A STUDY ON PASSIVE FILTER DESIGN OF ELECTRONICALLY INTERFACED DG

Thesis Submitted in Partial Fulfilment for theDegree of Master of Electrical Engineering

By

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2019

CERTIFICATE

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DECLARATION

I certify that except where due acknowledgement has been made; the work is that of the candidate alone. This thesis is a presentation of my original research work and has not been submitted previously, in whole or in part, to qualify for any other academic award. Furthermore, the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program.

The work was done under the guidance of Professor Dr. Sunita Halder Nee Dey, Electrical Engineering Department of Jadavpur University, Kolkata.

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Chapter 1

Introduction and Literature review

1.1 Introduction

The term “Distributed Generation” (DG) refers to power generation located at or near the consumption sites. In comparison to “central generation”, DG can eliminate the generation, transmission, and distribution costs while increasing efficiency by removing elements of complexity and interdependency. In many cases, distributed generators can provide lower generation costs, higher reliability, and increased security not realized via traditional generators. For instance, Pike Research (Boulder, United States) has identified 3.2 Gigawatts (GW) of globally existing microgrid capacity [20]. The North America leads to global microgrid generation with 2,088 MW operating capacity according to the report. On the other hand, Europe holds the second rank with 384MW installed microgrid capacity while Asia Pacific follows with 303 MW of operating capacity [20]. The installed microgrid capacity in the rest of world is around 404 MW [20]. DG facilities offer potential advantages for improving the transmission of power. Because they produce power locally for users, they aid the entire grid by reducing demand during peak times and by minimizing congestion of power on the network.

A microgrid is a modern power distribution system using local sustainable power resources designed through various smart-grid initiatives. A microgrid is similar to a conventional grid structure in terms of power generation, distribution, transmission, and control features are assumed as a minor model of actual grid form. However, microgrid technology differs from a conventional grid owing to the distance between power generation and consumption cycles as a microgrid is installed near the load-sites. Microgrid also integrate distributed generation plants such as combined heat and power (CHP), and renewable energy plants powered by solar energy, wind power, geothermal, biomass, and hydraulic resources with it [20]. Although the power rating of microgrid is limited to a few MVA and, it is relative to its application area and grid type. Power parks refer to interconnection of several microgrids that are installed to meet higher power demands where increased stability and control opportunities are necessary. In a macrogrid (conventional grid application), only one-third of the fossil fuel consumed is converted to electricity; the remainder is dissipated as heat energy. The interconnection of renewable sources in a microgrid contributes to decreased environmental emissions. It also provides energy security for a local community as it can be operated without the presence of wider utility grid. Microgrid technology generally provides three important goals such as reliability (physical, cyber), sustainability (environmental considerations), and economics (cost optimizing, efficiency). Microgrid technology is suitable for regions with an underdeveloped transmission infrastructure, such as remote villages where an islanded microgrid would be the most advantageous kind of power network.

In a microgrid system, backup resources are unnecessary because a single user does not have to supply a general load during critical consumption periods. One billion dollars of energy consumption can be conserved by managing a few hundred-summer peak hours by shifting or eliminating loads. Therefore, reliability is a major justification for microgrid operation [19].

Additionally, a microgrid provides significant reduction in generation costs while providing reliable and sustainable energy to loads. Microgrids are also proved to be economically viable. Microgrid technology is suitable for regions with an underdeveloped transmission infrastructure, such as remote villages where an islanded microgrid would be the most advantageous kind of power network. A microgrid can tackle the energy crisis since the transmission losses are greatly reduced.

A microgrid can communicate with consumers and thus manage demand and supply easily. In North America, in 2003, more than a hundred power plants were forced to stop power generation due to the cascading effect of failing plants. One feature of a microgrid is independent operation during widespread failure or during fluctuation of power (intentionally or unintentionally), or even for cost-optimization purposes. In reality, microgrid has black start facility if it is required due to any sort of disaster.

1.2 Distributed Generators

There are two different types of generation technologies applicable for microgrid such as renewable distribution generation (solar thermal, photovoltaic (PV), wind, fuel cell, CHP, hydro, biomass, biogas, etc.), and non-renewable distribution generation (diesel engine, stream turbine, gas engine, induction and synchronous generators, etc.).The use of wind energy has rapidly increased all over the world and has become a significant resource in microgrids, along with solar energy.

The power generation from renewable distribution generation is challenging, as they are intermittent power sources. The output power heavily depends on solar as almost every kind of renewable source is somehow related to a solar energy system. Thus, building a power system without any sort of non-renewable DGs is risky in term of reliability.

1.3 Microgrid Structure

A microgrid consists of three main components: micro generators (such as wind turbine, photovoltaic array, diesel generator, and fuel generator), local storage elements, and different loads. A microgrid can be single or three phase system. It may be connected to low voltage or medium voltage distribution networks. Figure 1.1 shows a sample structure of a microgrid.

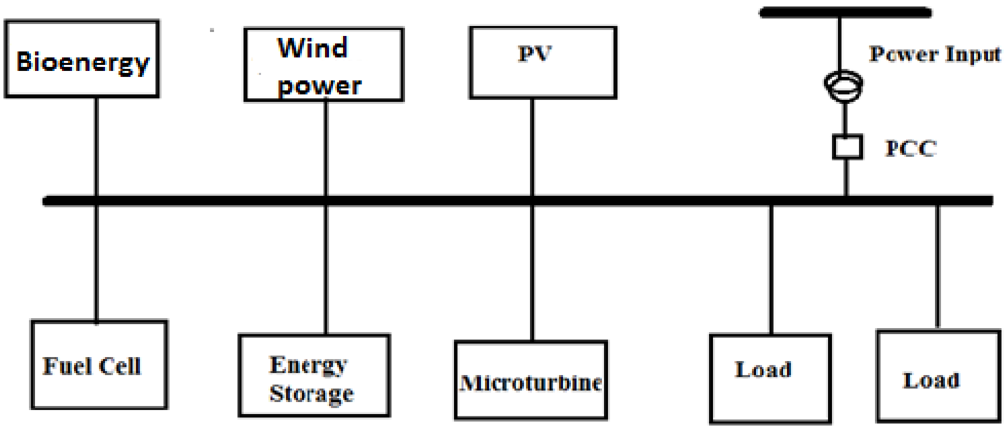

Fig 1.1: Microgrid architecture.

A microgrid can be AC or DC. A DC microgrid is generally DG resources are renewable and have dc output voltage. In ac microgrid, ac buses are appropriate for connecting mass ac loads to ac resources. Converter are used in dc microgrid are of the ac/dc type and connect the DC microgrid to the AC microgrids.

1.4 Operation Modes of Microgrid

Microgrid actually is a group of distributed resources (DR) units and loads, serviced by a distribution system and can operate in. (1) grid connected mode (2) The islanded mode (3) The ride through between the two modes.

1.4.1 Grid Connected Mode

It is the normal operating mode of a microgrid (MG) with no power quality disturbance on the main grid to which it is connected as shown in Fig.1.2. In this mode the MG may cater to its entire local load or may either import or export power from and to the main grid, depending on the total power generation of the local DGs.

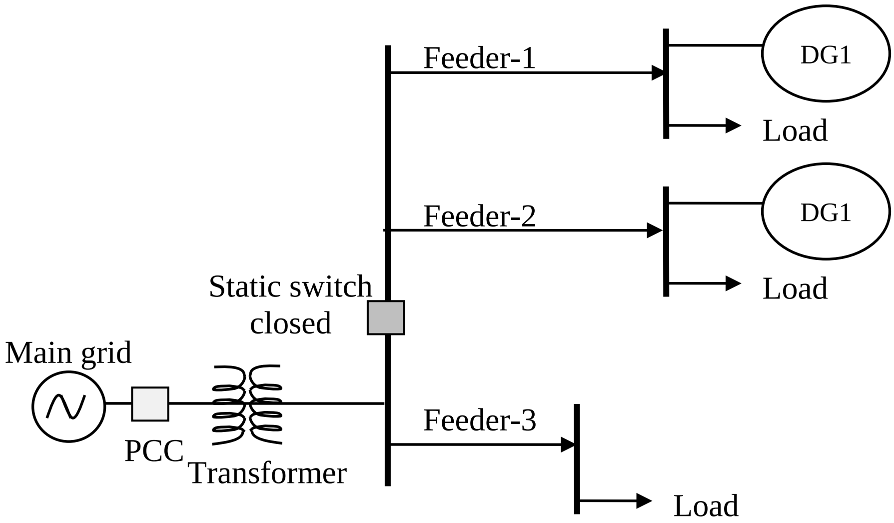

Fig.1.2: Microgrid in grid connected mode of operation.

1.4.2 Islanded Mode

Islanding is the phenomenon when the microgrid isolates itself from the main grid and takes up the local loads in the system and behaves as a single controlled entity as shown in Fig.1.3. The red circled marks in the Fig 1.3 show that the microgrid is disconnected from grid and also the load connected to grid.

There are several reasons of intentional islanding operation of a microgrid, but a very common one is an effective disconnection from the grid in anticipation of a power outage on the main grid side. The advantage of this intentional islanding operation is that instead of waiting for the outage in the main grid to occur an intentional islanding allows for a controlled transition that prevents potential failures or quality issues in the micro-grid.

1.4.3 The ride through between the Grid Connected Mode and Islanded Mode

A MG can operate in grid connected mode or in islanded mode. In grid-connected mode MG supplies or draws power to the utility grid depending on the generation and load demand. In case of an emergency and power short age during power interruption the MG shifts to island mode of operation.

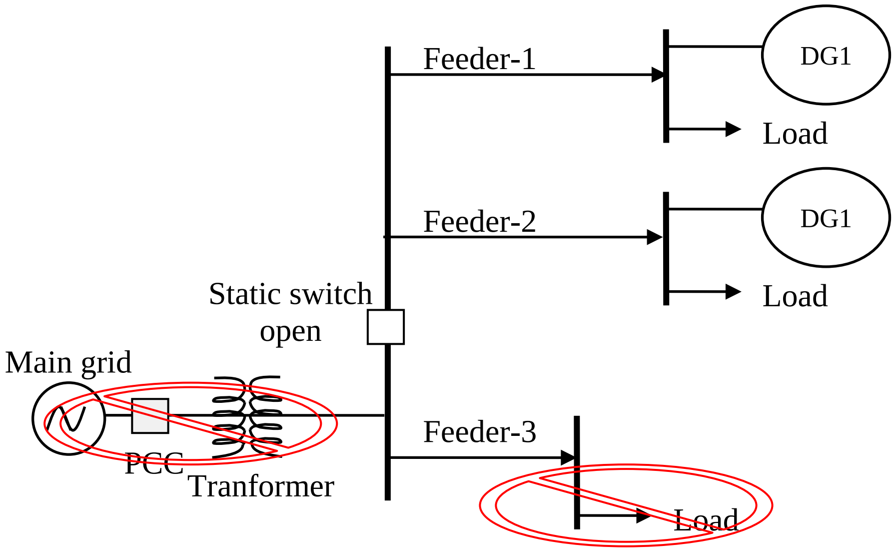

Fig.1.3: Microgrid in islanded mode of operation.

1.5 Technical Challenges

A microgrid is designed to seamlessly separate from the grid when problems in the utility grid arise, reconnecting again once these problems are resolved. Normally, in grid connected mode, the microsources act as constant power sources, which are controlled to inject the demanded power into the network. In autonomous mode, microsources are controlled to supply all the power needed by the local loads while maintaining the voltage and frequency within the acceptable operating limits. Autonomous operation is realized by opening the static switch, which disconnects the microgrid from the main grid. Once the microgrid is isolated from the main grid, the microsources supplies to the system are responsible for maintaining the voltage and frequency while sharing the power.

The bidirectional power flow for both import and export of power is possible during grid-interconnected operation. In event of faults, isolation for microgrid as well as resynchronization is achievable for islanded operation. During islanding, each distributed generation unit is able to balance power and share loads within the microgrid system. The increased penetration of distributed generation in microgrid system may provide several technical problems in the operation of the grid, such as steady state and transient over or under-voltages at the point of connection, protection malfunctions, increase in short circuit levels and power quality problems [6]. The control and protection of the microgrid as an autonomous system will also present challenging problems. All grid-connected of microsources are required to have protection methods that cause the microsource to stop supplying power to the utility grid if the frequency or amplitude of the voltage at the point of common coupling between the customer and the utility within specified limits.

Fig.1.3 shows power flows at the point of common coupling (PCC) between the utility and microsource.

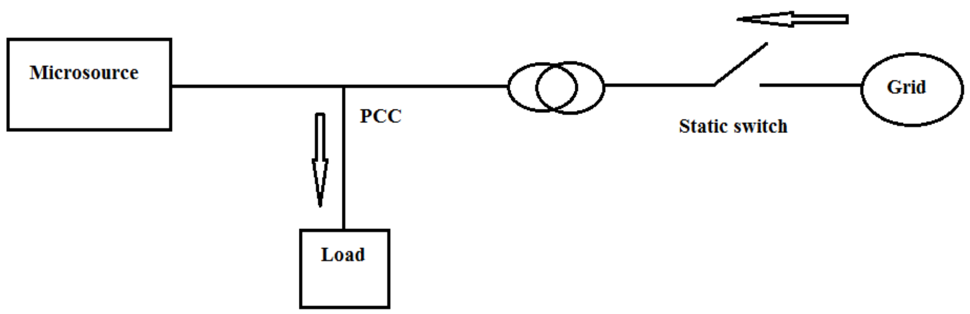

Figure-1.3: Microgrid power flow to utility grid.

