each phase have three switches. There the converter is represented by one sample delay and unity gain. As for any system the controller is designed for the worst conditions. In this case the worst condition is no load condition. The overall systems transfer function consists of matrix converter, output filter and the load.

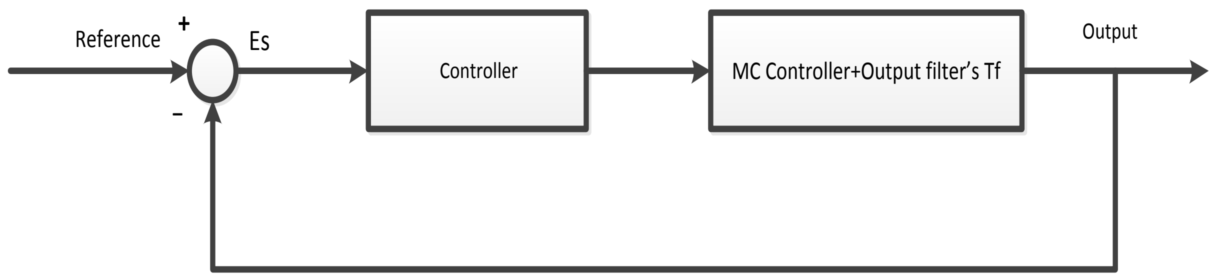

Figure 15 Controller with the System

The converter is denoted by a constant 1 and the output filter is actually considered as the whole system in this case. The transfer function of output filter is given here and is the system's transfer function here. The control scheme scenario for an ideal case of this filter is difficult as in this case it has infinite gain the cutting frequency. But due to inductor and the capacitor's impedance the practical case is not same. In practical case even the bidirectional switches have resistance losses. These all components have some internal resistances. The R_0 is actually the combination of all these internal resistances of these components. The detailed circuit is as;

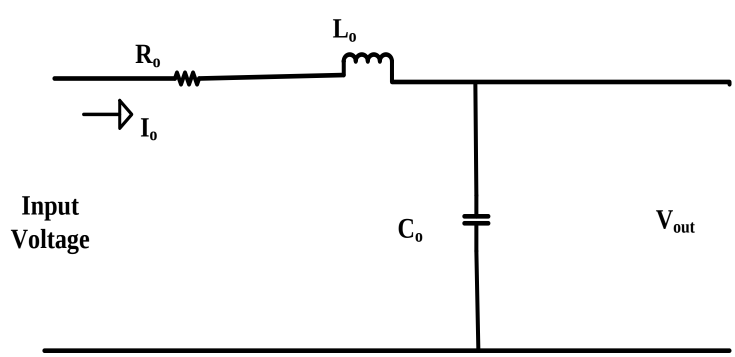

Figure 16 Output Filter's Circuit Diagram

By applying the KVL loop on the filter's circuit the transfer function is as below,

$$Tf = \frac{1/L_oC_0}{S^2 + \frac{r_0}{L}S + \frac{1}{L_0C_0}} \tag{3.1}$$

Capacitor has an internal resistance (r_o, r_c) also there are a conduction losses in the bi-directional switches determined by devices internal resistance. All of these values are grouped together in an inductor equivalent series resistor (r_o). The value of c_o=35 µFarad, the induct value as 583µH and the resistor's value as 0.203 Ohms. The resultant transfer function is given as,

$$Gp(s) = \frac{4.901e007}{S^2 + 233.3S + 4.901e007} \tag{3.2}$$

By plotting the Bode of the system transfer function it is the output filter's transfer function.

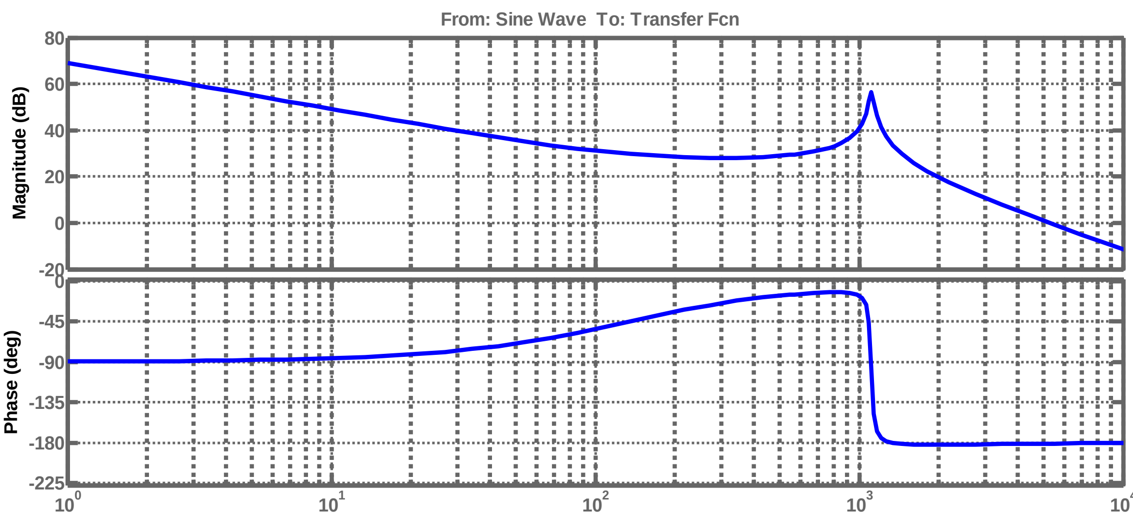

Figure 17 System with PID Controller's Bode Diagram

The Bode plot shows a high gain at the cutting frequency 1100Hz. This means that the selected values of the inductor and capacitor are right and is the correct representation of the system. As the Bode near the switching frequency it attenuates.

After this the transfer function is then converted in to Z domain through c2d command in the Matlab and using the switching frequency inverse as the perspective sampling time. The switching frequency is 12800 Hz, so in Z domain the transfer function can be written as.

$$G(z) = \frac{0.145Z + 0.144}{Z^2 - 1.6932Z + 0.981} \tag{3.3}$$

3.2 PID Controller:

For any system to be controlled the PID is first choice high category controller to be applied for the desired systems stability, although its response varies from system to the system. Normally it is applied in the series with plant as shown in the figure.

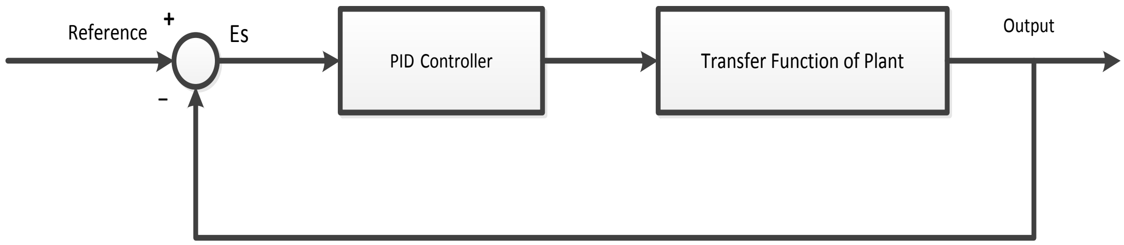

Figure 18 PID Controller with the System

The effects of P, I and D controller are shown in the table below how they contribute in a PID controller, which feature they have individually.

Table 2 Effect of P, I & D values in PID

Controller name	**Tr(Rise time)**	**Overshoot**	**Ts (settling time)**	**Steady state error**
Proportional	Decrease	Enhance	Little effect	Decrease
Integral	Decrease	Increase	Increase	Eliminate
Derivative	Little change	Decrease	Decrease	No change

For the system represented in the frequency domain is controlled by PID controller initially and the result were obtained to check the system's stability. The auto searching tool for the optimum values of P, I and controller is already available in Matlab Simulink and the values are tuned through that. The close loop system in the frequency domain is although stable but the tracking is very poor. The Bode plot for PID controlled system in frequency domain is given as below.

