M.Sc. Thesis

An Improved Algorithm to Reduce Total Harmonic Distortions in Inverters of Grid Tied Photovoltaic System

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An Improved Algorithm to Reduce Total Harmonic Distortions in Inverters of Grid Tied Photovoltaic System

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Acknowledgments

I am very grateful to my supervisor for the constant support throughout this research.

I dedicate this thesis to my parents.

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1 Problem Statement

To reduce the Total Harmonic Distortion (THD) in Current of grid-connect photovoltaic (PV) inverters under low-irradiance condition and varying reactive power demand.

2 Scope of thesis

Simulation of a Sugeno Fuzzy control algorithm applied to current controller to reduce total harmonic distortion in current of a grid-tied photovoltaic invertor under conditions of low irradiance and varying reactive loads.

3 Thesis Layout

This thesis consists of eight chapters.

Introduction: This chapter give an overview of the main topics relate to this thesis. The detailed explanations of these topics are explained in later chapters.

PV Systems: This chapter discusses the pv systems, their importance and their applications.

Hybrid Grid: This chapter discusses the hybrid grids, their type and importance.

Total Harmonic Distortion: This chapter discusses the concept of total harmonic distortion, its cause and its mitigation techniques.

Fuzzy Logic: This chapter discusses the concept of fuzzy logic, its application and its relevance to this thesis.

Mathematical Model of system under consideration: This chapter discusses the mathematics of the system being simulate and its flowcharts.

Simulation: This chapter discusses the simulation, and its results.

Conclusions: This chapter discusses the conclusions and further research suggestions.

4

Introduction

4 Introduction

Nowadays renewable energy continues to become a very important alternative of energy production over whole world so as to reduce dependence of grids on the conventional fossil fuels for electrical energy and power production. In recent years, solar and wind energy is usually preferred for the reason of the very low atmospheric and environmental effects, lower operative and production expenditures and not causing any air pollution. [1-4].

Renewable energy systems perform a complete shift from dormant to better and active by effective consumption of flexible electrical energy producers such as renewable power with smart grid (SG). SG is a relatively new and rapidly emerging technique for the distributed energy production systems [1], [3], [5], [6].

A hybrid grid typically consists of multiple type of power sources and resistive, active and reactive loads [7].

These sources can include [8]:

1. Diesel Generators (DG Sets)
2. Photo voltaic (PV) Systems
3. Battery Backup Storage Systems
4. Wind Energy Conversion Systems (WECS)

5. High temperature gas reactor (HTGR) [9]

Battery backup storage systems and diesel generators is use to cater for the irregular and intermittent nature of solar energy [10].

ON/OFF and continuous control strategy is very commonly use for diesel generators and other fossil fuel power production systems in a hybrid grid [11,12].

When these different type of source is connect to a grid, it is very important and critical to keep the power being produce clean of any harmonic distortion and fluctuations. The power produce by intermittent and irregular sources, such as PV and wind is known to introduce high amounts harmonic distortion. These harmonic can cause severe damage to the equipment and system connect to the hybrid grid.

The IEEE 514-2014 standard recommends to keep the Total Harmonic Distortion (THD) in current to below 5 percent [13].

One of the major source of harmonics in a hybrid PV grid is the inverter being use by the PV system. The switching circuits use in the inverters cause harmonic distortions. Two power converters for photo voltaic applications is use in the conventional grid connect inverters. The first stage is a DC-DC converter that is connect to the PV panel and tried to extract maximum PV power. Extracting maximum power from the source is call Maximum Power Point Tracking (MPPT) [14]. The next stage is a voltage source converter (VSC) that converts the DC from MPPT to AC as per grid requirements. These converters cause harmonic distortions.

Harmonic distortions is also observe in PV systems due to intermittence and low value of solar insolation [15]. Harmonic distortions also increase when there is sudden change in reactive power demands [16].

Inverters operating underload also produce harmonic distortions. [17].

In Ref. [18], power quality index is analyze in the traditional AC grid which is integrate with a substantially sized PV plant by using simulation software and geographical and meteorological data. Theoretically, the control of power quality and of DC grid connection has been well study by [19].