1.6 Harmonic issues

Due to the abundance of power electronic appliances, harmonic distortion has become one of the growing power quality concerns in recent years. Harmonic distortion is also caused by the nonlinearity of other power equipment such as transformers and rotating machines. Power systems, rich in harmonics, offer poor power factor and hence low efficiency operation. Due to the large concentration of nonlinear loads such as motor drives, investigation of harmonic distortion in industrial systems is getting special attention. Widespread integration of solar Photovoltaic (PV) systems into distribution systems brings additional challenges to the existing power quality scenario. Inclusion of solar PV systems in an industrial microgrid equipped with a large share of motor drives results in a significant increase in existing Total Harmonic Distortion (THD).

1.7 Role of Filters in Grid Connected Voltage source Inverters

Filters are used to reduce harmonics and for smoothening the output voltage of VSI. The role of the filter is to supply the grid with voltage that is without harmonic distortion. Therefore, it is mandatory to connect a filter to the inverter before connection to the grid. Filters are the most common approaches used for harmonic cancellation.

1.8 Literature Review

Frede Blaabjerg, Marco Liserre and Marco Liserre [1] give an overview of the structures for the DPGS based on fuel cell, photovoltaic, and wind turbines. In addition, control structures of the grid-side converter are presented, and the possibility of compensation for low-order harmonics is also discussed.

Moreover, control strategies when running on grid faults are treated. This paper ends up with an overview of synchronization methods and a discussion about their importance in the control.

Ioannis Bouloumpasis, Panagis Vovos, Konstantinos Georgakas and Nicholas A. Vovos [2] present a method of current harmonic reduction in a distorted distribution system. In order to evaluate the proposed method a grid with high-order current harmonics is assumed. The reduction of current distortion is feasible due to the pulse modulation of an active filter, which consists of a buck-boost converter connected back-to-back to a polarity swapping inverter. Using the proposed method, the current Total Harmonic Distortion (THD) of the grid is reduced below the acceptable limits and thus the general power quality of the system is improved.

Bandana Bhutia, Dr. S.M.Ali, and Narayan Tiadi [3] discussed about Design of Three Phase PWM Voltage Source Inverter for Photovoltaic Application. This paper presents the three phase DC-AC inverter, the three leg MOSFET operated inverter. It can be used to demonstrate the relationship of input DC, modulation index, filter selection and switching frequency third harmonic injection features.

Miroslav Begovic, Jun Zhang, Damir Novosel, Namhun Cho analyze some of the issues in the

Transforming landscape of distribution networks, especially microgrids, and some power quality implications - the harmonic distortion levels and reduction methods with increased penetration levels of the Photovoltaic Generators (PVGs) in the distribution network.

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Subramaniam Senthil Kumar, Natarajan Kumaresan, Muthiah Subbiah, Mahendhar Rageeru [5] explained stand-alone operation of self-excited induction generator (SEIG)-PWM rectifier systems for constant DC voltage applications. The configuration and implementation of the control scheme have been fully described. A method for predetermining the steady-state performance of the system for a given rectifier DC output has been explained with relevant analytical expressions derived for suitably reflecting the DC load resistance on the generator terminals. An ‘abc-dq’ axis model has also been formulated for the study of transient behaviour of the system for step changes in the driving speed and DC load on the system.

Milan Pradanovic and Timothy Green [6] describes a filter designed to incorporate an isolating transformer and the design of a complementary controller that rejects grid disturbance, maintains good waveform quality and achieves real and reactive power control.

Pradanovic and T. Green [7] describes a filter designed to incorporate an isolating transformer and the design of a complementary controller that rejects grid disturbance, maintains good waveform quality and achieves real and reactive power Control.

A.E.W.H. Kahlane, L. Hassaine and M. Kherchi [8] discussed that a LCL filter is often used to interconnect an inverter to the utility grid in order to filter the harmonics produced by the inverter. This paper deal design methodology of a LCL filter topology to connect à inverter to the grid.

Md Alamgir Hossain, Hemanshu Roy Pota, Walid Issa and Md Jahangir Hossain [9] reviews and categorizes different control methods (voltage and primary) for improving microgrid power quality, stability and power sharing approaches. In addition, the specific characteristics of microgrids are summarized to distinguish from distribution network control.

Moreover, various control approaches including inner-loop controls and primary controls are compared according to their relative advantages and disadvantages. Finally, future research trends for microgrid control are discussed pointing out the research opportunities.

Paolo Mattavelli, and Fernando Pinhabel Marafão [10] proposes a repetitive-based controller for active power filters, which compensates selected current harmonics produced by distorting loads. The approach is based on the measurement of line currents and performs the compensation of selected harmonics using a closed-loop repetitive-based control scheme based on a finite-impulse response digital filter**.**

Jaume Miret, Miguel Castilla, José Matas, Josep M. Guerrero and Juan C. Vasquez [11] present a linear current control scheme for single-phase active power filters. The approach is based on an outer voltage loop, an inner current loop, and a resonant selective harmonic compensator. The design of the control parameters is carried out using conventional linear techniques (analysis of loop gain and other disturbance-rejection transfer functions). The performance of the proposed controller is evaluated and compared with two reference controllers: a basic control and an advanced repetitive control. In comparison with these controllers, the proposed control scheme provides additional attenuation to the harmonics coming from the load current, the grid voltage, and the reference signal, resulting in a grid current with lower harmonic distortion.

Takaharu Takeshita, Takahiro Masuda and Nobuyuki Matsui [12] discussed about the voltage waveform in the electric power distribution system is distorted by harmonic producing loads. For harmonic suppression of the voltage and current in the distribution system, the authors propose the current waveform control of the distributed generation system with a PWM converter. The effectiveness of the proposed current waveform has been verified by simulations and experiments.

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Vipul C.Rajyaguru [14]presented a MATLAB based simulation of Grid connected PV system. The main components of this simulation are PV solar panel, Boost converter; Maximum Power Point Tracking System (MPPT) and Grid Connected PV inverter with closed loop control system is designed and simulated. A simulation studies is carried out in different solar radiation level.

Fang Z. Peng, Yun Wei Li, Leon M. Tolbert [15] discusses control and protection of power electronics interfaced distributed generation (DG) systems in a customer-driven microgrid (CDM). Particularly, the following topics will be addressed: microgrid system configurations and features, DG interfacing converter topologies and control, power flow control in grid-connected operation, islanding detection, autonomous islanding operation with load shedding and load demand sharing among DG units, and system/DG protection.

H.R. Baghaee , M. Mirsalim, M. J. Sanjari, and G.B. Gharehpetian [16] presented in paper, the impact of installation of distributed resources in the distribution systems from the perspective of increase in the fault contribution will be discussed and comparative study will be performed to analyze the effect of type and interconnection of distributed generation unit on the fault current contribution of the distribution systems.

Tawfikur Rahman, S. M. A. Motakabber and M. I. Ibrahimy [17] discussed about three phase inverter and designed an efficient three leg IGBT inverter for microgrid. The switching pulse controller of two level pulse width modulation (PWM), phase lock loop (PLL), DC voltage and current regulator and Uref generator, low-pass LC filters also been discussed in this paper.

Mahmud Wasfi [18] reviews solar energy conversion into electricity with particular emphasis on photovoltaic systems, solar cells and how to store electricity.

Mustafa Dursun, M. Kenan Dosoglu [19] describes a LCL filter designed for grid connected inverter. Proper theoretical analysis is done for the design of filter which reduces the harmonic in the output voltage.

Eklas Hossain, Ersan Kabalci, Ramazan Bayindir, Ronald Perez [20] deals with the recent evolution of microgrids being used around the world in real life applications as well as laboratory application for research. This study is intended to introduce the subject by reviewing the components level, structure and types of microgrid applications installed as a plant or modeled as a simulation environment. The paper also presents a survey regarding published papers on why the microgrid is required, and what the components and control systems are which constitute the actual microgrid studies.

1.9 Brief Description of the Thesis

Base on above literature review, this thesis investigates the role of passive filters of electronically interfaced DG for smoothening the inverter output voltage and harmonic reduction in a distribution system. A passive filter (LCL) is proposed. The performance of the proposed filter is to be tested for different operating conditions. The observations found are also to be compared with a filter present in open literature [19]

Chapter 2

Theory

2.1 Voltage source inverter

Inverters are used in a large number of power applications. There has been major upgrading in power electronics in last decade. An Inverter is basically a converter that converts DC power to AC power and it is referred to as Voltage Source Inverter (VSI). A voltage source inverter (VSI) is one that takes in a fixed voltage from a dc power supply, and converts it to a variable-frequency AC supply. VSIs are divided into three categories: 1) Pulse Width Modulated (PWM) Inverters, 2) Square-wave Inverters, and 3) Single-phase Inverters with Voltage Cancellation. This thesis concentrates on the PWM inverter. PWM inverters take in a constant dc voltage. The inverter should conduct the magnitude and the frequency of ac output voltages, and the diode rectifiers are required to fix the line to line voltage. The inverter uses pulse-width modulation techniques using its switches. There are various technologies of the pulse width modulation in an inverter to provide the output ac voltages nearly to sinusoidal wave. The input dc voltage and PWM technique of VSI control the magnitude and frequency of the output ac voltage respectively.

An inverter converts the DC electricity to AC electricity from sources like fuel cells, solar cell and batteries. Grid tied Micro inverters converts direct current from individual solar panels to alternating current for the electric grid. The Photovoltaic inverter can supply solar power to a profitable electrical grid or can be used in an off-grid. Photovoltaic inverters consist of photovoltaic arrays along with anti-islanding protection and maximum power point tracking.

2.2 Three phase Pulse Width Modulation (PWM) for inverter

In an inverter the output voltage can also be adapted by applying a controller itself in the inverter and this can be done by pulse-width modulation control using itself interior of an inverter. Here, a constant dc input voltage is disposed into the inverter and an unflappable ac output voltage is accessed by regulating the on and off duration of the inverter units. PWM techniques are represented by fixed amplitude pulses. This is the most suitable method of controlling the output voltage. The advantages enchanted by PWM techniques are mentioned as:

a) Without any other units in this method the output voltage can be controlled easily.

b) With the controlling of the output voltage, lower order harmonics can be erased or minimized. The higher order harmonics can be filtered calmly.

The major disadvantage of PWM method is that SCRs are costly as they should carry low turn-on and turn-off times. PWM inverters are very much suitable in industrial applications. After the modulated to achieve the output voltage control of inverter and to minimize the harmonics present by the width of these pulses. The various PWM techniques are as following:

a) Single-pulse modulation

b) Multiple pulse modulation

c) Sinusoidal pulse width modulation

2.3 Three phase voltage source inverter

A three phase voltage source inverter generates less harmonic distortion in the output voltage is utilized in the phase to phase AC load. Also afford extra productive supply voltage related to sinusoidal modulation technique. The circuit model of three-phase voltage source PWM inverter is shown in Fig.2.1. $T_A^+, T_A^-, T_B^+, T_B^-$ and T_C^+, T_C^- are the six power controllable switches that control the output. When an upper transistor is switched on then the corresponding lower transistors T_A-, T_B-, T_C- is are switched off. Therefore, the on and off states the upper transistors T_A+, T_B+, T_C+, can be used to regulate the output voltage. Each power switch can be on and off, the 'On' state is designated as '1', whereas the 'Off' state is designated as '0'.

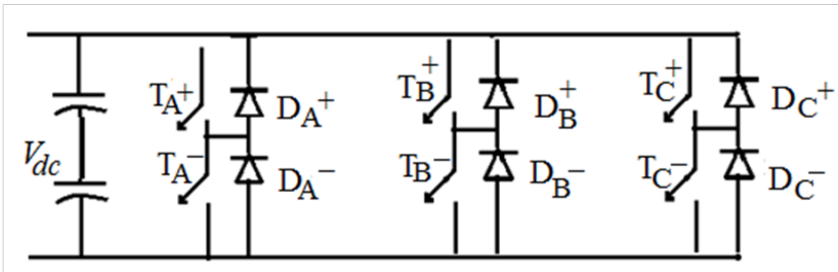

Fig 2.1: Three phase voltage source inverter.

Three phase power inverter has many applications - an ac-motor drive and uninterruptible power supplies are two main examples. This has three legs, each leg corresponds to each phase. When generating power to three different phases one must make sure that each phase is equal, meaning that it is balanced. The Harmonics in the output phase voltages are of major concern in the power distribution system. Each phase voltage faces similar harmonic distortion. Therefore, some of the powerful harmonics in the single phase inverter can be erased from the phase to phase voltage of a three phase inverter.

2.4 Harmonic distortion in distribution system

Inverters connected to a microgrid must support both grid-connected and islanded operation through their primary control loops. The presence of the grid greatly affects the harmonic current flows in the microgrid network, since the characteristics of stiff grids (e.g.: voltage, frequency) are not affected by power quality disturbances such as harmonics. There is a harmonic current sharing problem during islanded operation, due to the harmonic demand from local non-linear loads. In addition, these harmonic currents also induce voltage harmonic distortion at the point of common coupling (PCC). During grid-connected operation, the voltage source inverters (VSIs) are required to provide sinusoidal voltage and current into the grid. However, the VSIs can inject additional harmonic currents into the grid either due to the presence of voltage harmonics at the PCC and local non-linear loads. The injected harmonic currents increase the power losses and may cause stability problems in the local network. Harmonic current sharing and voltage harmonic distortion are the main power quality concerns during islanded operation of the microgrid. The harmonic currents also induce voltage harmonic distortion at the PCC due to current requirements from local non-linear loads. These voltage harmonics may cause stability issues due to resonances present on the microgrid and thus harmonic damping techniques must be considered. The harmonic currents increase due to improper harmonic current sharing, which results in higher voltage distortion at the PCC.