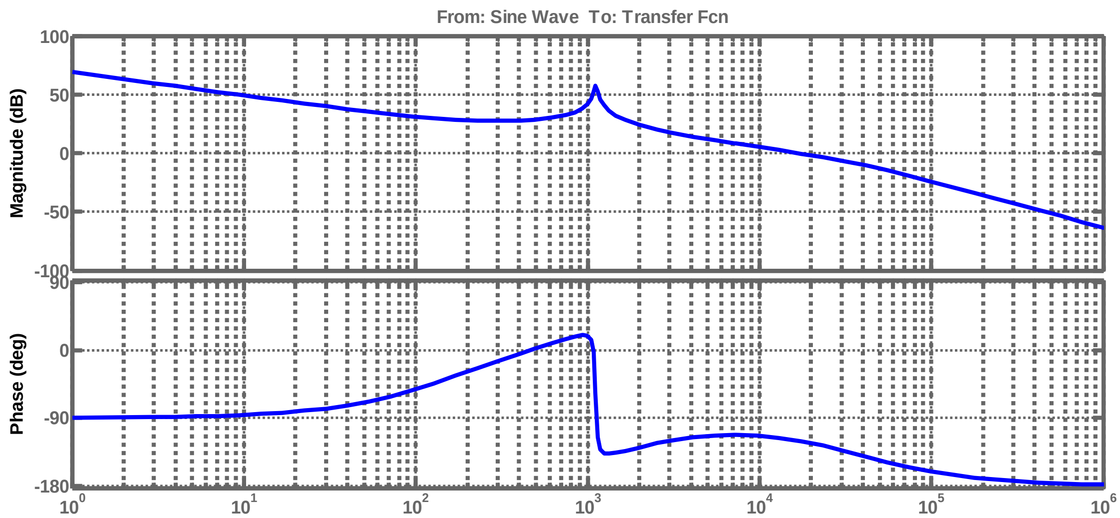

Figure 19 Bode diagram the System by Using PID Controller

However the response of PI controller was also checked for the results. After that the model is discretized into Z domain. Similarly the discrete PI controller were applied and checked for the result. The system's been totally un-stable with PID controller and even did not follow the signal. Although for PI controller the system is unstable but it's bode has phase as well as gain margin.

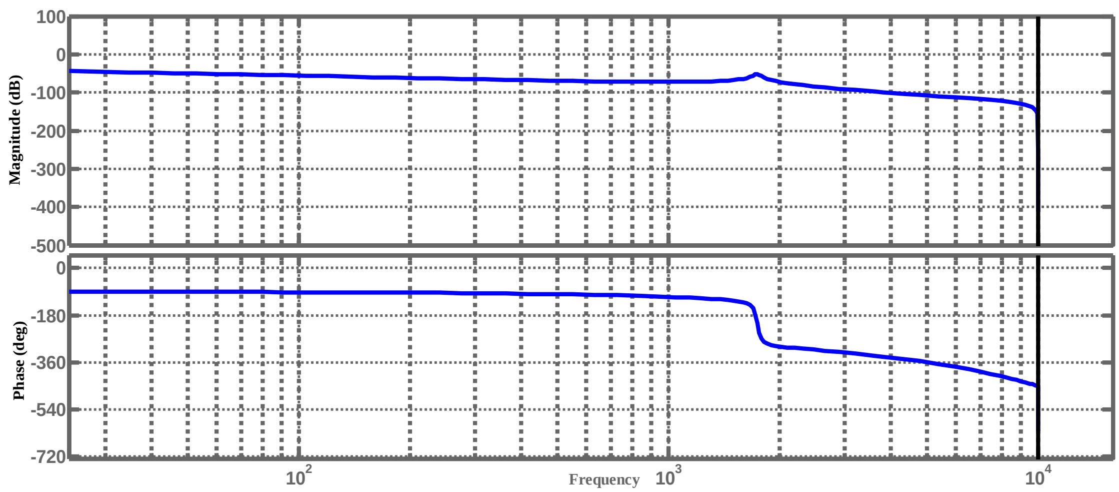

Figure 20 Bode of PI Controller System

3.3 Application of Resonant Controller on the System:

Resonant controllers of various categories are extensively used in many applications in PE converters mostly in inverters and AC drives. Due to its better performance and compact structure as compared to the other high level controllers' resonant controllers are preferred but their application is not that easy. One of the most important features is resonant controller hypothetically or ideally introduces very high gain at some specific frequency called as central resonance frequency. Due to the introduction of high gain at resonant frequency it can be easily used to track the signals having sinusoidal nature. The infinite AC gain production at resonant frequency and no phase shift at other frequencies is the main feature of a resonant controller [49]. In this system proportional resonant controller is used. The controller have sub controller in parallel form for each harmonic handling. The number of sub controllers depends upon the tracking of the harmonics. The basic transfer function of PR controller is given as below,

$$G_r(s) = K_p + \frac{K_r \omega_o s}{s^2 + \omega_o^{\,2}} \tag{3.4}$$

Kp and Kr are proportional and resonant gains respectively while ω_o is the central resonant frequency. However this transfer function cannot be use due non-ideal, infinite gain at central resonant frequency. Thus few non ideal terms are added to the controller's basic transfer function which make the controller behavior no-ideal.

$$G_r(s) = K_p + \frac{K_r \omega_o s}{s^2 + (\omega_o / Q)s + \omega_o^{\,2}} \tag{3.5}$$

Q is the factor added called controller's quality factor and has basic formula as,

$$Q = f_c / (f_H - f_L) \tag{3.6}$$

Where the term f_c is the central frequency representation, f_h, f_L are the upper and the lower frequency respectively. 0.707 drop of the system's central resonant frequency defines the borders for both upper and the lower frequencies [50][51]. The resonant controller is used in series with a classical controller that is designed through Siso tool of Matlab.

$$Gc(z) = 0.15 * \frac{Z^2 - 1.693Z + 0.9819}{Z^2 - 0.495Z - 0.49}$$

The value of Q is kept as large as possible because higher its value greater the disturbance rejection property the controller has, Q increases the gain of the system enough to track the desired reference signal. Q=1000 is selected. For each individual harmonic a separate sub controller in connected in the parallel with the fundamental transfer function of resonant controller as shown in the diagram below.

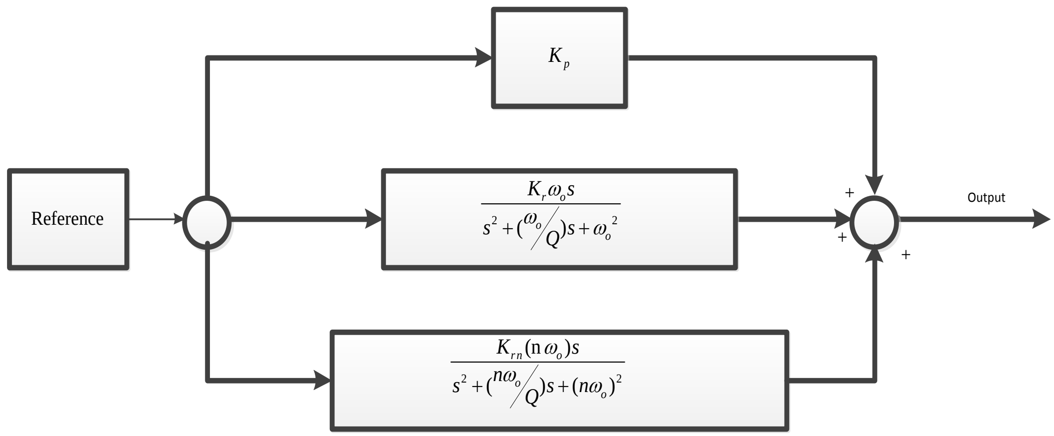

Figure 21 Schematic Diagram of Proportional Resonant Controller

The equation will become then,

$$G_r(s) = K_p + \frac{K_r \omega_o s}{s^2 + (\omega_o/Q)s + \omega_o^2} + \frac{K_{rn}(n\omega_o)s}{s^2 + (n\omega_o/Q)s + (n\omega_o)^2} \tag{3.7}$$

For example for a resonant controller if we want to track a system up to 5th harmonic then the desired controller's transfer function will be as,

$$G_r(s) = K_p + \frac{K_r \omega_o s}{s^2 + (\omega_o/Q)s + \omega_o^2} + \frac{K_{3r}(3\omega_o)s}{s^2 + (3\omega_o/Q)s + (3\omega_o)^2} + \frac{K_{5r}(5\omega_o)s}{s^2 + (5\omega_o/Q)s + (5\omega_o)^2} \tag{3.8}$$

For a resonant controller to track a system up to desired harmonic must give the high gain peak exactly at same frequencies where these harmonics are present. For example for a 50 Hz system and fifth harmonic tracking the system the high gains peak must be at 50hz, 150Hz and 250 Hz respectively.

Similarly for our system 400 hertz, the Bode of controller must have high gain peak at fundamental frequency and the Bode of the controller shows that by changing the value of resonant gain and the Q changes the gain in bode diagram as shown in the figure below.