Adequate power production quality degree can pledge the electrical devices operating in a good electromagnetic compatible environment and enhance the lifetime of equipment.[20]

Highly ecessive harmonic can create the multiple issues for power generation transmission and distribution network. These issues can include:

1. Noise
2. interference with communication systems
3. over-heating of transformers

4. mechanical vibrations of the actuators, pumps and motors
5. information loss
6. over-heating of capacitors
7. over-heating of cables [21]

In this study a fuzzy logic approach is use to minimize the THD in the current being inject by an inverter in the hybrid grid under varying insolation conditions and reactive power demand.

Figure 4-1 shows world map for solar irradiance and PV power potential. Pakistan lies in the region with moderate to high values of solar irradiance. Thus, a large potential for distributed PV solar power generation exists in Pakistan.

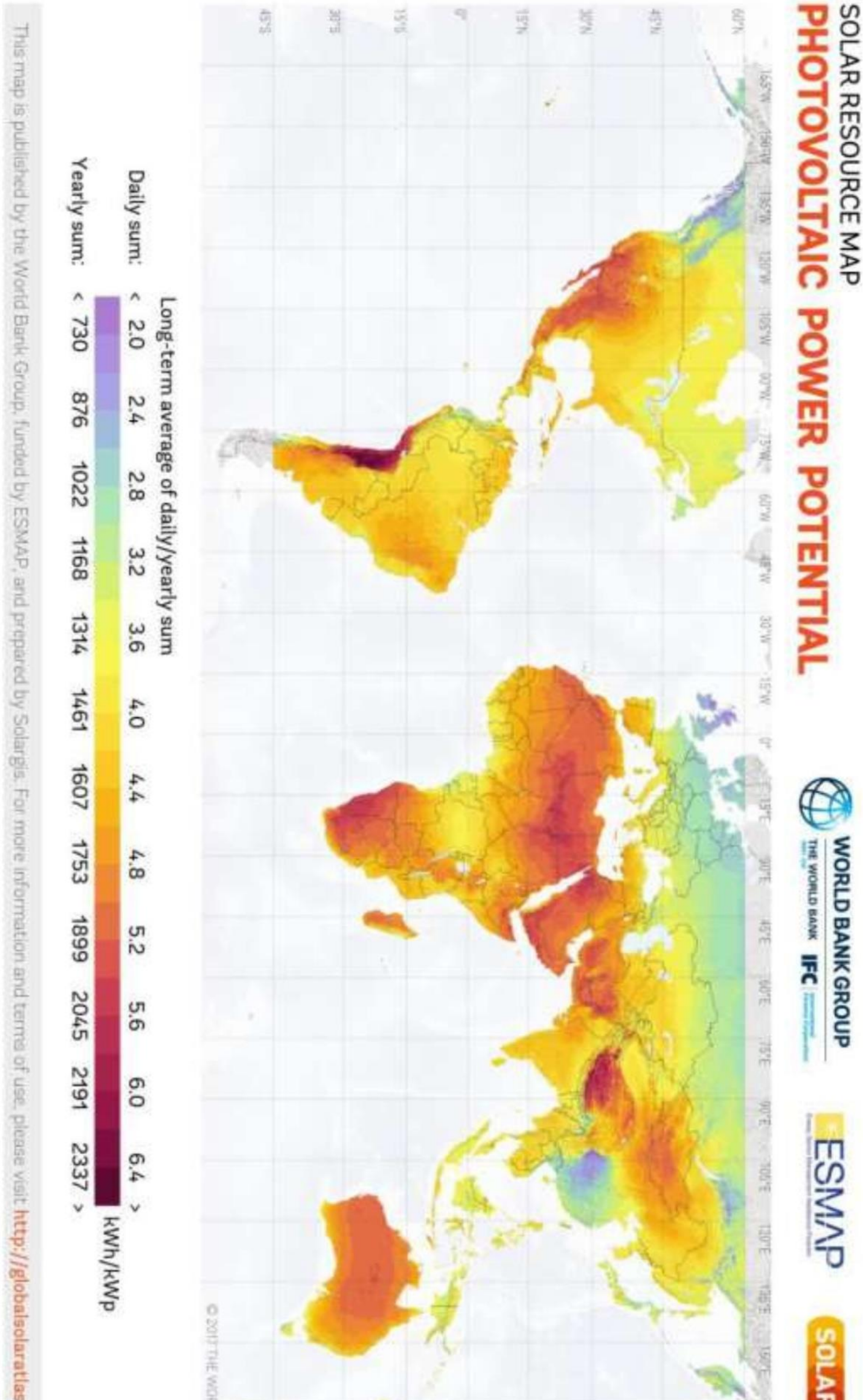

Figure 4-1 World Solar Map

5

Renewable Energy Resources

5 Renewable Energy Resources

Renewable, energy is the type of energy collect from replenishable resource, that is usually naturally replenish on a humanly timescale. These can include solar, air, ocean waves, geothermal heat sources and ocean tides [22]. Renewable energy sector usually provide energy in many of the very important areas.

Four of these are;

1. air and water heating/cooling

ii. electricity power production

111. rural power services