Harmonic current injection into the grid is one of the major concerns in grid-connected inverters, since these harmonic currents increase the power losses and may cause stability problems in the local network. The grid interconnection standards address the harmonic current injection problem and specify individual harmonic limits. In addition, these standards also specify that the total harmonic current distortion (THD) of the current injected into the grid should be less than 5% with the inverter at the rated output power and at ideal grid conditions. It is well known that grid voltage distortion present at the PCC of the inverters increases their current harmonic output.

2.5 Harmonic reduction techniques

Harmonic reduction techniques can be classified into two categories; wave shaping and filtering technique. These techniques have been chosen by their ability to comply with the harmonic standards, particularly the requirement of total harmonic distortion (THD) level of connected loads.

The role of a filter is to supply voltage to the grid without harmonic distortion. Therefore, it is mandatory to connect a filter to the inverter before connection to the grid. Filters are the most common approaches used for harmonic cancellation. A good filter can reduce harmonics as well as smooth the output voltage.

2.6 Filters

The harmonics caused by the switching of the power conversion devices are the main factor causing problems to sensitive equipment or the connected loads, especially for applications above several kilowatts, where the price of filters and Total Harmonic Distortion (THD) is also an important consideration in the system’s design phase.

The inductance of the input or output circuits of the power conversion devices have conventionally been used to reduce these harmonics. However, as the capacity of the systems have been increasing, high values of inductances are needed, so that realizing practical filters has been becoming even more difficult due to the price rises and the poor dynamic responses.

An L, LC or LCL filter is usually placed between the inverter and the grid to attenuate the switching frequency harmonics produced by the grid-connected inverter. Compared with L and LC filter, LCL filter has better attenuation capacity of high-order harmonics and better dynamic characteristic.

2.7 Filter Topologies

The output filter reduces the harmonics in generated current caused by semiconductor switching. There are several types of filters. The simplest variant is filter inductor connected to the inverter's output. But also combinations with capacitors like LC or LCL can be used.

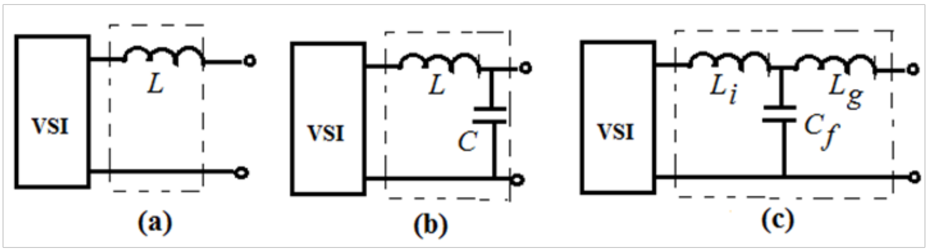

Fig. 2.2: Basic filter topologies.

2.7.1 L Filter

The L-filter shown in Fig. 2.2(a) is a first order filter with attenuation 20 dB/decade over the whole frequency range. Therefore the application of this filter type is suitable for converters with high switching frequency, where the attenuation is sufficient. The filter is greatly sensitive with the dynamics of the whole system.

2.7.2 LC Filter

The LC-filter is depicted in Fig. 2.2(b). It is a second order filter and it has better damping behaviors than L-filter. This simple configuration is easy to design and it works mostly without problems. The second order filter provides 12 dB per octave of attenuation after the cut-off frequency f_0, it has no gain before f_0, but it presents a peak at the resonant frequency f_0. The design of the filter is a compromise between the value of the capacity and inductance.

The high capacitor has positive effects on the voltage quality. On the other hand, higher inductance value is required to achieve demanded cut-off frequency of the filter. The resonant frequency of the filter becomes dependent on the grid impedance and therefore this filter is not suitable for a grid-connected VSI.

2.7.3 LCL Filter

The attenuation of a LCL-filter is around 60dB/decade for frequencies above resonant frequency, therefore lower switching frequency for the converter can be used. It also provides better decoupling between the filter and the grid impedance and lower current ripple across the grid inductor. Therefore LCL-filter fits best for grid connected VSI.

The LCL filter has good current ripple attenuation even with small inductance values. However it can bring also resonances and unstable states into the system. Therefore the filter must be designed precisely according to the parameters of the specific converter.

2.8 Filter design

A LCL filter can reduce harmonics and also smoothen the output voltage. The main function of the LCL filter is to reduce high order harmonics on the output side, however poor design may cause an increase in distortion. Therefore, the filter must be designed correctly and reasonably.

Several characteristics must be considered in designing a LCL filter, such as current ripple, filter size and switching ripple attenuation. The following parameters are needed for the filter design [8]:

1. $V_{LL} =$ Line to line RMS voltage at the inverter output terminal,
2. $V_{ph} =$ Phase voltage at the inverter output terminal,
3. $P_{Inv} =$ Inverter active power, $S_r =$ Rated apparent power,
4. $V_{dc} =$ DC link voltage,
5. $f_g =$ Grid frequency,
6. $f_{sw} =$ Switching frequency

The base impedance and base capacitance of the system are as given below:

$Z_b =$ base impedance $= \frac{V_{rms}^2}{S_r}$, $C_b =$base capacitance $= \frac{1}{\omega_g Z_b}$ where $\omega_g = 2\pi f_g$

The first step in calculating the filter components is the selection of the inverter side inductance (L_i), which can limit the output current ripple by up to 10% of the nominal amplitude (Fig.2.2(c)). It can be calculated according to the equation given below

$$L_i = \frac{V_{dc}}{16 f_{sw} \Delta I_{L\max}} \tag{2.1}$$

Where $\Delta I_{L\max}$ is the 10 % current ripple specified by,

$$\Delta I_{L\max} = 0.01 \times \frac{P_{Inv}\sqrt{2}}{V_{LL}} \tag{2.2}$$

The filter capacitor $\left(C_f\right)$ is selected based on the fact that the maximal power factor variation acceptable by the grid is 5%. Then the filter capacitor is given by,

$$C_f = 0.05 C_b \tag{2.3}$$

The grid side inductance $\left(L_g\right)$ can be calculated by:

$$L_g = r \times L_i \tag{2.4}$$

r is the ratio of L_g and L_i. It is seen that in order to limit the current ripple in the converter side inductance (to reduce Power loss in the filter) and increase the filter attenuation, it is required that the converter side inductance be dominant in the filter. The value of r for a desired ripple attenuation can be obtained from the Fig.2.3.

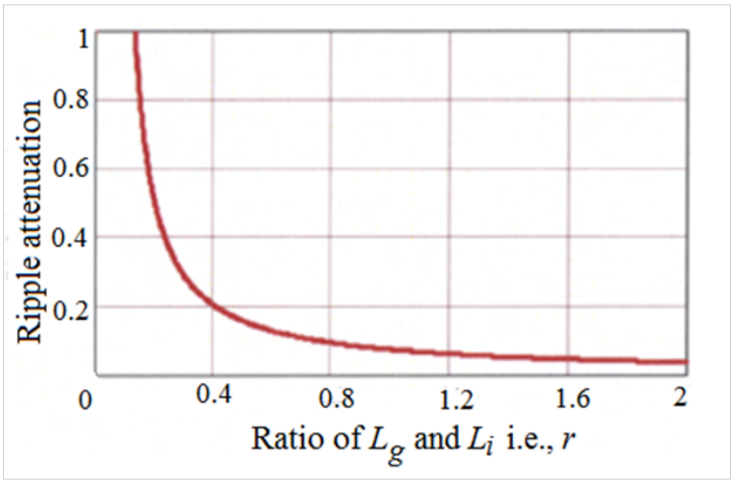

Fig.2.3: Ripple attenuation as a function the ratio of L_g and L_i

In this thesis r is assumed to as 0.75.

Chapter

Modeling and Simulation

3.1 Voltage source inverter

A Voltage source inverter (VSI) is modeled and is shown in Fig.3.1.

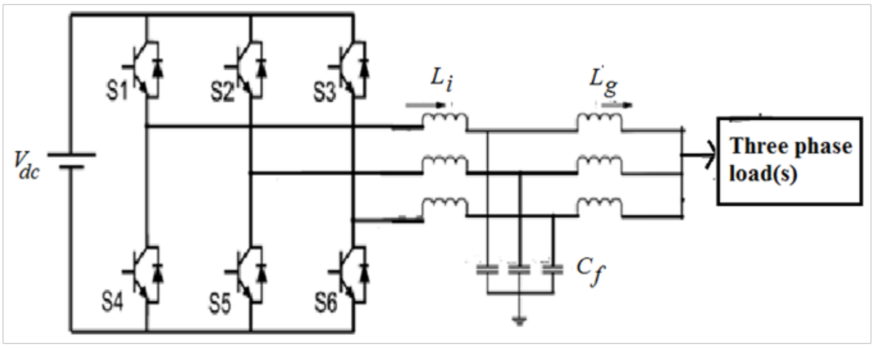

Fig.3.1: Schematic diagram of the VSI.

The grid is connected to the inverter as shown in Fig.3.2. A 1000 W linear load is connected to the grid. A LCL filter has been inserted between the inverter and grid in order to reduce harmonics in the output voltage of the inverter.

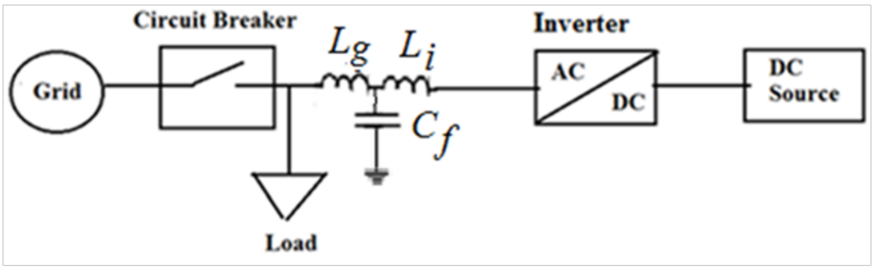

Fig.3.2: Single line diagram of grid connected inverter.

The parameters of LCL filter has been calculated considering equations (2.1), (2.3) and (2.4) for harmonic reduction of the system. Another LCL filter has been considered from reference [19] to compare the effectiveness of the proposed filter. The parameters of both the filters are shown in Table 3.1.

Table 3.1: LCL filter parameters and system data

System Parameters	LCL Filter Parameters from Reference[19]	Proposed LCL Filter Parameters
$V_{LL} = 112\text{V}$	$L_i = 3.35\text{mH}$	$L_i = 0.08\text{H}$
$f_g = 60\text{Hz}$	$L_g = 0.126\text{mH}$	$L_g = 0.06\text{H}$
$P_{Inv} = 1000\text{W}$	$R_f = 1\Omega$	$R_f = 1\Omega$
$f_{sw} = 15\text{kHz}$	$C_f = 12\mu\text{F}$	$C_f = 50\mu\text{F}$
$V_{dc} = 220\text{V}$	$C_{DC} = 1000\mu\text{F}$	$C_{DC} = 1000\mu\text{F}$

3.1.1 Grid connected VSI with proposed LCL filter

A simulink model has been developed according to the parameters given in Table 3.1 and is given in Appendix A (Fig.A.1). The three phase circuit breaker separates the inverter from the grid. Initially the inverter is synchronously connected with grid and at $t = 0.5$ sec the breaker gets opened and disconnects the inverter from the grid. The response of the system is observed for 1 second.

The variations of voltage at the grid terminal (red colour) and inverter terminal (blue colour), with time are shown in Fig. 3.3a and Total Harmonic Distortion (THD) of the inverter terminal voltage is shown in Fig.3.3c. It is clearly observed from Fig.3.3a that the inverter voltage and grid voltage waveforms are almost overlaid, as expected.Fig.3.3b is an enlarged view of Fig.3.

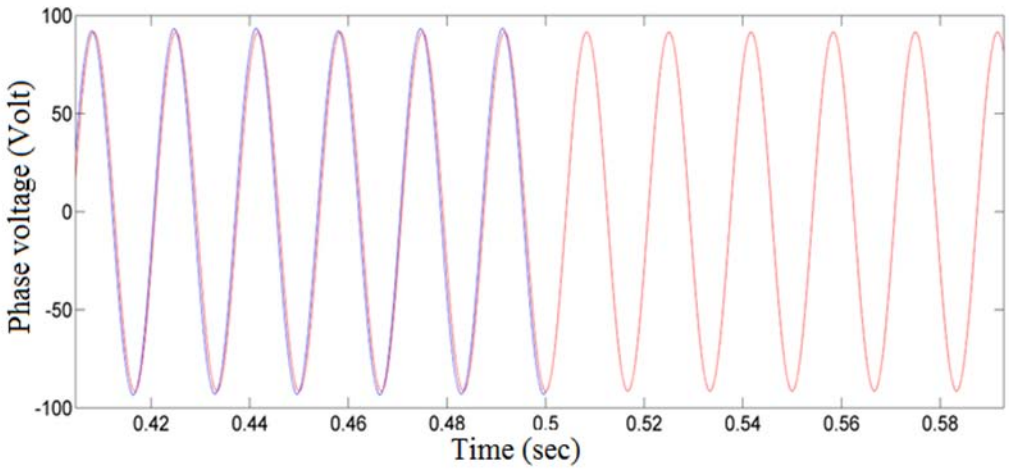

Fig.3.3a: Grid and inverter side voltage with proposed filter.