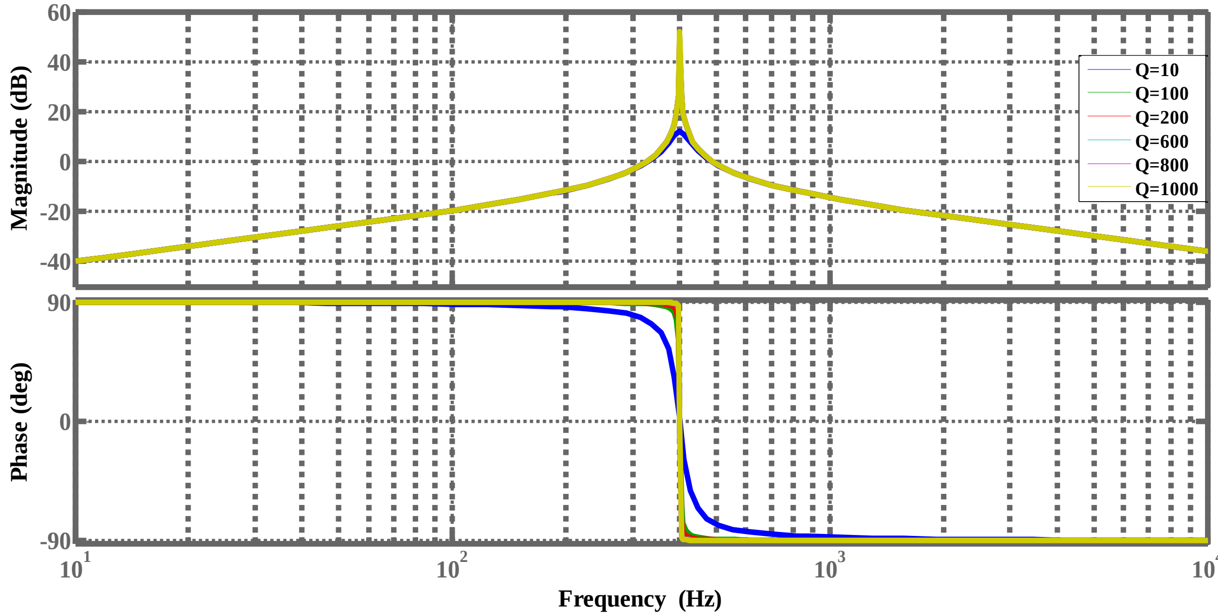

Figure 22 Bode Diagram of Resonant Controller with the Various Q Values

Similarly the effect of increase or decrease in the value of proportional gain is shown in the bode diagram of controller.

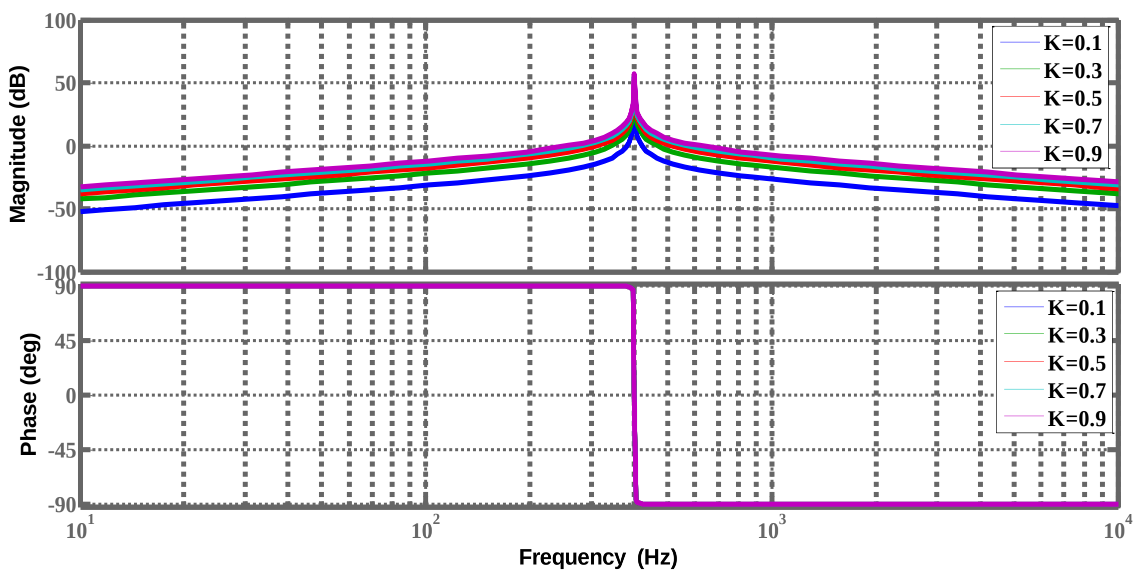

Figure 23 Bode Diagram of the Resonant Controller with the Variuos Valeus of K

Upon application of controller at the system up to the third harmonic the system is stable with a phase margin of 54.4 degrees and gain margin of 11 dBs, the selected value of resonant gain is

0.5 and Q is 1000. But the system is stable even for the 5th harmonic tracking. For the simplicity and cost practically a resonant controller is limited to a state as close as it is possible.

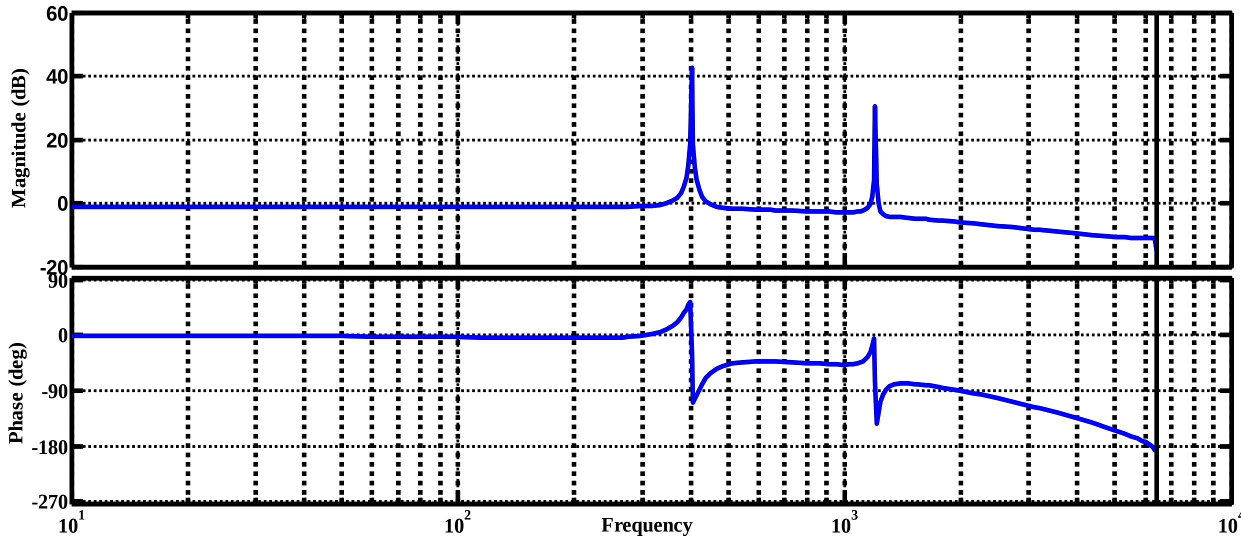

Figure 24 Bode Diagram of the System when Controlled by PR controller Up to 3rd harmonic

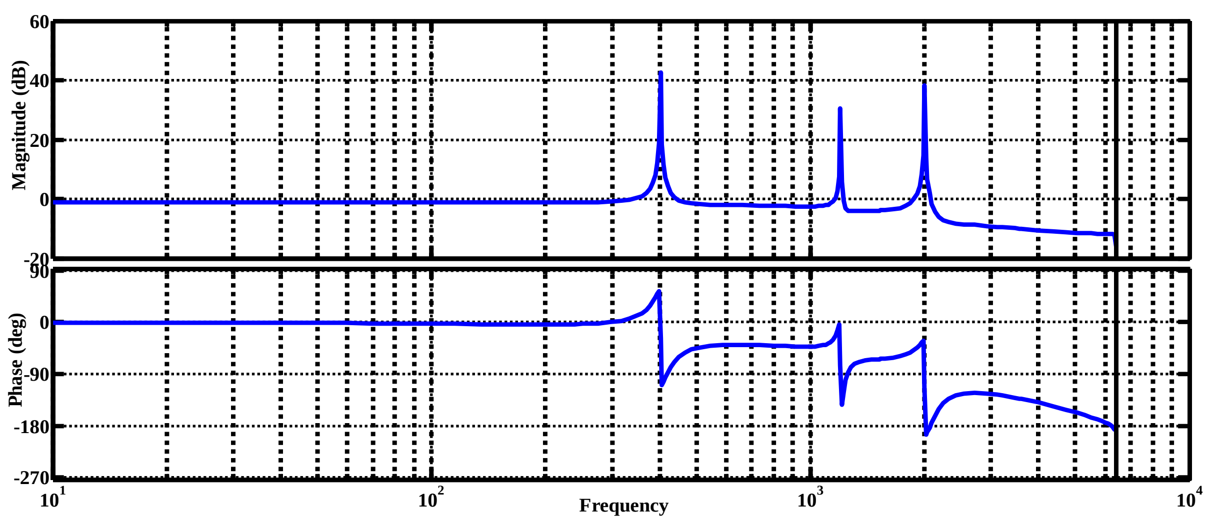

Figure 25 Bode Diagram of the System Controlled by PR Controller Upto 5th Harmonic Tracking