1v. transportation[23].

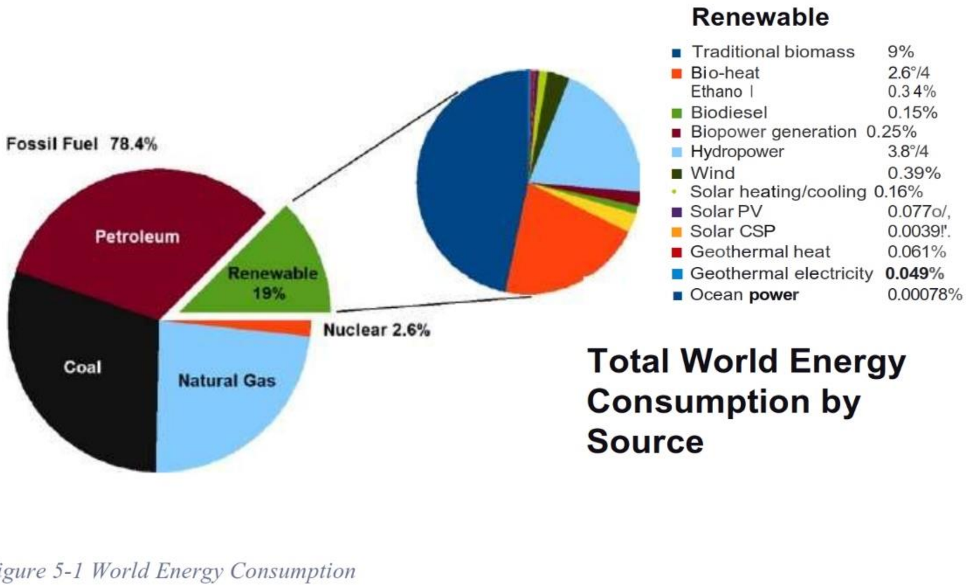

Figure 5-1 World Energy Consumption

According to the REN21's 2018 article, the renewable energy sector contribute 19.3 percentage to our global energy use, or consumption in

2015. REN21's 2018 report also states that renewable energy sector contribute about twenty percent to the production of electrical energy in 2016. The renewable energy consumption is usually composed of;

- 4.2 percent as green heat energy (geothermal energy resources, modern biomass energy, and solar thermal systems)
- 3.9 percent from hydel electrical power
- 8.9 percent consisting of sources of traditional green biomass
- And the remaining 2.2 percent is electrical power being produced from solar PV and thermal, air, ocean waves, geothermal heat sources and ocean tides.

Continuously increasing worldwide global interest in the renewable energy production technology was approximately close to US$286 billion in year 2015. China and the United States of America (USA) heavily invest in renewable energy production systems such as biofuels, solar, air, ocean waves, geothermal heat sources and ocean tides [24]. Around the world there is an estimate of 7.7 million global jobs being create and associate with the renewable energy industry. Photo voltaics solar energy production companies being a large renewable establishment in this industry [25]. In recent years around the globe, more than fifty percent of all new electricity power production capacity install is renewable energy [26].