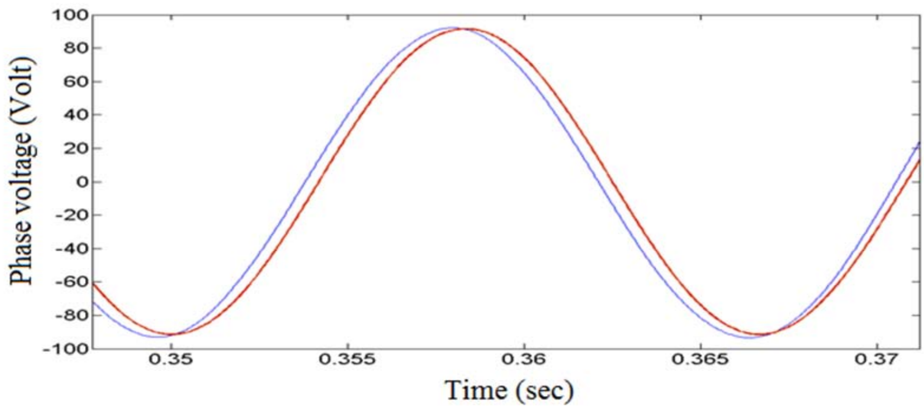

Fig.3.3b: Enlarged view of Fig.3.3a.

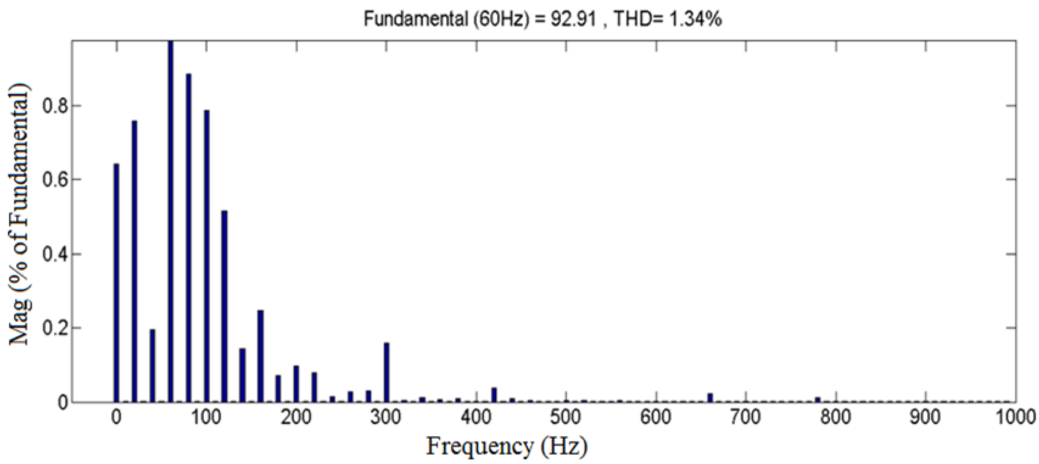

Fig.3.3c: Harmonic content of inverter output voltagewith proposed filter.

The phase voltage of the grid and inverter were overlaid for first 0.5 sec and it is clear from Fig.3.3c and Table 3.2, that the harmonics is present in the output voltage from the proposed filter. Harmonic analysis of the AC output voltage has been done and THD of voltage is 1.3% which is far below the acceptable limit (5%). So the proposed filter works properly and gives satisfactory output.

Table 3.2: Inverter output with proposed

Peak value of phase voltage at inverter output (V)	Frequency (Hz)	THD of Voltage at inverter terminal (%)
91.44	60	1.3

3.1.2 Performance evaluation

Next the LCL filter parameters of Fig 3.2are tuned as given in Table I of reference [19] and same simulation has been performed. The variations of output voltage at the grid terminal (red colour) and inverter terminal (blue colour) are shown in Fig.3.4a and Total harmonic distortion (THD) of the voltage is shown in Fig.3.4c.
It is clear from Fig.3.4a that the inverter voltage and grid voltage waveforms are almost same as expected.Fig.3.4b is an enlarged view of Fig.3.4a.

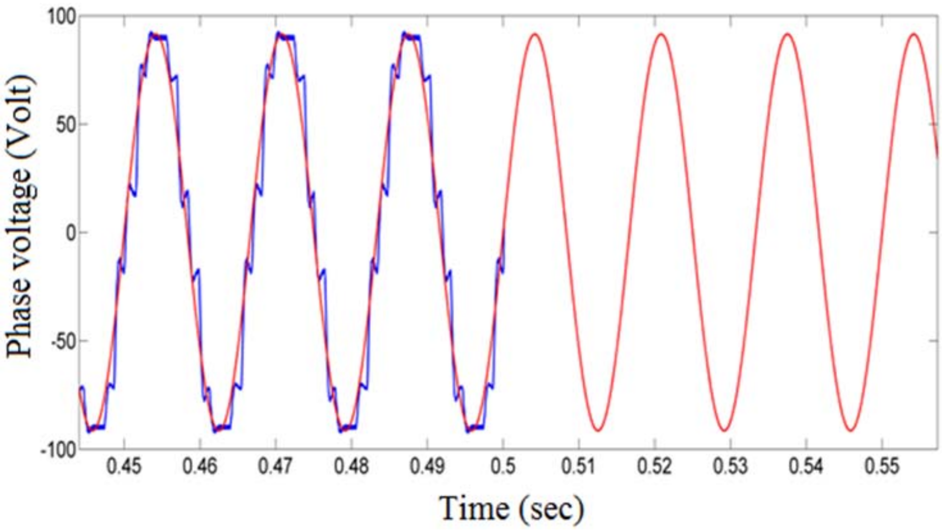

Fig.3.4a: Grid and inverter side voltage with reference filter.

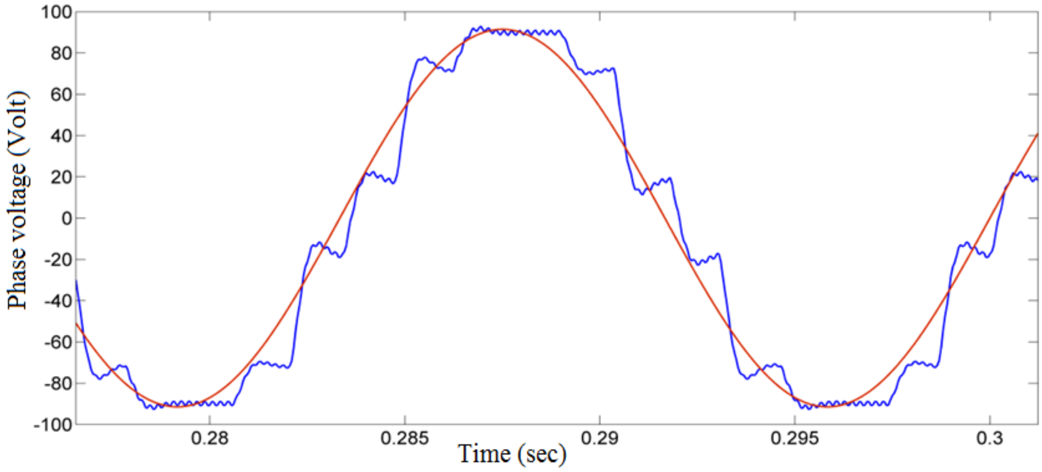

Fig.3.4b: Enlarged view of Fig.3.4a.

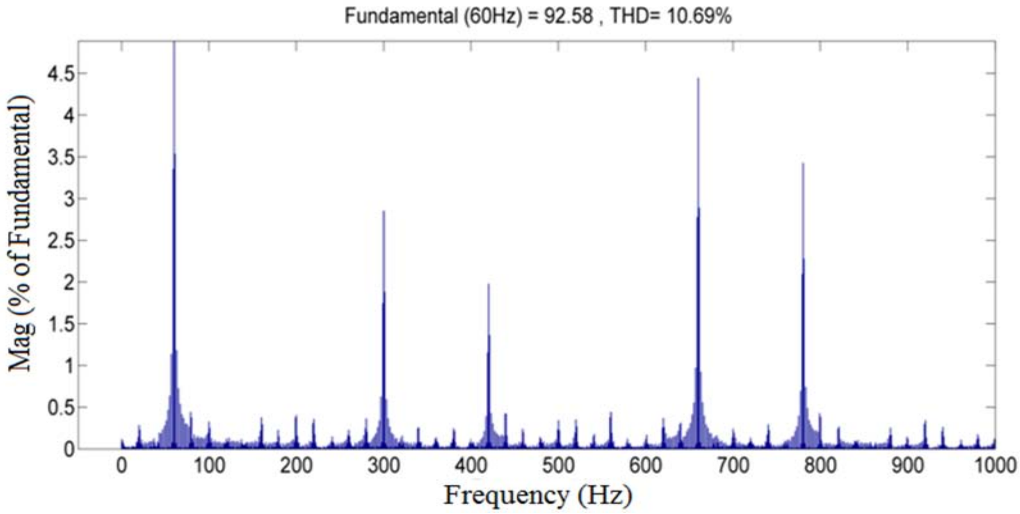

Fig.3.4c: Harmonic content of inverter output voltagewith reference filter.

Table 3.3: Inverter output with filter ofreference [21

Peak value of phase voltage at inverter output (V)	Frequency (Hz)	THD of Voltage at inverter terminal (%)
91.44	60	10.69

It is clear from Fig.3.4b and Table 3.3 that the output voltage for the reference filter contains more harmonics as compared to Fig.3.3b. Harmonic analysis of the AC output voltage shows that the THD of voltage is 10.69% which is above the acceptable limit (5%). Therefore the present filter does not work properly and gives unsatisfactory output as compared to proposed filter. So the proposed filter performs better than filter presented in reference [19]

3.2 Development of a distribution system as a microgrid

A microgrid of 13.8 kV voltage level is considered to test the performance of the proposed filter and is shown in Fig.3.5. The details of two DGs and loads are shown in Table 3.4 and 3.5 respectively. The microgrid is connected with main grid through transmission lines L1 and L2. The microgrid is disconnected from main grid through circuit breaker CB7. The VSI gets disconnected from the microgrid through circuit breaker CB8. The parameters of the VSI are different from Table 3.1 to match the voltage level and as given in Table 3.6. The LCL filter parameters tuned following

Table 3.1. A Matlab Simulink model of Fig.3.5 has been developed and is shown in Appendix A (Fig.A.2).

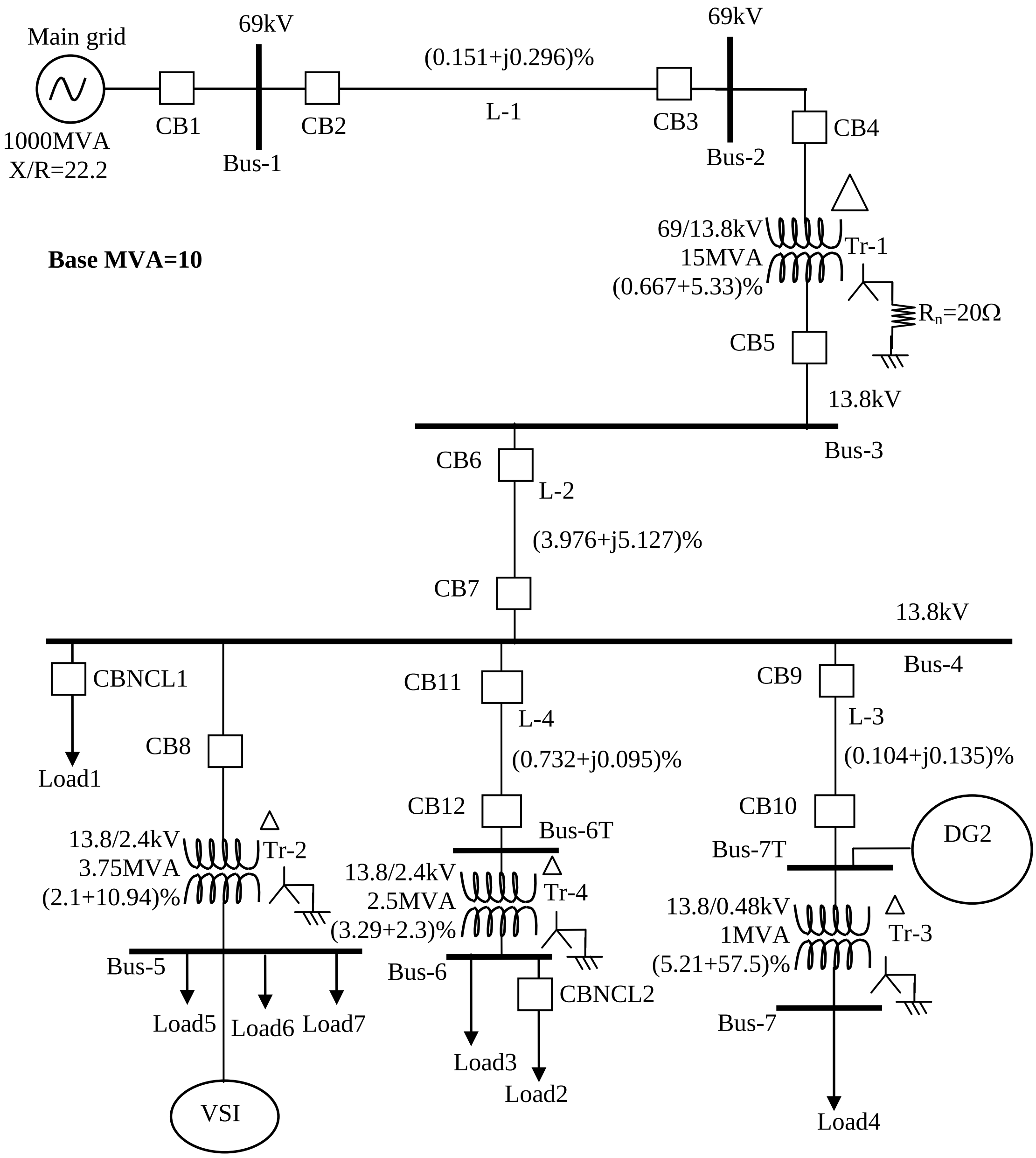

Fig.3.5: Single line diagram of the test system.