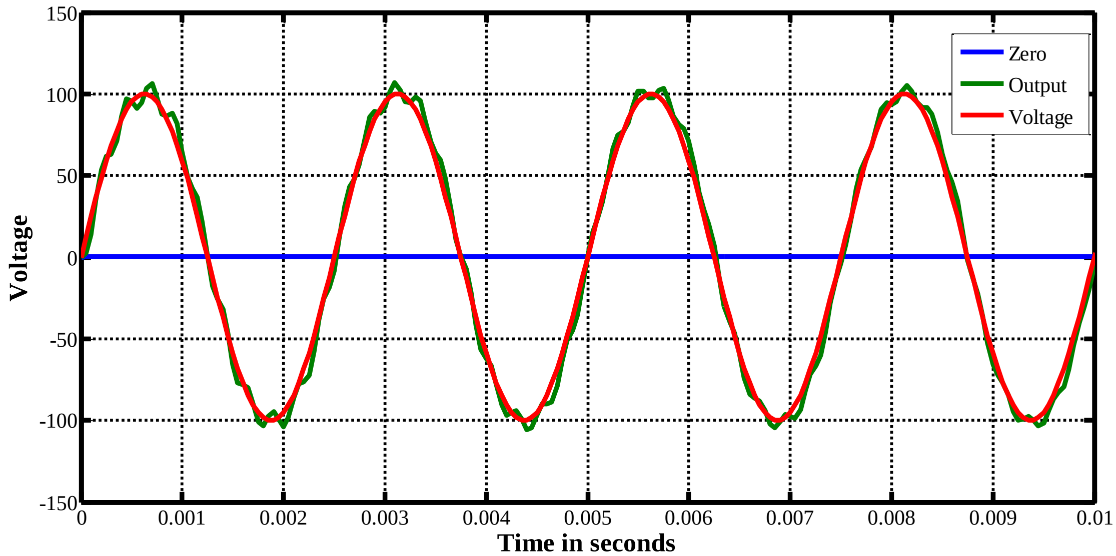

Figure 26 Reference Vs Output Voltage Waveform

After some time the error is reduced and accurate tracking of the output waveform occurs which is given as below.

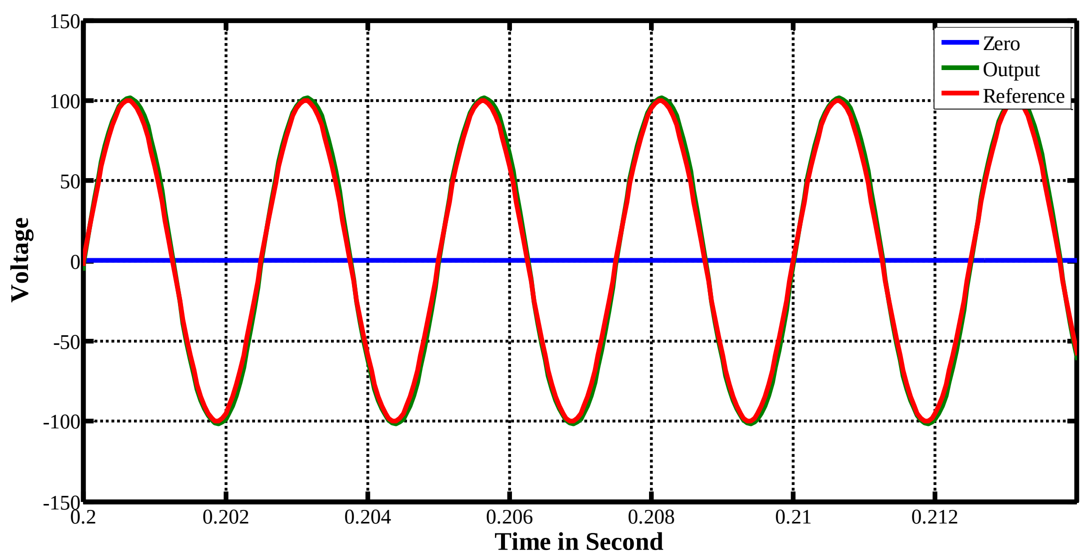

Figure 27 After 0.2 Seconds the Tracking of Controller's Output Waveform Vs the Reference Waveform

In the sinusoidal reference signal tracking normally iterative repetitive controller, common repetitive controller or a type of resonant controller may be used depending upon the design parameters and the loop to track (current or voltage). As compared to PID or classical second order linear controller PR controllers shows best results for the sinusoidal reference tracking and provides high gain enough to track exactly the reference signal. The bode diagrams for the third and fifth harmonic matrix converter controller are shown in the above diagrams. The exact tracking of reference signal approves the valued assigned to all gains and technically a correct controller.

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Annexure I

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Design and comparison of PID and Proportional Resonant controllers for Matrix converter

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Abstract

In this paper we represent a comparison between PID and Proportional resonant controllers for matrix converter used for unbalance load application. The simulation has been done in Matlab Simulink. A linear model transfer function of matrix converter has been taken to be control by Proportional Resonant controller and PID controllers. Various parameters are taken to find out the close loop system stability. First PID controller and then Proportional resonant controller checked for close loop system's responses. Optimal controller has been suggested on the basis of best performance for reference sinusoidal tracking.

***Symbols*:** Matrix Converter, PID Controller, Proportional Resonant Controller (PR).

1. Introduction:

Matrix converter is AC-AC converters. They have advantage over classical voltage source converters due to the presence of less number of energy storage components which cause losses as well as ageing of the converters [1]. But we cannot say matrix converter is pure static solution for AC-AC conversion [2]. In the direct matrix converter the main energy components are its output and input filters. For each phase of input, it is connected via 3 switches per phase to connect with subsequent 3 output phases as shown.

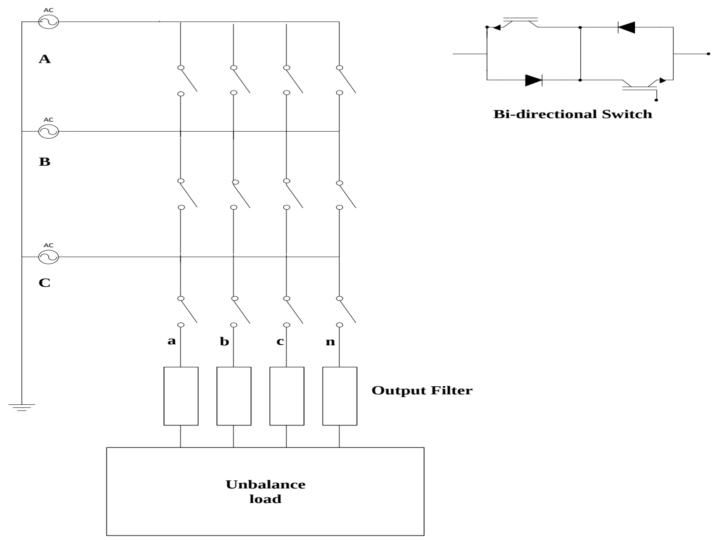


Figure 1. Three Phase Matrix Converter diagram

Input filter is applied mainly to stop switching noise to enter into the supply system and also to reduce the angle between V and I [3]. On the other side the output filter is completely a very important phenomenon for our system. It is basically low pass LC filter. Its main purpose is to get rid of the ripples present in the output waveform.

For linear system we consider our system transfer function as transfer function of output filter and load as represent the matrix converter by unity gain and one sample delay unite. For a system having unbalance, balance or no load conditions, the worst scenario is that of no load .First we check our system's response as open loop system. It shows that our system is unstable. After that various controllers were applied and the system is consider as close loop. The system input Voltage is 415 with 50 hertz and output is 100 Volts with 400 hertz and our rating is 7.5 Kilo-volt-ampare. In this paper a single voltage control loop is used. As the internal current loop is very fast as compared to the outer voltage loop so it is recommended to not use the internal current loop [4].

2. System parameters and Output filter:

As at output matrix converter gives our desired frequency sinusoidal waveform. As in direct matrix converter the output waveform is purely derived by consequent sampling of input waveform through switching. There are two types of harmonics exist in our system, the low frequency harmonics and high frequency harmonics. Due to fast switching the high frequency harmonic are more visible in input current waveform for which input filter is use as alternative path. Low frequency harmonics are caused due to switching ripples in the incoming voltage and current waveform, non-linearity included in converter. These all leads to low frequency harmonics in the waveforms of perspective input current and output voltage. Thus the output waveform is not that smooth having harmonics which lowers the power quality. To purify the output waveform and to extract sinusoidal waveform at output a low pass LC filter is use which actually distorts the harmonics from the waveform. To design a control system and to analyze it, the system compensators and filters are select as low pass so the higher frequency regarding knowledge is not accountable here.