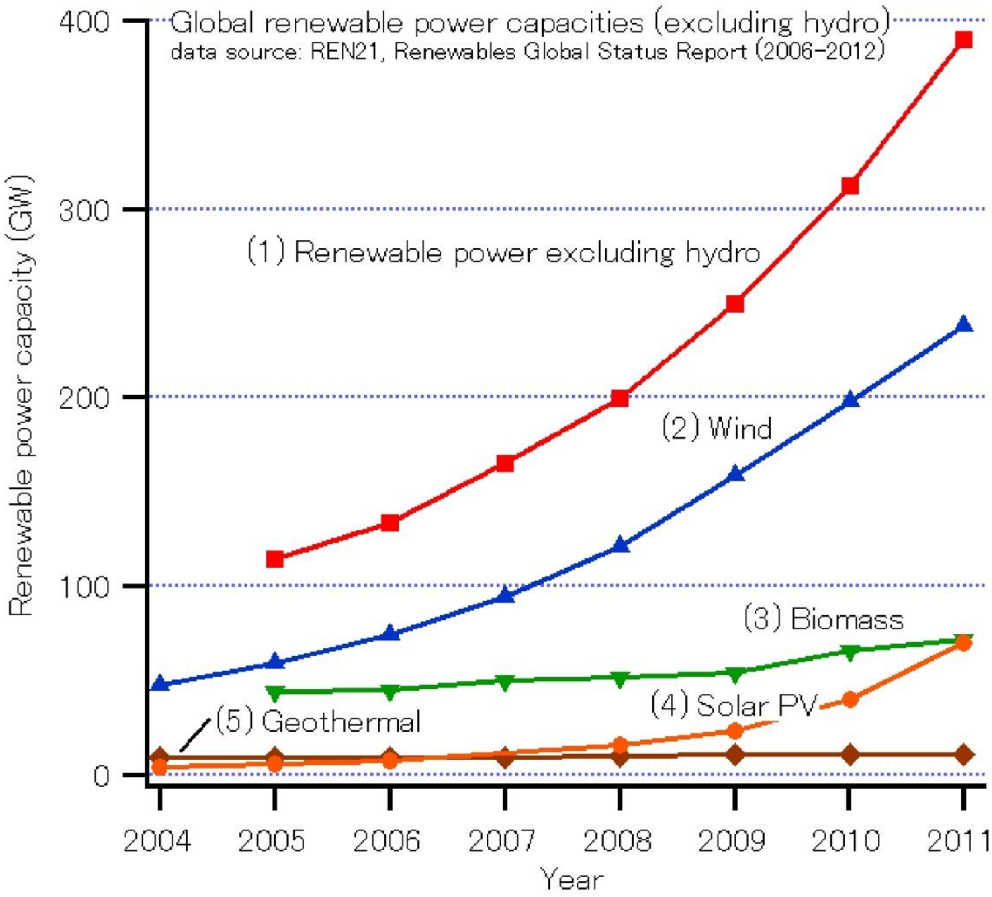

Figure 5-2 Renewable Power Capacity

At the country-level, more than 30 states round the globe already use the renewable energy production that contribute about twenty percentage of country's total power supply. National renewable energy production market is project to continue to increase strongly in the coming decades[27]. In some cities and many country that include Norway; they produce all the required electricity utilizing renewable energy systems now. Multiple more country have already fixed an optimistic target to achieve hundred percent (100 percentage) renewable power production in the near future[28]. About 47 states and countries round the globe now have achieved over fifty percent of electrical power from renewable energy resources [29] [30][31]

Renewable power resource exist over wide topographical location. While in its comparison the traditional fossil derived fuel, that is concentrate and available in very limit count of states. Swift deployment and development of power efficiency, renewable energy and technology has resulted in substantial environment change reduction, energy security, economical advantages and benefits[32]. The results in a current analysis of the scientific works on environment conclude that as Green House Gas (GHG) producing plants start to be called responsible and liable for the hazardous damage ensuing from increasingly more Green House Gas (GHG) emissions that resulted in worse environment variation, very high value of legal liability reduction could provide influential and effective incentive about development and placement of renewable energy sector[33].