Table 3.4: Distributed generations in the microgrid

Distributed Generators (DGs)	Type of DG	Rating (MW)	DG location
DG1	VSI	1	Bus-5
DG2	Conventional	2.25	Bus-7T
Total distributed generation		**3.25**	

Table 3.5: Loads connected to the microgrid

Load	Active Power (MW)	Reactive Power (MVAR)	Type	Position
Load 1	1.5	1	Linear	4
Load 2	0.8	0.4	Linear	6
Load 3	0.75	0.25	Linear	6
Load 4	1.2	0.6	Linear	7
Load 5	0.02	0.0035	Nonlinear	5
Load 6	0.00373	0.0004	Nonlinear	5
Load 7	0.012	0.0025	Linear	5
Total Load	4.2893	2.2564		

Table 3.6: Inverter parameters

DC input Voltage (V)	Peak value of phase voltage at inverter terminal (V)	Switching frequency (kHz)
2400	2000	5

3.3 Microgrid operation in grid connected mode

It is assumed that the inverter is connected with microgrid through the proposed filter and the microgrid is in grid connected mode. The CB7 and CB8 are in closed position. The filter parameters are tuned as proposed in Table 3.1. It is observed that the microgrid is capable to cater all the loads connected to it. As the output voltage and frequency of the inverter is stable. The total load connected to microgrid is 4.28 MW and total load connected to the inverter is 24.93 kW. The variation in phase voltage, frequency, total harmonic distortion (THD) of phase voltage and active power at inverter terminal (bus 5) are shown in figures 3.6a to 3.6d respectively.

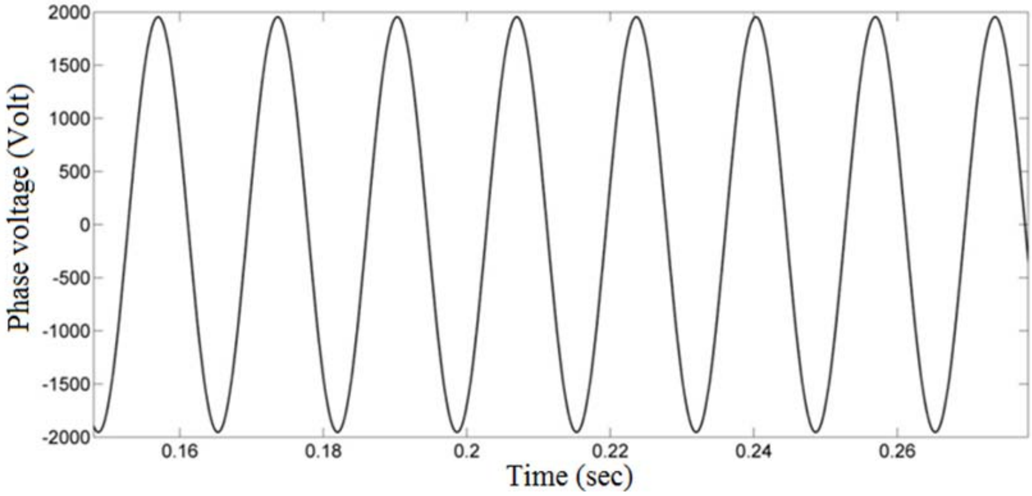

Fig.3.6a: Inverter terminal voltage in grid connected mode with proposed filter.

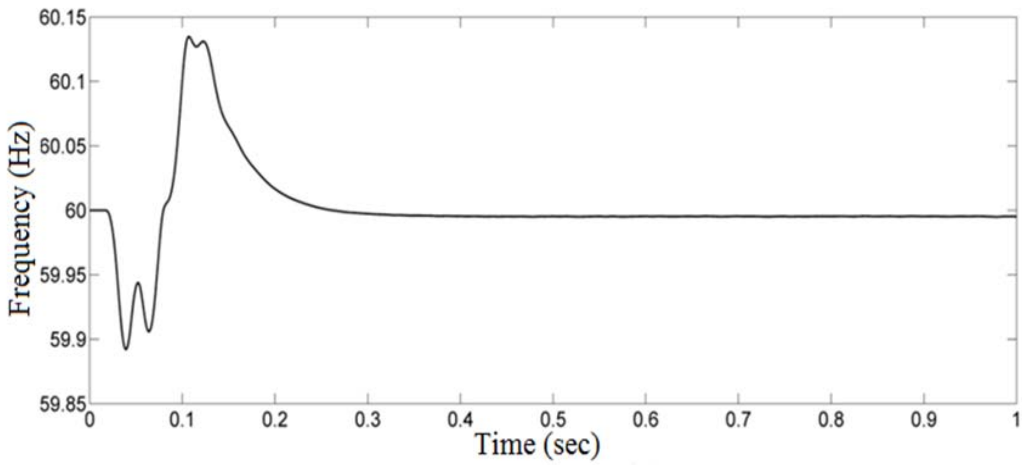

Fig.3.6b: Frequency of inverter output voltage in grid connected mode with proposed filter.

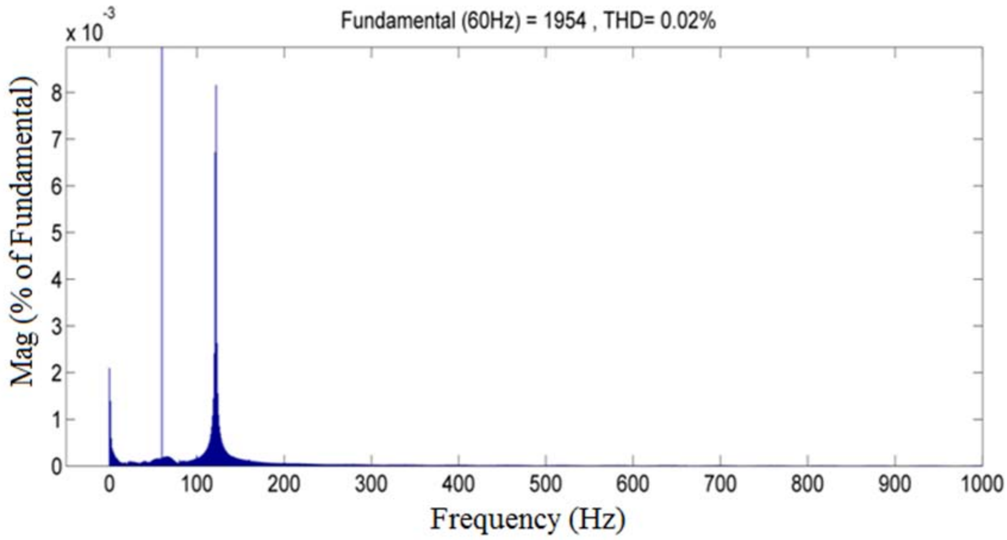

Fig.3.6c: Harmonic content of inverter output voltage in grid connected modewith proposed filter.

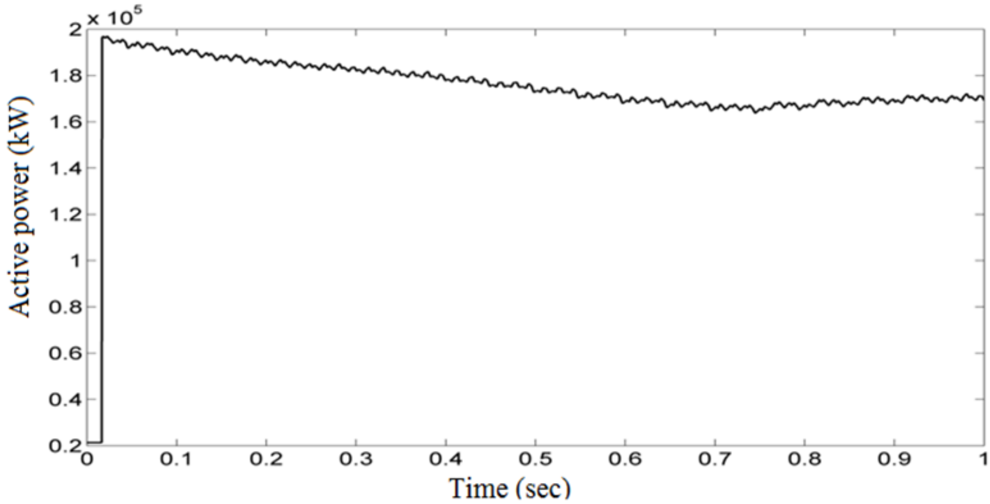

Fig.3.6d: Active power output of inverter in grid connected mode with proposed filter.

Table 3.7a: Inverter output with proposed filter in grid connected mode

Peak value of phase voltage at inverter output (V)	Active Power (kW)	Frequency (Hz)	THD (%) of Voltage at bus 5
2000	16.9	60	0.02

It is clear from Fig.3.6a that the VSI is able to maintain its terminal voltage in grid connected mode. Fig.3.6b shows that VSI is able to maintain the grid frequency after a small transient. Fig 3.6c and Table 3.6a shows that the THD of voltage at inverter bus goes down abruptly in grid connected mode.

3.3.1 Performance evaluation

Next the LCL filter parameters of Fig 3.6 are tuned following reference [19] and same simulation as described in article 3.3 has been performed and results are tabulated in Table 3.6b. The variation in phase voltage, frequency, total harmonic distortion (THD) of the phase voltage and active power output of the VSI terminal (bus 5) are shown in figures 3.7a to 3.7d respectively.

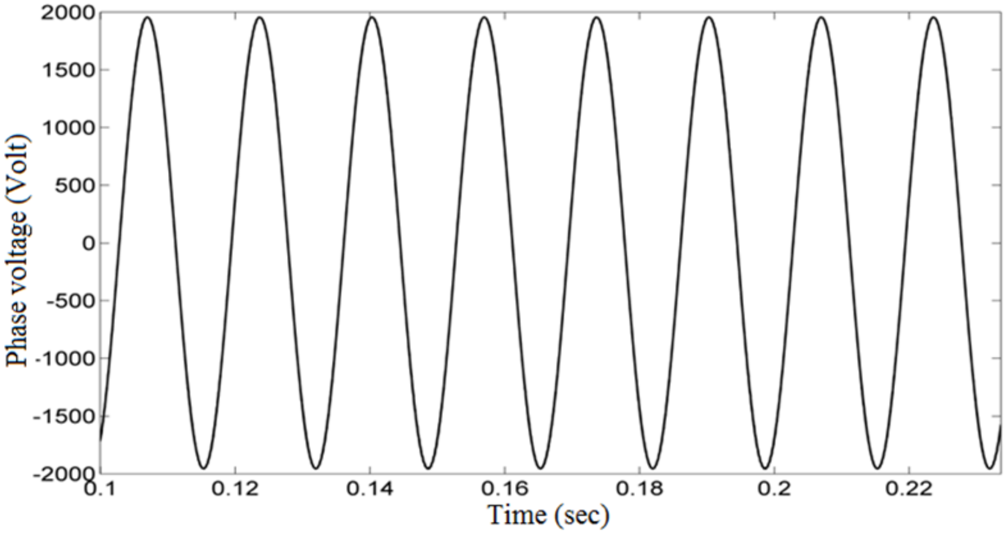

Fig.3.7a: Inverter terminal voltage in grid connected mode with reference filter.

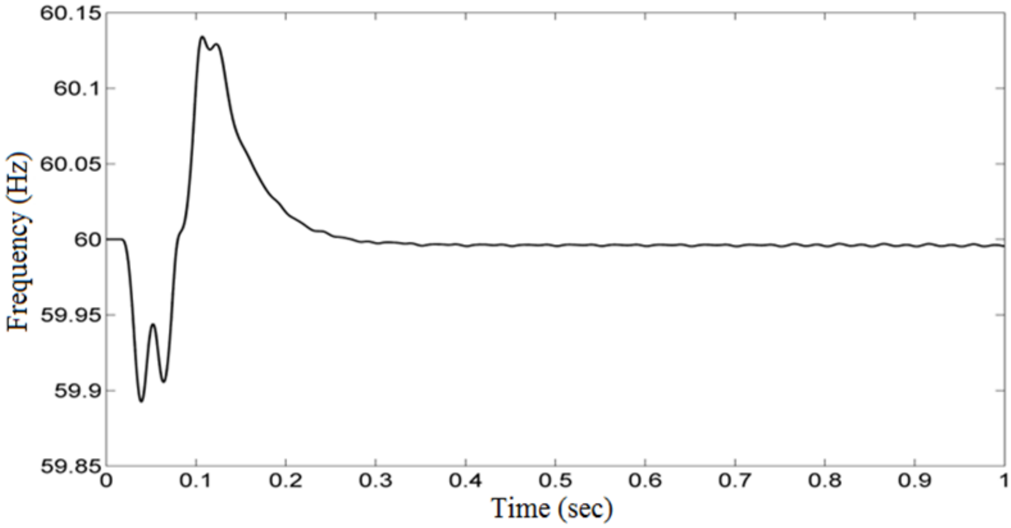

Fig.3.7b: Frequency of inverter output voltage in grid connected mode with reference filter.