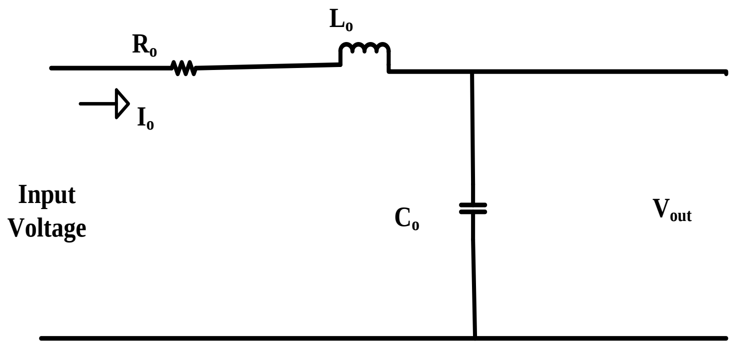


Figure 2. Output filter diagram

The cutoff frequency is dependent on controller bandwidth and is approximately taken as 1/10th of the switching frequency [5]. The values of inductor and capacitor depend upon the cutoff frequency of filter as,

$$f_{resonant} = \frac{1}{2\pi\sqrt{L*C}} \quad (1)$$

To use this converter as a voltage source converter as inductive load is connected at the other side in normal case. For this purpose inductor value is taken very small and high value of capacitor to keep cut off frequency but very exceeding value of capacitor may lead to inrush current flow into the system. So we have to be in balance between these two extreme conditions [6]. The value of inductor is taking as 0.58mH with an internal resistance of 0.8 Ohms. From the equation by putting the values in equation as,

$$C = \frac{1}{\omega^2 * L} \quad (2)$$

While ω =2*π*f and L=0.58mh. The value of f is taken as 1.1 KHz.

$$C = \frac{1}{(2*\pi*1100)^2 * (0.00058)} \quad (3)$$

For approximation the capacitor value is selected as 35*10-6 Farads. Now the transfer function of the filter circuit in frequency domain is as,

$$Tf = \frac{1/L_oC_0}{S^2 + {r_0}/{L}\, S + 1/L_0C_0} \quad (4)$$

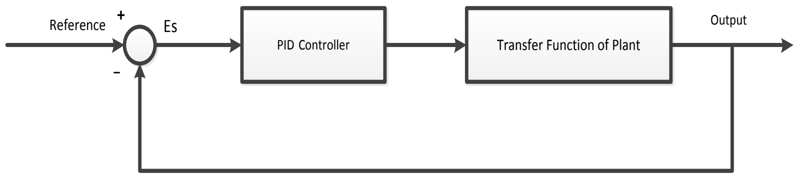
By putting the values of ro, Co and Lo in the above transfer function and by converting that transfer function into discrete form taking 12800 Hz sampling frequency. The discrete transfer function is presented as,

$$G(\mathrm{z}) = \frac{0.145Z + 0.144}{Z^2 - 1.6932Z + 0.981} \quad (5)$$

Here I applied a PID controller for the above system’s stability and checked the system response through various parameters shown.

3. PID Controller:

As we know PID is basically combination of 3 types of controllers Kp (proportional), Ki (Integral controller) and Kd (derivative controller). The values of the above three controllers are arranged so that over all controller stabilize our system. Kp controllers have the flaw to cannot eliminate steady state error but it actually decreases the Tr (rise time). Similarly Ki controller decreases steady state error but increase settling time. Similarly Kd decrease both overshoot and settling time.



Controller name	Tr(Rise time)	Overshoot	Ts (settling time)	Steady state error
Proportional	Diminish	Enhance	Little effect	Diminish
Integral	Diminish	Increase	Increase	Eliminate
Derivative	Little change	Diminish	Diminish	No change

Figure 3. PID Controller with plan

Table 1 Effect of P, I & D values in PID

Here P, PI and then PID are applied directly in series with the plant transfer function. The final system a PID is selected in frequency domain. The values for the perspective P, I and D are hunted through controller design in Simulink Matlab, which gives us the optimized values. By applying the above conditions although the close loop transfer function is stable for continues time system but it has very minute gain enough to track sinusoidal signal [7]. By applying PID the system shows no results even more due to derivative action of PID, which make the system the numerator of the system zero at certain unknown value which make our system unable to run at that point.

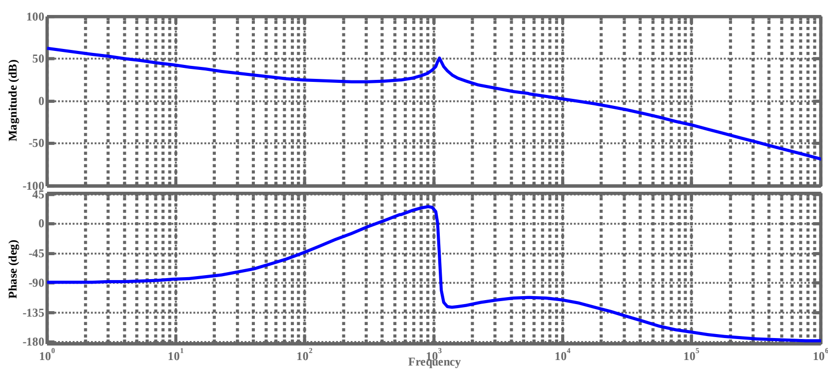


Figure 4. Bode of continuous of the system with PID controller

In discrete model it shown very poor model response and the controller was almost unable to track the reference sinusoidal signal.

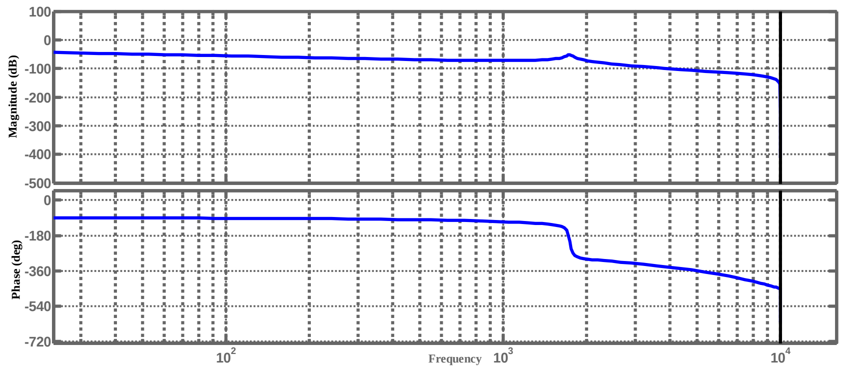


Figure 5. Bode of the discrete system PI controller

4. Proportional Resonant Controller:

I used a parallel proportional resonant controller with a proportional gain of 3. Basically an ideal Proportional resonant controller gain value is infinity ideally but practically we put some real values for our system. Normally we use PR control to reduce steady state error up to zero. Therefore it is an efficient controller to use in the systems involving sinusoidal signals. Here in our system as we use a system involved sinusoidal signals or AC power so the PR controller work very efficiently in such systems to track the desired input reference signal. Due to very high gain value at fundamental frequency it provides us better disturbance rejection and also can handle individual harmonic. We can say that PR controller is actually an AC integrator having similarity with an integrator which introduces infinite DC gain. As the controller provides infinite gain ideally for AC frequency systems but it provides neither gain nor phase shift at other frequencies [8]. In PR controller we deal individually with each harmonic, but going for higher order harmonics may complicate our system. This in return will also complicate our system hardware. The digital hardware will be more difficult to implement as a result. The transfer function of ideal PR controller is given as below.

$$G_{res}(s) = K_p + \frac{K_r \omega_o s}{s^2 + \omega_o{}^2} \tag{6}$$

Kr is resonant gain, K_p is proportional gain, ω_o is resonant frequency. In non-ideal system some changes are considered. Here a new term Q was introduced, Q is called as quality factor and its value is as [8],

$$Q = f_{central} / (f_H - f_L) \tag{7}$$

The terms here are $f_{central}$ is the central resonance frequency, f_H is the upper level frequency f_L is the lower level frequency. These both upper and lower frequencies are selected so as the system gain drop to 0.707 of central resonance frequency. Normally it is recommended to have higher value of Q, for this purpose the values of both lower and upper frequencies are chosen closer to the value to fundamental or central resonant frequency [9]. We keep the value of Q high in order to achieve high gain.