Among the trans-world open opinion polls, a very compelling support about rapidly encouraging renewable energy resource such as solar power (PV and thermal) and wind power exists[34].

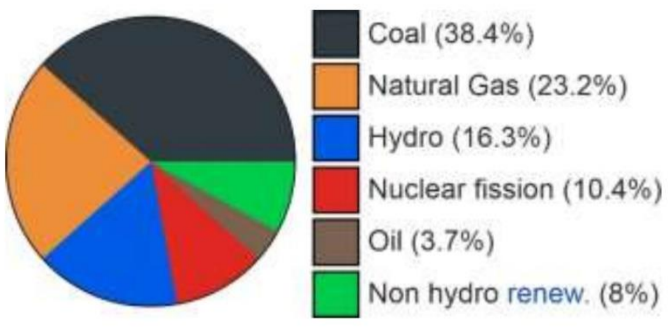

Figure 5-3 Energy Mix

6

PV Systems

6 PV Systems

A photo voltaic system, also called a PV system or, alternatively, a solar power system, is a power production system that is design to provide effectively usable solar power by means of photo voltaics phenomena. Most often, it consists of a setup of multiple components, that include PV solar panels for absorbing and converting solar irradiances into Direct Current electrical power, PV solar invertors to convert the electric power from Direct Current to Alternating Current, and also metal framework, current carrying cables, and supplementary electrical accessories for set up of a functioning electrical system. Some solar PV systems and solar thermal systems also use a sunlight tracker system to considerably enhance the total operation of the solar system and include a integrate battery backup storage solution, as the price for battery storage device is expect to sharply decrease. Solar photo voltaic modules array usually just encompass the setup of solar photo voltaic panels, the most eye catching part of the photo voltaic system, and usually don't include all of the supplementary associated equipment, usually summarize on the balance of the system (BOS). Moreover, photo voltaic systems can efficiently convert solar irradiance directly in electrical power and photo voltaic (PV) solar system must not be confuse with multiple other solar related systems, for example solar thermal system or concentrate solar power, use for cooling/heating.

Photo voltaic systems widely range from household, residential rooftop-mount or commercial building-integrate systems with a capacity that varies from some hundred to several hundreds of kilowatts (kW), to huge grid-connected power production houses of thousands of megawatts (MW). These days, a majority percentage of PV system is directly grid-connected, whereas, off-grid or stand-alone systems currently only account for a smaller portion of the PV solar renewable energy market.

Operating silently without any noise and without any moving components or toxic environment emissions, e.g GHG, PV systems have develop from being only a small, niche scientific research market applications into a reliable and mature technology use for country-wide green electricity power production. A rooftop solar PV system recoups and produce back the invest energy during its preparation, manufacturing, transportation, installation and maintenance within 0.7 to two years and usually produce about ninety five percent of net clean and green renewable energy over a span of 30-year of its service lifetime [35][36][37].

Due to the rapidly increasing exponential growth of photo voltaic renewable energy system, price for photo voltaic renewable energy system have rapidly and exponentially decline in since their first introduction in commercial market. However, the price of the photo voltaic renewable energy system differs by marketplace and the magnitude of the photo voltaic system. Price for residential fivekilowatt (KW) photo voltaic renewable energy system in the Unite States of America (USA) were very much around $3.29 per watt of electricity in 2014 [38] while in the most penetrate market of the Germany, price for rooftop photo voltaic renewable energy system of up to hundred kilowatt kW already decline to €1.24 per watt of electricity [39]. Nowadays, solar PV module in a photo voltaic renewable energy system account for lower than 1/2 of the photo voltaic renewable energy system overall expenditure,[40] passing on the rest to the residual BOS parts and other related expenditures, that usually can comprise marketing, advertising, customer gaining, licensing, permitting, system checkup, interconnect of the photo voltaic renewable energy system to the grid , installation labor and financing expenditures [41].