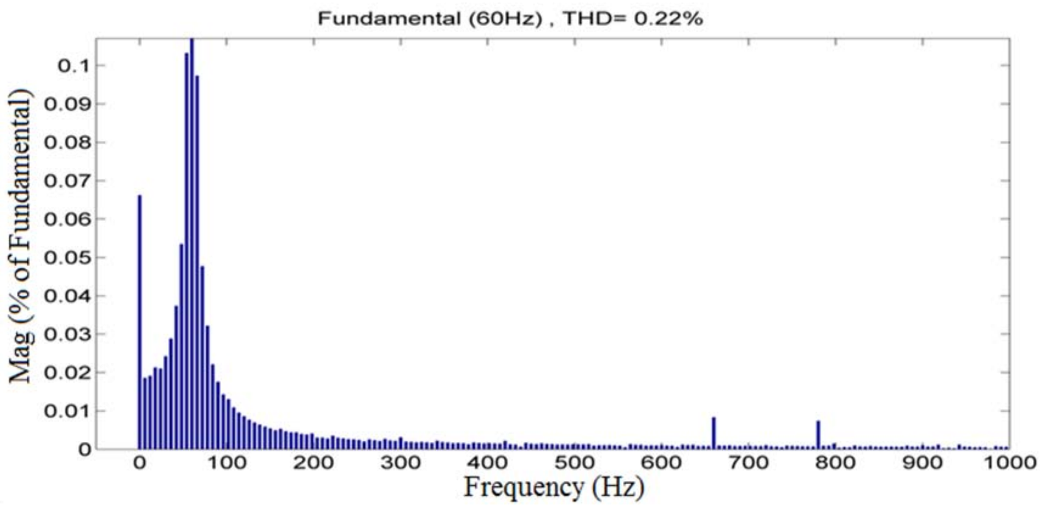

Fig.3.7c: Harmonic content of inverter output voltage in grid connected modewith reference filter.

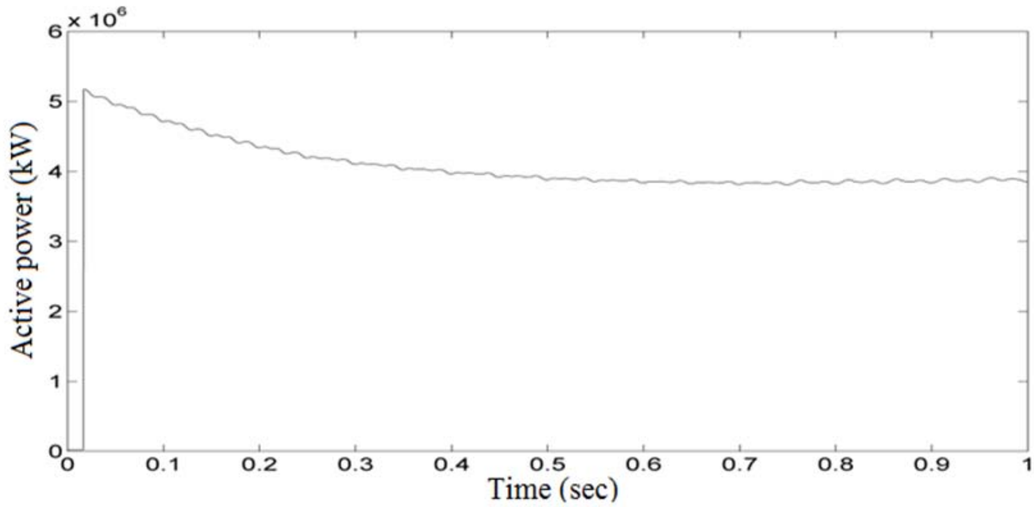

Fig.3.7d: Active power output of inverter in grid connected mode with reference filter.

Table 3.7b: Inverter output in grid connected mode

Peak value of phase voltage at inverter output (V)	Active Power (kW)	Frequency (Hz)	THD (%) of Voltage at bus 5
2000	38	60	0.22

It is clear from Fig.3.7a that the VSI is able to maintain its terminal voltage in grid connected mode. Fig.3.7b shows that VSI is able to maintain the grid frequency after a small transient. Fig 3.7c and Table 3.7c shows that the THD of voltage at inverter bus increased in grid connected mode. Fig.3.7d shows that inverter output power finally become steady.

Tables 3.7a and 3.7b shows that both the filters are able to provide satisfactory operation when VSI is in grid connected mode through a microgrid. THDs of VSI terminal voltage are far below of acceptable limit (5%) due to the presence of the grid. But %THD is still lesser in case of proposed filter.

3.4 Inverter operation in isolated mode

It is assumed that the inverter is operating in isolated mode which means CB8 in Fig.3.5 is open and filer parameters are tuned as proposed. It is observed that the inverter is capable to cater all the loads connected to it (24.93 kW).

The variation in phase voltage, frequency and total harmonic distortion (THD) of the phase voltage and active power at inverter terminal (bus 5) are shown in figures 3.8a to 3.8c respectively. Table 3.8a shows that the THD of inverter bus voltage increases in isolated mode but still it is less than 5%.

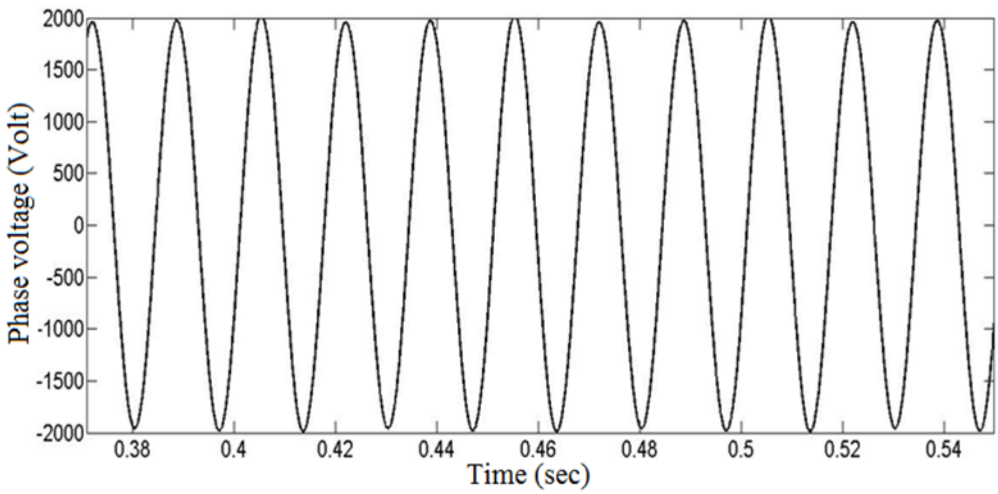

Fig.3.8a: Inverter terminal voltage in isolated mode with proposed filter.

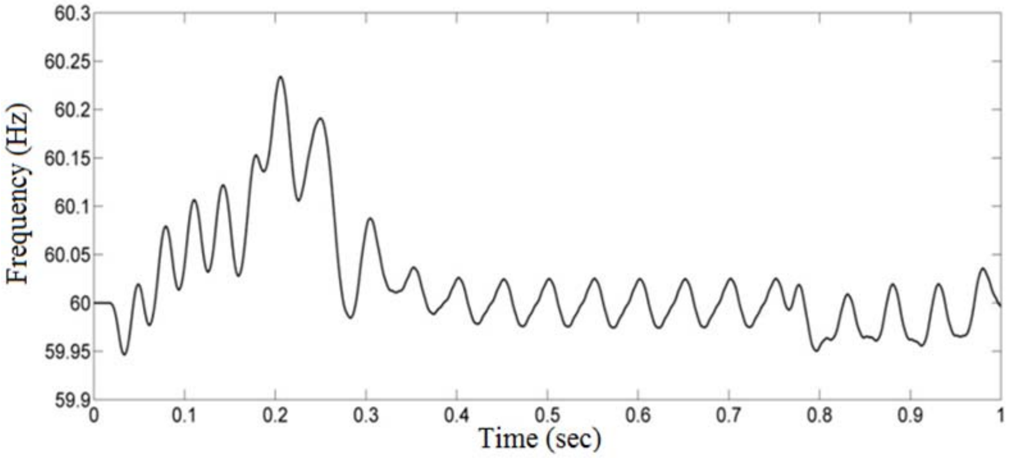

Fig.3.8b: Frequency of inverter output voltage in isolated mode with proposed filter.

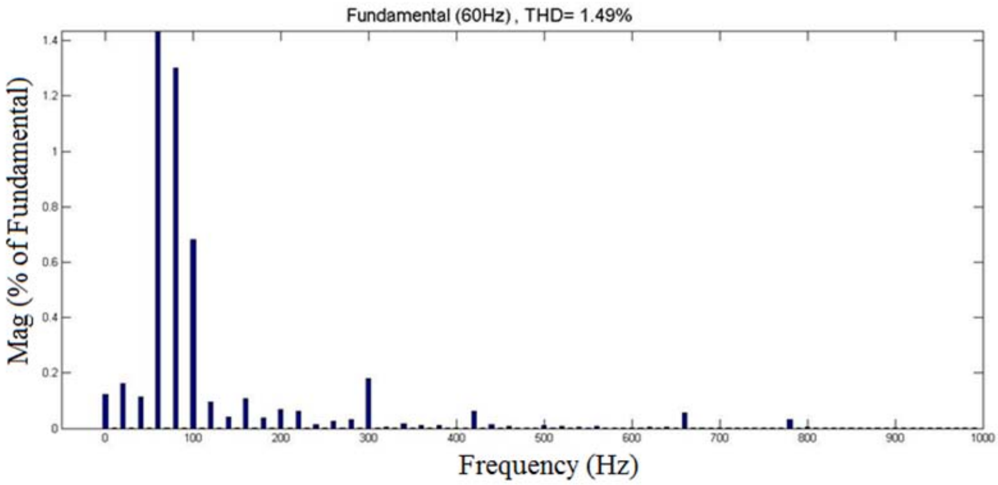

Fig.3.8c: Harmonic content of inverter output voltage in isolated mode with proposed filter.

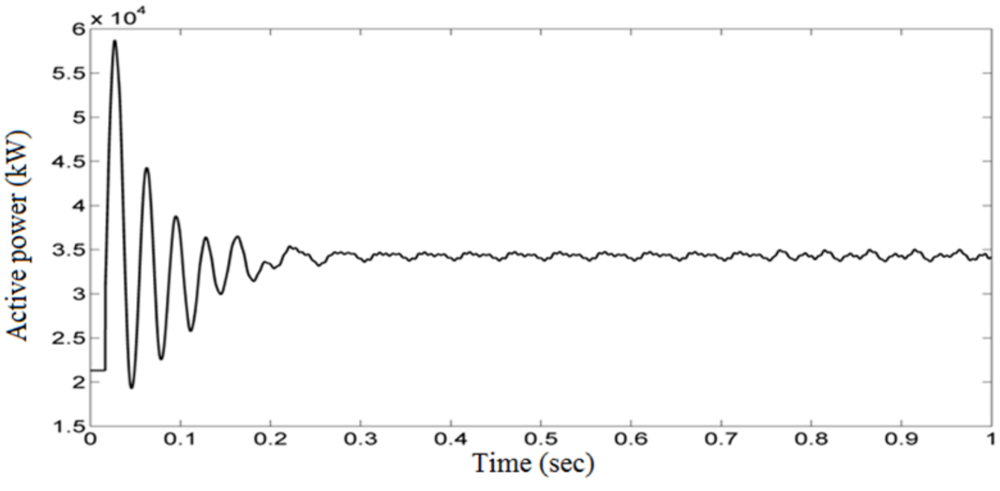

Fig.3.8d: Active power output of inverter in isolated mode with proposed filter.

Table 3.8a: Inverter output in isolated mode with proposed filter

Peak value of phase voltage at inverter output (V)	Active Power (kW)	Frequency (Hz)	THD (%) of Voltage at bus 5
2000	35	60	1.49

Fig 3.8a shows that VSI output voltage is almost sinusoidal and steady. It is observed from Fig.3.8b that the system frequency is undulating around 60Hz which indicated the VSI is able to operated stably even in isolated mode. The VSI output power is increased to35 kW cater the present load in absence of grid and DG1.

3.4.1 Performance evaluation

Here the LCL filter parameters of VSI are tuned following ref [19] and same simulation as described in article 3.4. has been performed. The variation of inverter output voltage, frequency and total harmonic distortion (THD) of the inverter terminal voltage (bus 5) are shown in figure 3.9a to 3.9c respectively. The VSI active power is shown in Fig.3.9d. Table 3.7b shows that the THD of inverter bus voltage increase in isolated mode but still it is less than 5%.

It is observed from Fig 3.9a that VSI output voltage contains more non-linearity as compared to Fig.3.8a. Fig.3.9b indicates that the system frequency is not getting any stability around 60Hz and it goes on increasing. So no stable operation of VSI is possible in isolated mode with present filter. The VSI output power is decreased to 25 kW cater the present load in absence of grid and DG1.

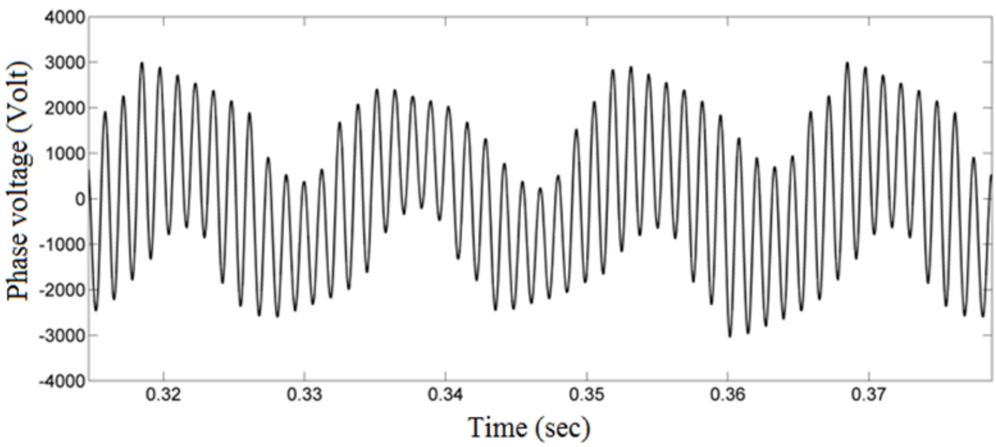

Fig.3.9a: Inverter terminal voltage in isolated mode with reference filter.