We can say for this purpose we choose a tiny band pass. On the contrary to have lower Q value gives us poor rejection of disturbances accompanied by lower gain. This will result in a higher steady state error. To efficiently reject the disturbances and to track the reference input, the value of Q is chosen larger keeping in mind the system's overall stability. The non-ideal transfer function of PR controller including Q is as below.

$$G_{res}(s) = K_p + \frac{K_r \omega_o s}{s^2 + (\omega_o / Q)s + \omega_o^2} \tag{8}$$

This is the equation for 1st harmonic, for each harmonic we add a separate block with the value of n equal to the value of prescribed harmonic.

$$G_{res}(s) = K_p + \frac{K_r \omega_o s}{s^2 + (\omega_o / Q)s + \omega_o^2} + \frac{K_{rn}(n\,\omega_o)s}{s^2 + (n\omega_o / Q)s + (n\omega_o)^2} \tag{9}$$

For example if we want to provide desired gain at 3rd and 5th harmonics then our desired equation will be as,

$$G_{res}(s) = K_p + \frac{K_r \omega_o s}{s^2 + (\omega_o / Q)s + \omega_o^2} + \frac{K_{3r}(3\omega_o)s}{s^2 + (3\omega_o / Q)s + (3\omega_o)^2} + \frac{K_{5r}(5\omega_o)s}{s^2 + (5\omega_o / Q)s + (5\omega_o)^2} \tag{10}$$

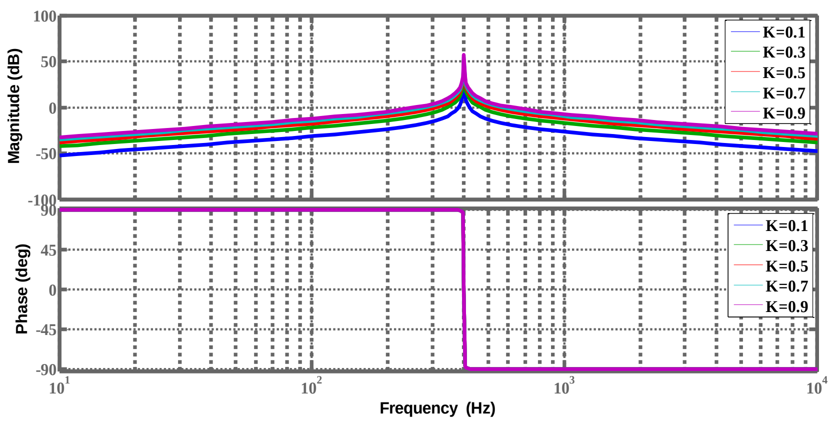


Figure 6. Bode of the Controller by changing the value K (resonant gain)

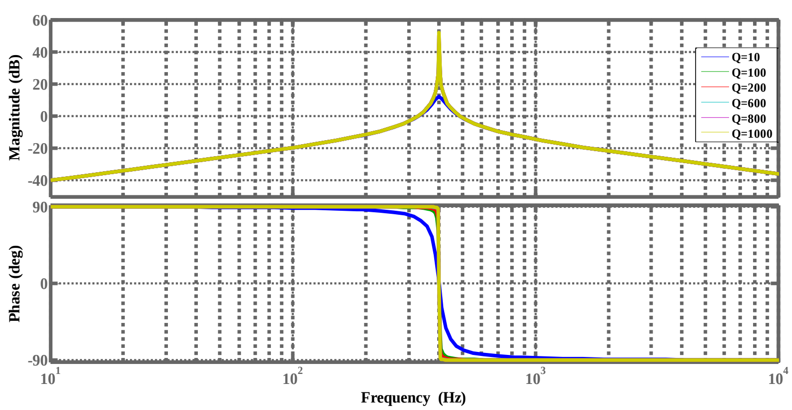


Figure 7. Bode of the Controller by changing the value Q.

Each new block for perspective harmonic there will be an addition of new block in the controller block depending upon the system requirements. For PR controller a linear second order controller designed through SI SO tool is use in conjunction with plant's transfer function. Here the only two controllers are applied at 1st and 3rd harmonics and it shown satisfactory results. Initially a controller at 5th harmonic has been applied as shown in the figure (8) to note the changes in results due to the addition of new controller block. The gain is provided as shown in the figure (8) at 400 Hz, 1200Hz and at 2000Hz.

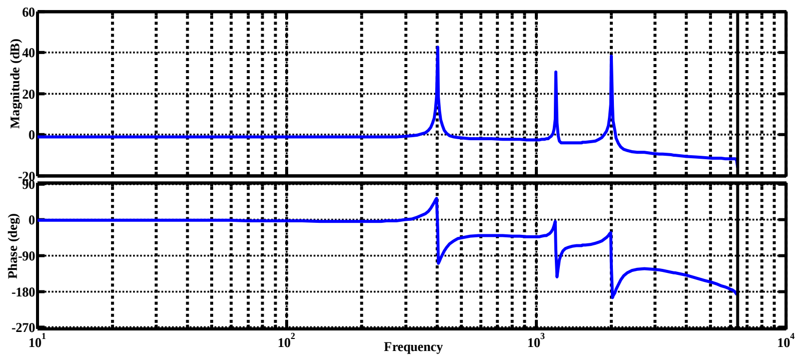


Figure 8. Bode of the system using 5th harmonic PR Controller

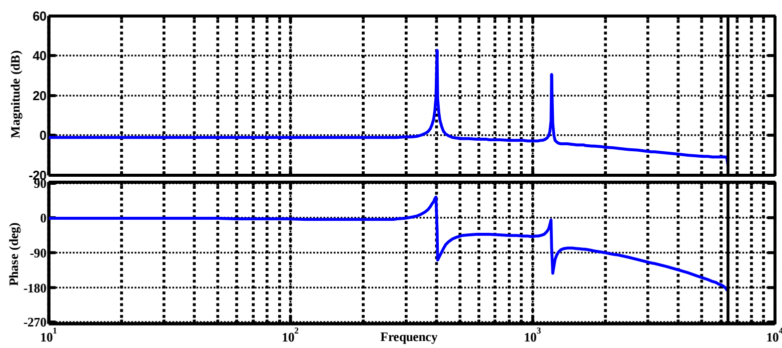


Figure 9. Bode of the system using 5th harmonic PR Controller

The gain margin is 11dBs and phase margin is 54.4 degrees by selecting the value of Q=1000 and resonant gain value as 0.5. The results from bode and output wave shows that we already have enough gain. However this addition of controller block for 5th harmonic will further complicate our system and also will increase the price of overall controller development. The bode plot shown an increase in the gain at that very harmonic where a control block has been applied. In the sinusoidal tracking high gain is needed for periodic signals distortion. The sub-controller provides that desired gain at the applied harmonic. However, high gain may lead the system towards more error by increasing the magnitude of the output signal more than the desired level. From the figure (7) below it is clear that controller provide desired at fundamental frequency(400Hz) and at 3rd harmonic(1200Hz).The output voltage signal with the reference tracking is shown in the below diagrams. By applying error signal initially even at 10V magnitude our system shows stability. Due to the introduction of error initially it shows very less distortion before 0.02 seconds which then smoothens after 0.04 seconds as shown in the figures below.

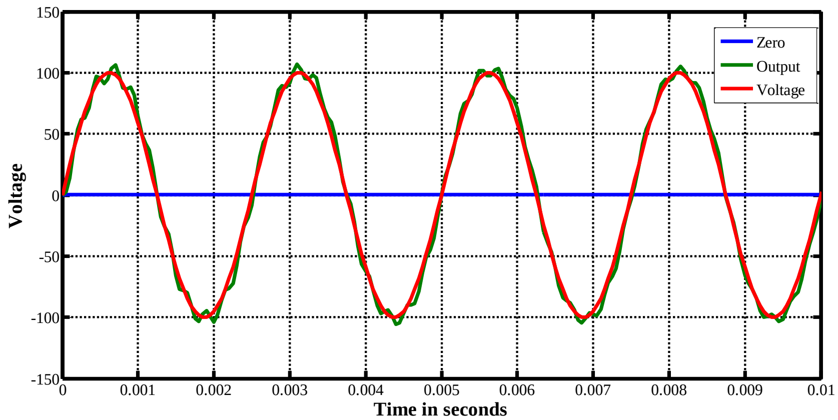


Figure 10. Output Voltage sine wave

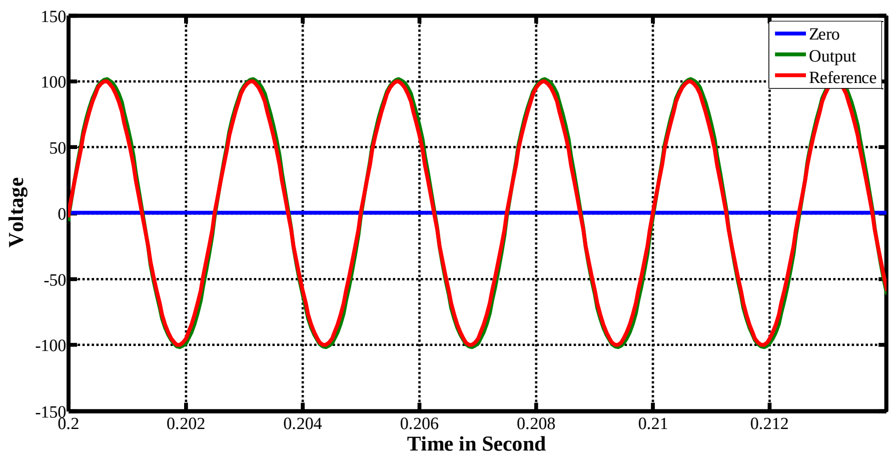


Figure 11. Output sine wave after 0.2 second

5. Conclusion:

For sinusoidal tracking in matrix converter it is strongly recommended to not apply PID controller. The main reason behind is for sinusoidal signal tracking a high gain is needed at the desired time for harmonics distortion. The PR controller on the other hand provides better results and better reference sinusoidal tracking as compared to PID controller. The total harmonics distortion is PR controller is also less than the 5% as required per international standards and the gain margin is 11dBs and phase margin is 54.4 degrees already. Therefor it is suggested to use PR controller for matrix converter control as compared to PID controller.