7

Hybrid Solar System

7 Hybrid Solar System

Hybrid solar photo voltaic power system is hybrid energy production system which can pool solar energy from a photo voltaic renewable energy equipment with another energy producing power source [42][43]. One very well-known type of a hybrid system is a photo voltaic and diesel hybrid power producing system,[45][44] joining photo voltaic renewable energy system with conventional fossil fuel gensets, e.g diesel gensets, as photo voltaic energy seldom has a substantial expenditure and is treat with higher precedence on electric grid. The fossil fuel power generator is usually use to continuously compensate for the difference between the currently existing power demand and the currently real generate power from the photo voltaic renewable energy systems [43].

As solar energy is intermittent and fluctuating, and the production capability of the fossil fuel genset is usually limit to a particular range of power, it is quite usually a practicable solution to incorporate an appropriately sized battery backup so as to improve the photo voltaic renewable energy system's input to the total electricity production of hybrid energy grid system [43][45].

The best model business case for diesel usage reduction with photo voltaic renewable energy system and wind energy can usually be found in remote distant locations for the reason these kind of site is often not connect to the utility grid and transport of the diesel fuel over very long distance is not very expenditure effective [42]. Many of these applications can normally be found in the mining field [46] and on remote distant islands [43][47][48]

In 2015, a scientific research case-study conducts in seven country conclusively conclude that in all the case generating expenditures of energy can be significantly reduce by hybridizing the mini smart grids with photo voltaic renewable energy system. However, the capital financing expenditure for fossil fuel power electricity grids with solar photo voltaic renewable energy system is very crucial and largely depend on the project ownership model of the photo voltaic renewable energy system. While expenditure falls for state-own utility can be very significant, the same scientific research study also identify the near-term economic advantages to be minor, insignificant or also negative for privately owned utility systems, such as independent power producers (IPP), given the data of historical expenditure at the time when the study was done [49][50].

8

Total Harmonic Distortion

8 Total Harmonic Distortion

Harmonic distortion is the presence of sinusoid waveforms in power other than the fundamental frequency of wave. For example if fundamental is 50 Hz, presence of sinusoids other than 50Hz will contribute to harmonic distortion. Total Harmonic Distortion is calculated as

$$\mathrm{THD_F} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}$$

Here in the above equation Vn represents value of root mean squared of voltages of nth harmonics while here n = 1 is basic fundamental frequency of sinusoid.

8.1 Causes of THD

Following are the most common causes of total harmonic distortion in grid.

- Non-linear Circuit components, e.g.
    - Diodes
    - Transistors
    - Thyristors
- Power source operating under non-optimal conditions, e.g.
    - Inverters operating at under-load
    - Grid-Tie PV systems operating in low irradiance [4]
- Varying reactive loads

- Sudden addition or removal of reactive loads
- Load-shedding

- Intermittent power source (e.g. Wind Turbine [5]

IEEE 519-2014 standard recommends that the Current THD should be kept below 5%.

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L

where

I_{sc} = maximum short-circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

8.2 THD reduction techniques

Following techniques are usually employed to mitigate total harmonic distortion.

8.2.1 Hardware Techniques

- Line Reactors
- Harmonic Filters

  - Active Harmonic Reduction Filter Circuits
  - Passive Harmonic Reduction Filter Circuits
- Isolation Transformers [6]

8.2.2 Software Techniques

- Virtual Complex Impedance Loop
- Reactive Current Reference Control
- DC Link Voltage Control [7]

In this thesis, reactive current reference control has been combined with Sugeno Fuzzy Logic Control system to achieve lower Total Harmonic Distortion in grid current. The Sugeno Fuzzy Logic Control is explained in next section.

9

Fuzzy Logic

9 Fuzzy Logic

It is a logical method to decision basing on "degree of truthfulness" instead of common 1, zero Boolean logic upon what almost all of the current computer systems are created.

9.1 Types of Fuzzy Control Systems

There are two types of fuzzy control systems named after the founding scientists and researchers called Mamdani fuzzy control systems and Sugeno fuzzy control systems.