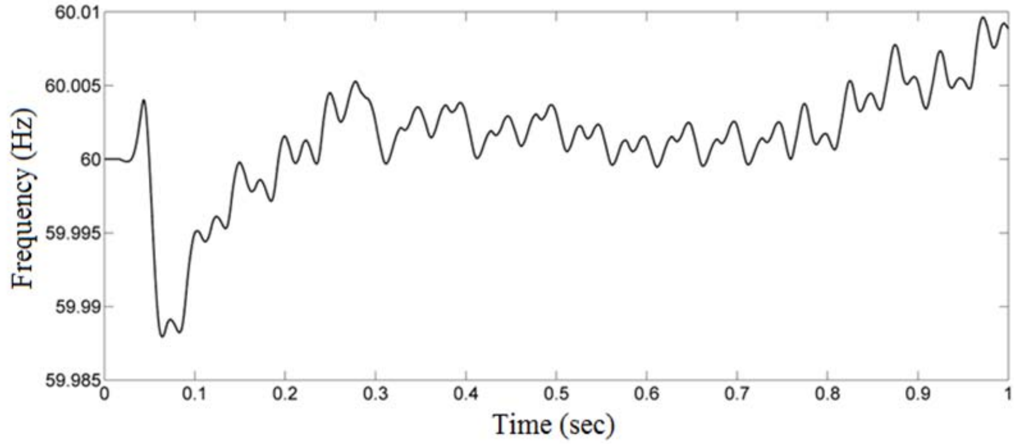

Fig.3.9b: Frequency of inverter output voltage in isolated mode with reference filter.

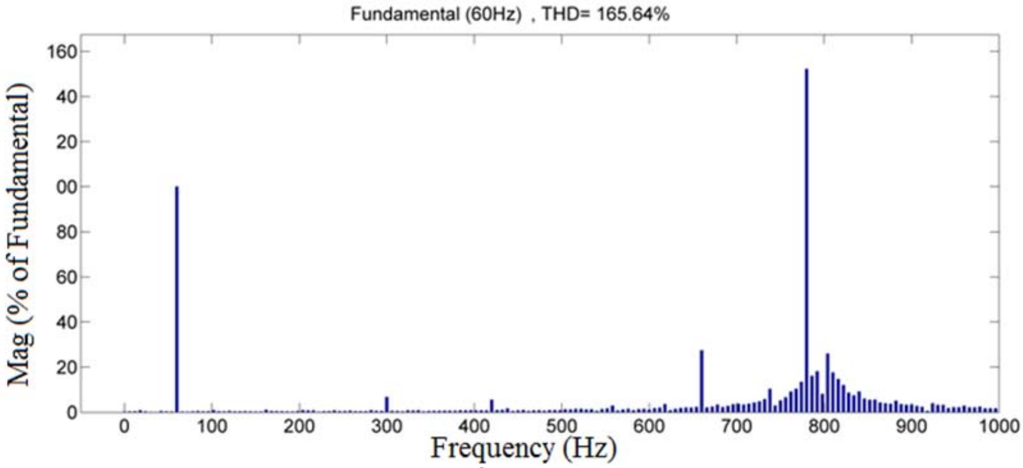

Fig.3.9c: Harmonic content of inverter output voltage in isolated mode with reference filter.

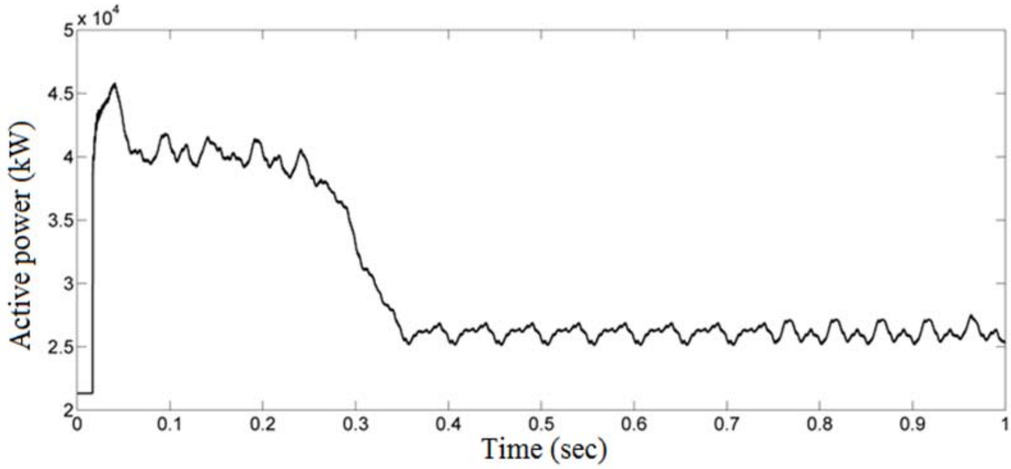

Fig.3.9d: Active power output of inverter in isolated mode with reference filter.

Table 3.8b: Inverter output in isolated mode with reference filter

Inverter output volt (Peak value) in Volts	Active Power (KW)	Frequency (Hz)	THD (%) of Voltage at bus 5
3000	25	60	165.64

From the above figures it is clear that the harmonics in the output voltage from the reference [19] filter contains more in isolated mode. Harmonic analysis has been performed and THD of voltage is 165.64% in isolated mode which is far away from the acceptable limit (5%). So the reference filter designed here does not work properly and gives unsatisfactory output as compared to the proposed filter.

Chapter 4

Conclusion and Future scope

4.1 Conclusion

A LCL filter has been designed to reduce harmonics and for smoothening the output voltage of a Voltage SourceInverter (VSI) to operate in grid connected mode as well as in isolated mode..

The output voltage of VSI is found to be smoother and contains less harmonics when it is connectedwith Grid at PCC through the proposed filteras compared to filter presented in reference [19]. Harmonic analysis of the VSI output voltage is far below the acceptable limit for the proposed filter (1.3%) whereas it is (%THD) is beyond acceptable limit for the reference filter (10.69%). Therefore the present filter performs better when it is connected to grid at PCC.

The performance of the proposed filter is explored when the VSI is connected to grid through a microgrid. In this case both the filters are able to provide satisfactory operation. THDs of VSI terminal voltage are far below of acceptable limit (5%) due to the presence of the grid. But %THD is found to be lesser in case of proposed filter.

VSI provides smoother sinusoidal voltage and contains less harmonics in in presence of proposed filter even in isolated mode of operation as compared to reference filter. Harmonic analysis of VSI output voltage shows that % THD is 165.64% for reference filter whichis far away from the acceptable limit (5 %). The % THD is 1.9% with proposed filter in isolated mode. So the proposed filter designed performs better as compared to the reference filter.

4.2 Future Scope

1. The dc source can be replaced by solar cells to get better model of Solar PB generation.
2. The solar PV generation can modelled based on solar irradiation and MPPT method.
3. Controllers may be designed to control the magnitude, frequency and harmonic content of output voltage of VSI in presence of varying load.

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It is found that clear from Fig.3.4b and Table 3.3 that the output voltage from the proposed filter contains more harmonics as compared to Fig.3.3b. Therefore the present filter does not work properly

m3: isolated mode in microgrid: From the above figures it is clear that the harmonics in the output voltage from the reference [21] filter contains more harmonics in isolated mode. THD

RaplaceTHD analysis by harmonic analysis

References

1. F. Blaabjerg et al., "Overview of Control and Grid Synchronization for Distributed Power Generation Systems", *IEEE Transactions on Industrial Electronics*, vol. 53, no. 5, October, 2006, pp. 1398- 1409.
2. I. Bouloumpasis et al., "Current harmonics compensation in microgrids exploiting the power electronics interfaces of renewable energy sources", *Energies*, vol. 8, issue 4, pp.2295-2311, 2015.
3. Bandana Bhutiaet et al., "Design of three phase PWM voltage source inverter for photovoltaic application", *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering*, vol. 2, issue 4, pp.1364- 1367, April 2014.
4. Miroslav Begovic, Jun Zhang, Damir Novosel, Namhun Cho "Harmonic distortion in microgrids and distribution systems with photovoltaic generators" 2015 48th Hawaii international conference on system science.
5. Subramaniam Senthil Kumar et al., "Modelling, analysis and control of stand-alone self-excited induction generator-pulse width modulation rectifier systems feeding constant DC voltage applications", *IET Generation, Transmission & Distribution*, vol. 8, issue. 6, pp. 1140–1155, 2014.
6. Meenakshi jayaraman, and Sreedevi VT "Implimentation of LC and LCL passive filter for harmonic reduction in PV based renewable energy sources" 2017 National power electronics conference (NPEC), College of Engineering Pune, India December 18-20, 2017
7. M. Pradanovic and T. Green, "Control and filter design of three phase inverter for high power quality grid connection," *IEEE transactions on Power Electronics*, vol.18. pp.1-8, January 2003.
8. A.E.W.H. Kahlane et.al. , "LCL filter design for photovoltaic grid connected systems", *Revue des Energies Renouvelables SIENR'14 Ghardaïa (2014) pp.227-232, 2014.*
9. Md Alamgir Hossain et. al. "Overview of AC microgrid controls with inverter-interfaced generations", *Energies*, vol. 10, issue 9, pp.1-27, 2017.

10. P. Mattavelli, and F.P.l Marafão, "Repetitive-based control for selective harmonic compensation in active power filters", *IEEE Transactions on Industrial Electronics*, vol. 51, no. 5, pp. 1018-1024, October 2004.
11. J. Miret et al., "Selective harmonic-compensation control for single-phase active power filter with high harmonic rejection", *IEEE Transactions on Industrial Electronics,* vol. 56, no. 8, pp. 3117-3127, August 2009.
12. Takaharu Takeshita Nobuyuki Matsui, "Current Waveform Control of Distributed Generation System for Harmonic Suppression on Distribution **System",** vol. 1, *28th Annual Conference of the Industrial Electronics Society, **I**ECON 02* , 2002.
13. Takaharu Takeshita, Takahiro Masuda and Nobuyuki Matsui, "Current Waveform Control of Distributed Generation System for Harmonic Voltage Suppression", vol.2, 32nd Annual Power Electronics Specialists Conference, 2001. PESC. 2001.
14. Vipul C. Rajyaguru, "Design and simulation of grid connected PV system", *International Journal of Engineering Technology*, *Management and Applied Sciences*, vol.4, issue 8, ISSN 2349-4476 , August 2016, pp.192-198.
15. Fang Z. Peng, Yun Wei Li, Leon M. Tolbert, "Control and protection of power electronics interfaced distributed generation systems in a customer-driven microgrid", Proc. IEEE Power & Energy Society General Meeting, Calgary, AB, Canada, 26th 30th July 2009,pp. 1-8.
16. H.R. Baghaee et al., "Effect of type and interconnection of DG Units in the fault current level of distribution networks", ***13th*** *International Power Electronics and Motion Control Conference*, October 2008.
17. Tawfikur Rahman, S. M. A. Motakabber and M. I. Ibrahimy, "Design of switching mode three phase inverter", 2016 international conference on computer and communication engineering (ICCCE).
18. Mahmud Wasfi "Solar energy and photovoltaic systems" multidisciplinary journals in science and technology of selected areas in renewable and sustainable energy, February edition 2011.
19. Mustafa Dursun, M. Kenan Dosoglu "LCL Filter Design for Grid Connected Three-Phase Inverter", pp.1-4, IEEE, 2nd International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT) , 2018 .
20. Eklas Hossain, Ersan Kabalci, Ramazan Bayindir, Ronald Perez "A comprehensive study on microgrid technology" International journal on renewable energy research, Ramazan Bayindir, 2014

Appendix-A

A.1 Matlab Simulink Models

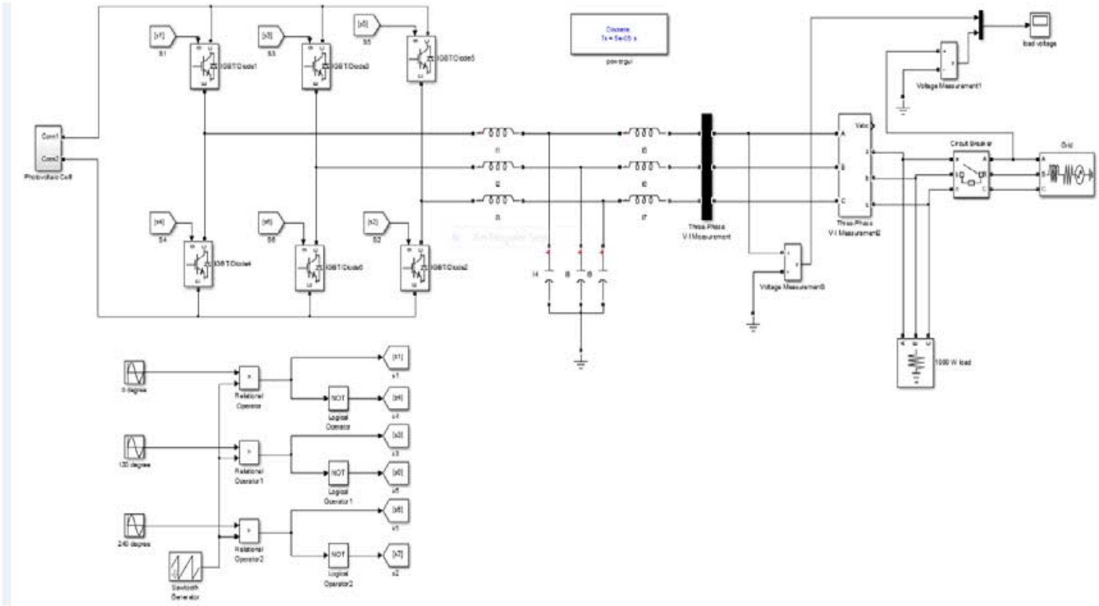

Fig A1: Matlab simulink model of grid connected inverter of reference (21) with proposed filter