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Annexure I I

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Design and Analysis of Optimal Controllers for Grid Connected Inverters for Photo Voltaic Applications

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Abstract

The focus of this research article is to model and analyze optimal controllers for a two level, pulse width modulated, grid connected inverter using Matlab. The Proportional Resonant controller and Linear Quadratic Regulator are being investigated. The controllers are designed such that their performance is satisfactory. The simulation results are presented to illustrate the performance of the designed controllers under robust grid conditions.

Keywords: Grid Connected Inverter, Current Control, Linear Quadratic Regulator, Proportional Resonant Controller, Photo Voltaic Systems.

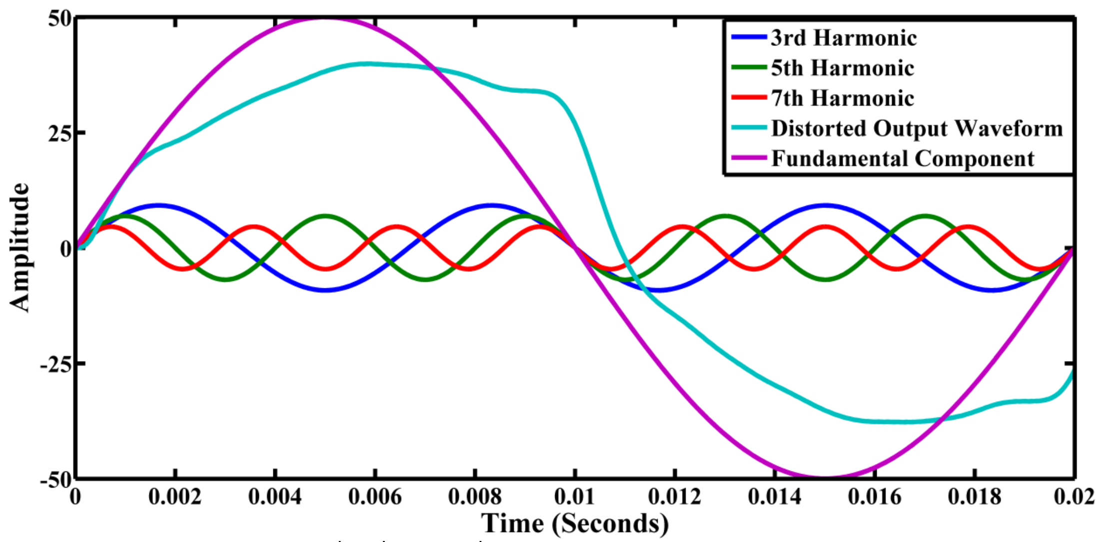
Introduction

The power quality, importance increases in Renewable Energy Systems (RES) especially Photovoltaic (PV) systems. The increase in the number of the Photovoltaic systems connected to the grid has increased the importance for the implementation of a unified standard for these installations. In this regard, the standards followed are IEEE 1547 and IEEE929 along with IEC 612727.According to these standards, the overall allowable limit of the Total Harmonic

Distortion (THD) is 5%. The odd harmonics from 3rd to 9th should be under 4% each and allowable limit of the odd harmonics from 11th to 15th must be 2%.

These standards present a challenge to the design engineers to develop current control systems that is able to not only meet these requirements, but is also capable of rejection of the grid variation in order to ensure a reliable operation of the installed PV system according to the prescribed standards of IEEE.

Fig.1. shows a sinusoidal waveform with the fundamental frequency of 50 Hz and a distorted



waveform in the presence of 3rd, 5th and 7th harmonics. As seen from the figure that the presence of harmonics can result in a reduction of the power quality. The conventional controllers fail to mitigate the harmonics and thus there arises a need to adopt advance current controllers that can effectively remove the harmonics [7].

The main objective of this article is to design a grid connected PVS and investigate the performance of Proportional Resonant (PR) and Linear Quadratic Regulator (LQR) by simulating the systems in *Matlab*. The performance of CCs is analyzed under high distortions using the axioms of control theory.

Fig. 1. Current Waveform under Harmonics

Mathematical Modeling of the Grid Connected System

The control system forms an integral part of the PVS[1][2][3][4]. The control of the renewable energy system has two main parts. The grid side control and the input power control [6]. The grid side control mainly handles the power flow and its control from the grid side. It may include control of active and reactive power, synchronizing the grid and quality of the power. The input power control ensures that maximum power is extracted from the renewable energy systems, keeping in view the safety and reliability of the whole system.

The control scheme that is applied to control the converter of the grid side in the renewable energy systems has two interlinked control loop. The inner current loop has a faster response and it controls the grid current.It is the main loop for the quality of power that is fed to the utility. It also ensures the protection of the equipment by controlling the current. The external voltage loop is responsible for controlling the voltage across the capacitor that serves as the D.C. link.Inherently system will be unstable if the output grid current of an LCL filter is directly feed backed, so to stabilize the system, there must be an additional feedback loop. Additional feedback can be provided either by the main inductor current or by capacitor current[5]. If the gain for the PWM block is assumed to be unity then the relationship between the output current and reference input current is given by the following transfer function;

$$I_u = \frac{Gz(s)}{1+Gz(s)} I_{ref} - \frac{G_{plant}(s)}{1+Gz(s)} \text{Vutility} \tag{1}$$

$$Gz(s) = G_{plant}(s) * G_{controller}(s) \tag{2}$$

To make the system more realizable and closer to real time scenarios a disturbance function can be introduced which is given by the following equation as

$$\text{Disturbance}(s) = V_{utility}(L_g C s^2 + K_c C s + 0.5) \tag{3}$$

The system values that are used for the Matlab simulation are given in the Table 1.

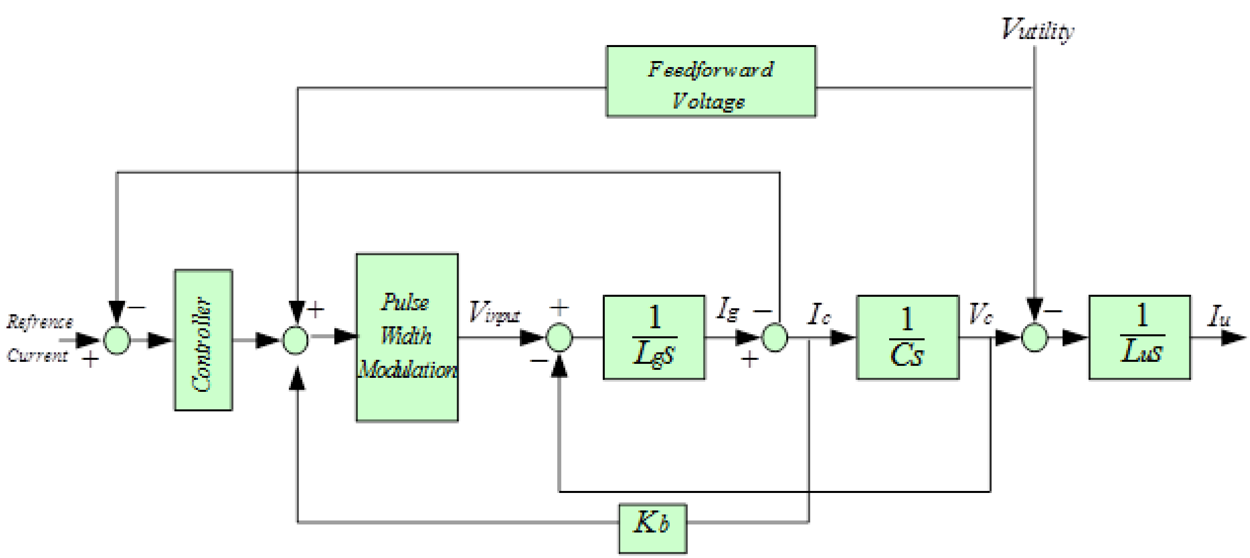


Fig. 2. Control Structure of the Grid Connected Inverter

Table 1. Component Values of the Grid Connected System

Sr. No.	Electrical Parameter	Symbol	Value
1	Peak Voltage of the Grid	V_{peak}	230 *V (rms)*
2	DC link voltage	V_{dc}	800 *Vdc*
3	Grid inductor	L_g	350μH
4	Utility inductor	L_u	50 μH
5	Capacitor	C_s	22.5 μF
6	Switching frequency	f_s	10 *kHz*
7	Grid Frequency	f_g	50*Hz*
8	Output Current	I_{out}	50*A*