	Mamdani	Sugeno
Similarity	The antecedent parts of the rules are the same	
Difference	The consequent part fuzzy sets	The consequent part are singletons or mathematical function
Advantages	1 Easily understandable by human expert 2 Simpler to formulate rules 3 Proposed earlier and commonly used	4 More convenient in mathematical analysis 5 Guarantee continuity of the output surface
Applications	Good for capturing expertise of human operator	Good for embedding linear controller and effective when the plant model is known

9.1.1 Advantages of the Sugeno Systems

Sugeno fuzzy control systems work well with various linear control techniques, such as general-purpose PID control. Sugeno fuzzy control systems are computationally efficient. Sugeno fuzzy control systems guarantee continuity of the output variables surface. Sugeno fuzzy control systems work well with most optimization and adaptive control techniques. And Sugeno fuzzy control systems well-suite to usual mathematical analysis.

Given the enhanced computational efficiency, Sugeno Fuzzy Logic Control Systems are better suited for this research. Fuzzy Logic Control Toolbox in MATLAB 2018a has been used to implement this control system.

9.1.2 Advantages of the Mamdani Systems

Mamdani fuzzy control systems are intuitive to human mind. Mamdani fuzzy control systems have widespread acceptance. Mamdani fuzzy control systems are well-suite to human input.

10

System under consideration

10 System under consideration

A hybrid grid is simulated in MATLAB 2018a with following source and loads.

Power Sources	Loads
• 250kW PV array connect to a 3-phase grid connect PV inverter • 40MVA AC Generator	• 250kW heating load • 2MW resistive load • 30MW/2MVAR reactive load

Table 1Power Sources and Loads

As a hybrid grid consists of different type of power sources and loads that's why a 250kW solar system is used alongside a 40MVA AC generator to form a hybrid grid. This grid consists of various loads including 2MW resistive load, 30MW/2MVAR reactive load and 2MW resistive load.

Reason for choosing various loads instead of a single load is to model an actual grid condition in a better way. The reactive power demand of 30MW load can be varied from 0.5MVAR to 3MVAR. In this research the reactive power demand is varied and effects on Total Harmonic Distortion in grid current are observed.

Figure 10-1 shows the complete hybrid grid that is simulated in MATLAB 2018a.