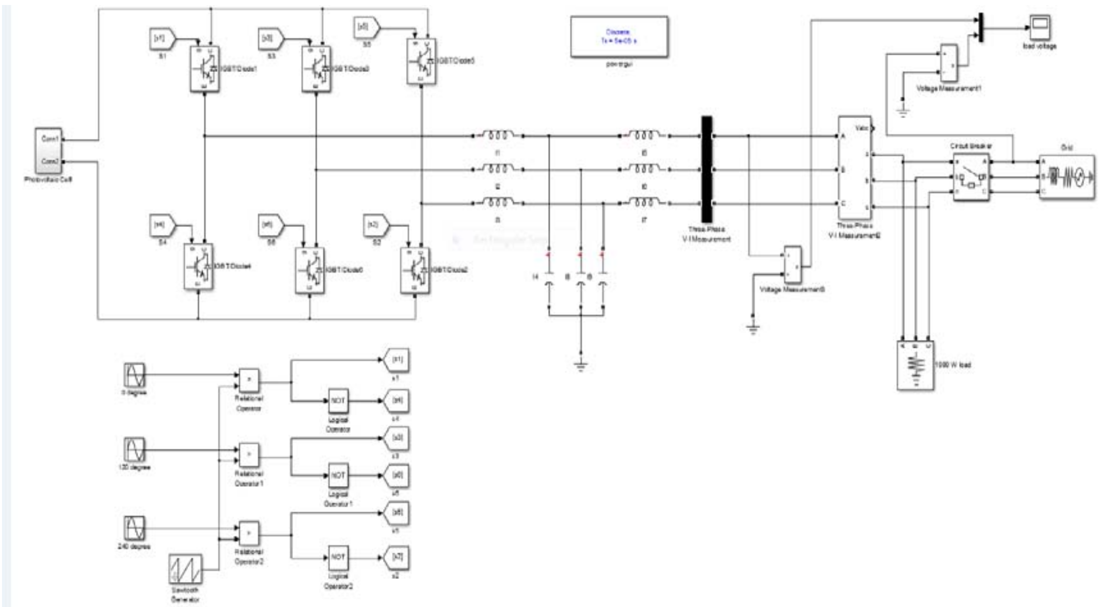

Fig A2: Matlab simulink model of grid connected inverter of reference (21) with given filter

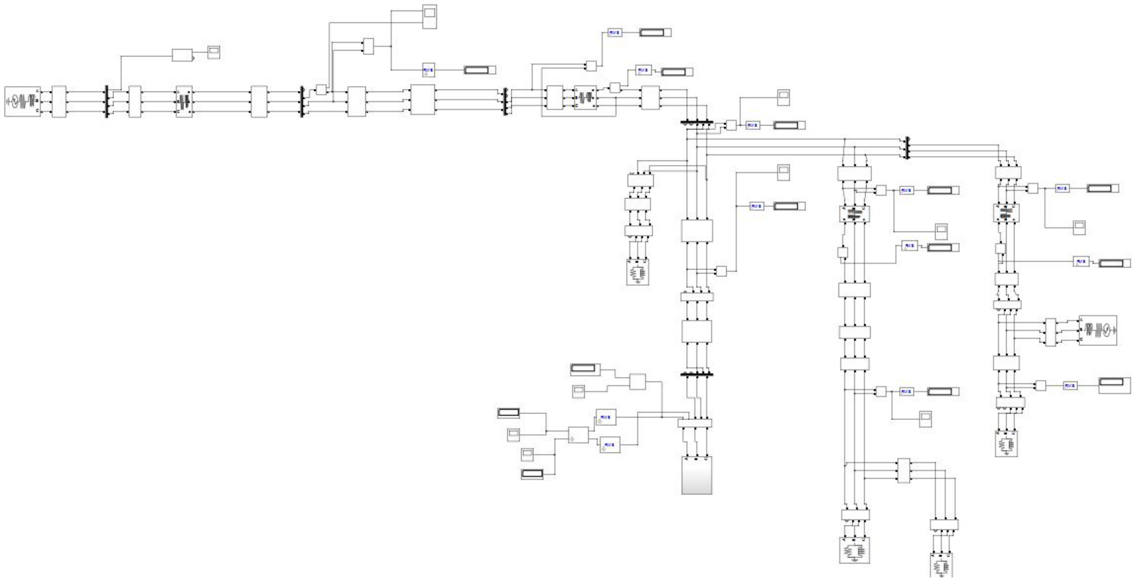

Fig A3: Matlab simulink model of distribution system connected inverter with proposed filter

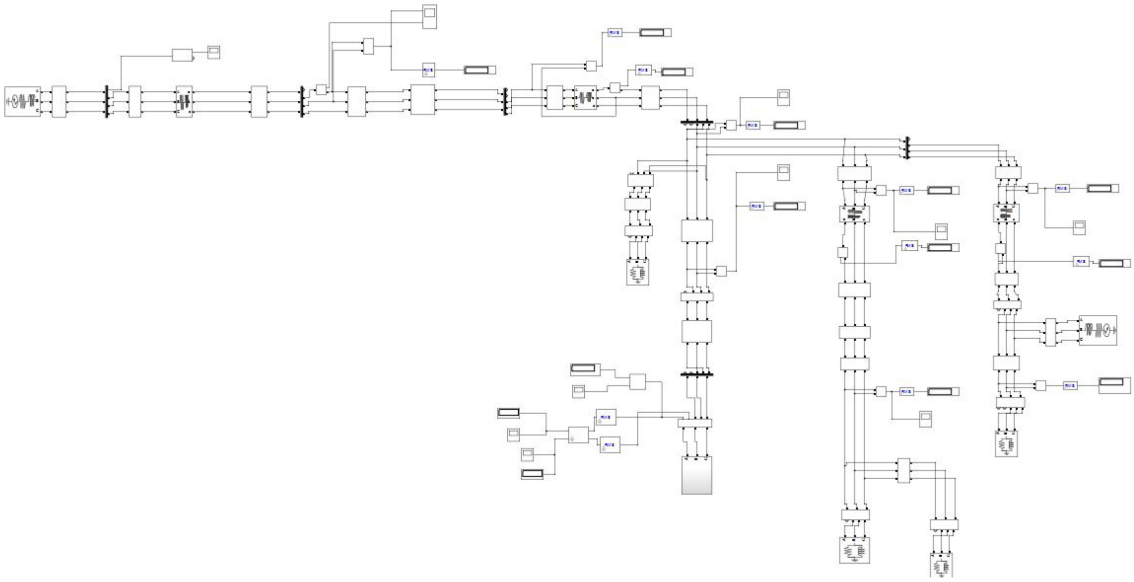

Fig A4: Matlab simulink model of distribution system connected inverter with ref (21) filter

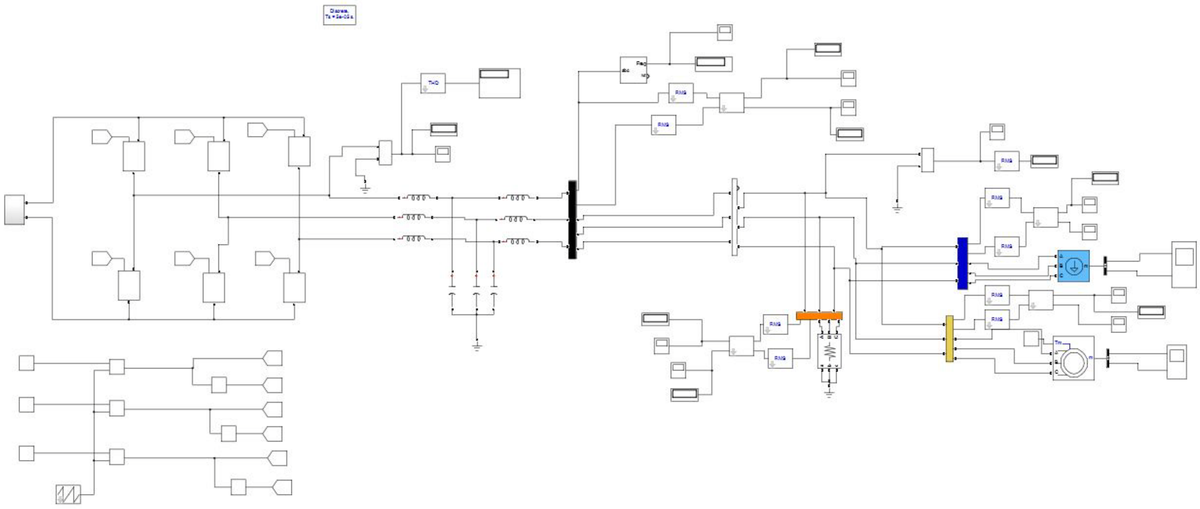

Fig A5: Matlab simulink model of inverter in isolated mode with proposed filter

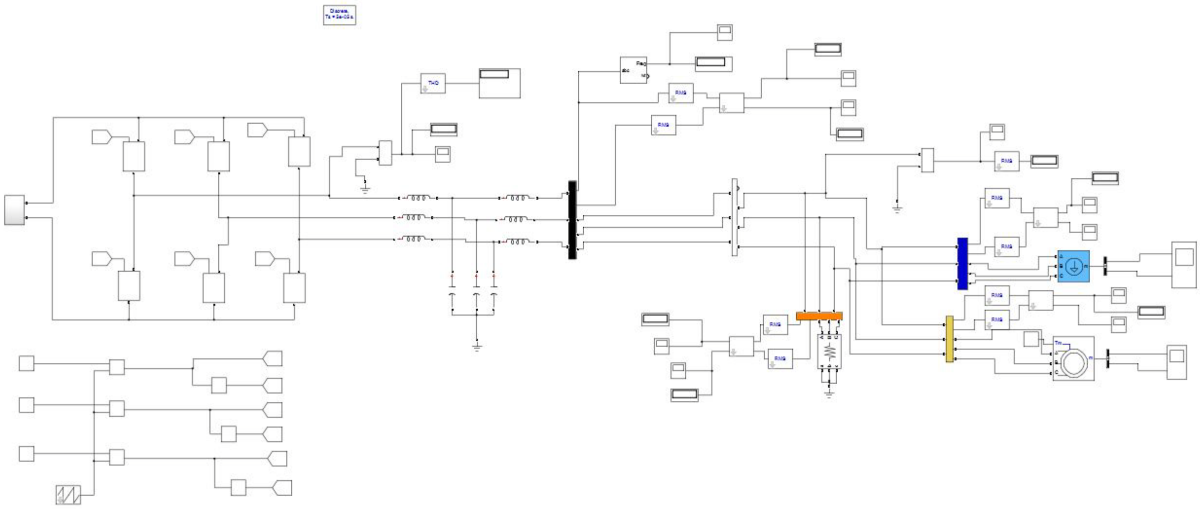

Fig A6: Matlab simulink model of inverter in isolated mode with ref (21) filter

Calculation of Filter parameters:

$$\omega_g = 2\pi f_g$$

C_b=base capacitance $= \dfrac{1}{w_g Z_b}$ where

The base impedance and base capacitance of the system are as given below:

Z_b = base impedance $= \dfrac{V_{rms}^2}{S_r}$, C_b=base capacitance $= \dfrac{1}{w_g Z_b}$ where $w_g = 2\pi f_g$

The first step in calculating the filter components is the selection of the inverter side inductance (L_i), which can limit the output current ripple by up to 10% of the nominal amplitude (Fig.2.2(c)). It can be calculated according to the equation given below

$$L_i = \frac{V_{dc}}{16 f_{sw} \Delta I_{L\max}} \quad (2.1)$$

Where $\Delta I_{L\max}$ is the 10 % current ripple specified by,

$$\Delta I_{L\max} = 0.01 \times \frac{P_{Inv}\sqrt{2}}{V_{LL}} \quad (2.2)$$

The filter capacitor (C_f) is selected based on the fact that the maximal power factor variation acceptable by the grid is 5%. Then the filter capacitor is given by,

$$C_f = 0.05 C_b \quad (2.3)$$

The grid side inductance (L_g) can be calculated by:

$$L_g = r \times L_i \quad (2.4)$$

r is the ratio of L_g and L_i. It is seen that in order to limit the current ripple in the converter side inductance (to reduce Power loss in the filter) and increase the filter attenuation, it is required that the converter side inductance be dominant in the filter.
The value of r for a desired ripple attenuation can be obtained from the Fig.2.3.

A.2 Calculation of Filter Parameters

$\omega_g = 2\pi \times 3 \times 60 = 1130$ rad/sm, $Z_b = \frac{2500^2}{66000} = 94.70$ ohm

C_b=base capacitance $= \frac{1}{\omega_g Z_b} = = \frac{1}{1130 \times 94.70} = 9.3\ \mu$F

From equation (2.3), $C_f = 0.05 C_b = 0.05 \times 9.3 \cong 47\ \mu$F

From equation (2.2), $\Delta I_{L\max} = 0.01 \times \frac{P_{Inv}\sqrt{2}}{V_{LL}} = 0.01 \times \frac{66 \times 10^3 \times \sqrt{2}}{2500} = 0.373$ A

From equation (2.1), $L_i = \frac{V_{dc}}{16 f_{sw} \Delta I_{L\max}} = \frac{2400}{16 \times 5000 \times 0.373} = 0.08$ H

It is required that the converter side inductance be dominant in the filter in order to limit the current ripple in the converter side inductance. Therefore the grid side inductance $\left(L_g\right)$ is assumed as 0.06 H. From equation (2.4),

$$r = \frac{L_g}{L_i} = \frac{0.06}{0.08} = 0.75$$