Matlab Simulation Results

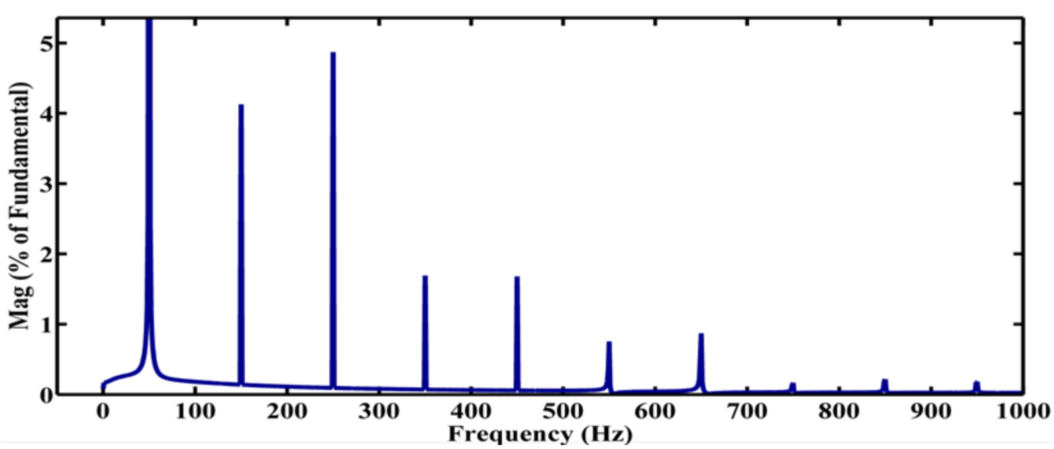


Fig. 3. Frequency Spectrum for PI Controller having THD=8.05%

Fig. 3 shows the Fast Fourier Transform (FFT) analysis of the PI controller when the a THD of 2.74% was introduced in the utility voltage. The THD values at the output was found to be 8.05% . Though it was able to reduce the THD values, but it failed the ANSI-IEEE recommended THD values which is 5 %. The odd harmonic at 250 Hz was the highest harmonic that the PI controller failed to suppress.

Frequency Response of Optimal Controller Under Harmonic Distortions

A novel Proportional Resonant (PR) controller was designed using Harmonic Compensators (HC) for higher order harmonics. The frequency spectrum analysis was obtained as shown in Figure.

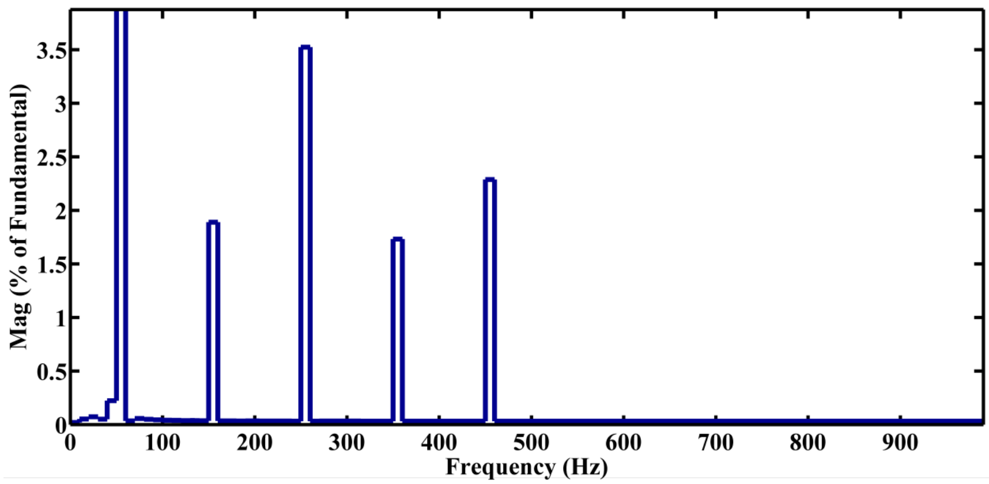


Fig. 4. Frequency Spectrum for Proportional Resonant Controller having THD 4.96%

As shown in the Figure that the PR controller was able to achieve the prescribed limits of ANSI-IEEE of 5% of THD. The highest harmonic was observed at 250 Hz (5th Harmonic) with the magnitude of 3.4% of the fundamental frequency. By using the PR controller THD is 0.4 % less than the prescribed limits of recommended THD values. As it was stated earlier, the increase in the performance of the controller was achieved at the cost of the increased complexity at the same time.

Frequency Spectrum Analysis of Linear Quadratic Regulator (LQR)

The frequency spectrum analysis of the conventional controllers showed that they were unable to meet the operating requirements. In order to reduce the THD to the acceptable limits a Linear

Quadratic Regulator (LQR) was designed. The state space model was achieved by using the state space block of Matlab. The values of the gain are given by

Q=[0.5 0 0; 0 135 0; 0 0 10000000]

R=0.3

Fig. 5 shows the frequency spectrum of a LQR. The LQR though successively reduced the THD to 4.51%. It is important to note that adjusting the gains of a LQR controller is an iterative process and there is no hard fast rule that states how they should be adjusted. After a trial and error process the LQR controller was being adjusted so that it can reduce the THD to 4.51% as compared to 8.05% of a PI controller. A further adjustment in the gains may have reduced the THD limits further, but it results in the severe performance degradation of the LQR. Therefore, the gain of an LQR was being kept such that it achieves a THD of 4.51%.

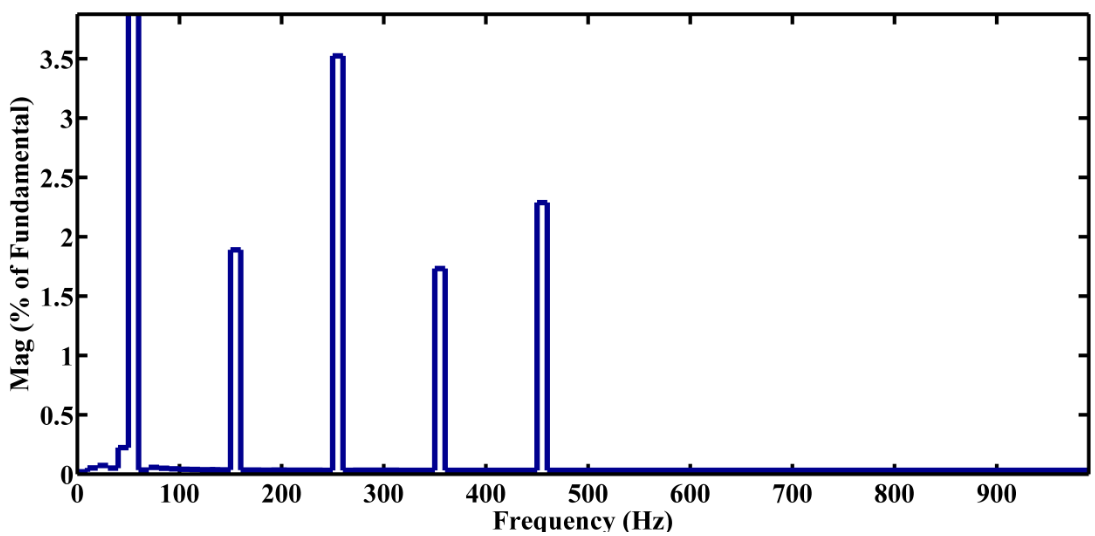


Fig 5 Frequency Spectrum for LQR having THD 4.51%

Conclusion

This paper presents an analysis of the optimal controllers for Utility connected PV systems. The results show that the allowed IEEE THD values are 5% and the only controllers that are able to keep the THD values under this limit are optimal controllers PR and LQR. The PI controller is easier to implement, but they are prone to inherent limitations due to which they fail to perform according to the standards of ANSI-IEEE under distortions. In the future, further investigation of both controllers on Real Time Digital Simulator (RTDS) would be done to verify the results obtained from Matlab.

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