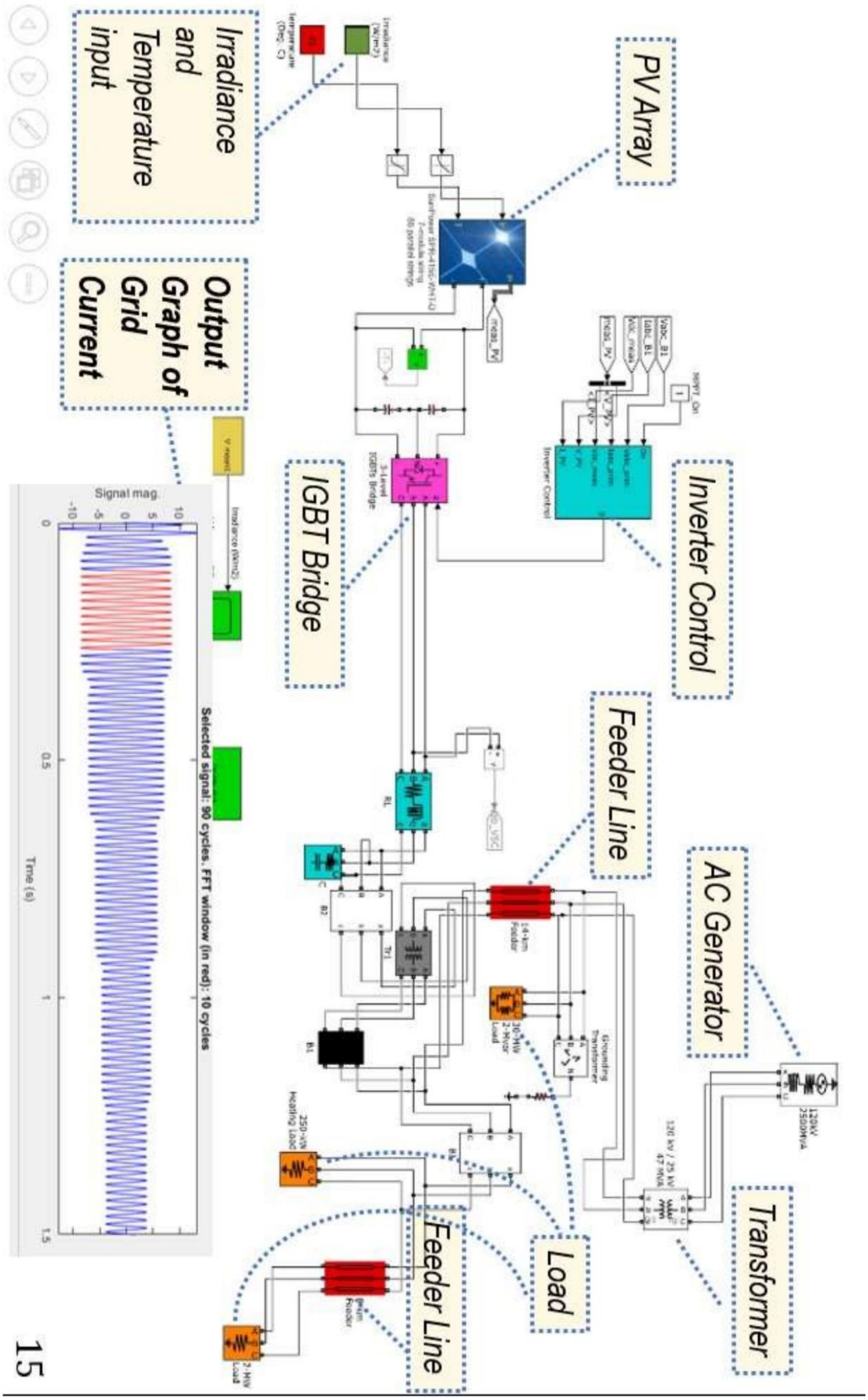

Figure 10-1 Complete Hybrid Grid

10.1 PV Array Parameters

Following are parameters for the PV array that was simulated in

MATLAB.

Module	SunPower SPR-415E-WHT-D
Power at STC (W)	415
Vmp: Voltage at Max Power (V)	72.9
Imp: Current at Max Power (A)	5.69
Voc: Open Circuit Voltage (V)	85.3
Isc: Short Circuit Current (A)	6.09
Nominal Operating Cell Temp (°C)	45.8
Open Circuit Voltage Temp Coefficient (%/°C)	-0.229
Short Circuit Current Temp Coefficient (%/°C)	0.031
Max Power Temp Coefficient (%/°C)	-0.353
No. of module in a string	7
No. of parallel strings	88
Total Array Power (kW)	255.64

Table 2 PV Array Parameters

Array structure is as follows:

- 7 panels in series in each string
- 88 strings in parallel

A total number of 616 panels are used. Total array power is more than 250kW. This is to incorporate the power loss due to environmental conditions, e.g. temperature, clouds, dust, lower solar irradiance at dawn and dusk etc.

11

Simulation

11 Simulation

11.1 With Unity Power Factor Control Technique

Following simulation steps is performed, first, with reactive current reference set to zero (the most common technique used in inverters):

- Irradiance is vary from 1000W/m2 to 200W/ m2 in 5 intervals of 0.3s each
- Total Harmonic Distortion (THD) in Grid Current is measured.
- After this the inverter is operate at 50 percent underload condition.
- Total Harmonic Distortion (THD) in Grid Current is again measured.

11.2 With Fuzzy Logic Control Technique

Above steps is repeat with Sugeno Fuzzy Logic Controller.

- A Sugeno Fuzzy controller is simulated. This controller is a part of the current controller in the Grid-tie PV Inverter.
- The fuzzy controller take measurement of the reactive current in the grid.
- It then generate a reference for reactive current using Fuzzy Logic Rules.
- The generate reference is given to the current regulator.
- The current regulator generate output current according to the

reference.

11.3 Inverter Simulated in MATLAB

The main components of the inverter are:

1. 3-level IGBT Bridge
2. Inverter Control Block
3. Filter Circuit

Figure 11-1 shows the inverter that has been simulated in MATLAB 2018a.

11.3.1 3-level IGBT bridge

This block inverts the DC into AC according to the control signals from Inverter Control Block.

11.3.2 Inverter Control Block

This block acts as the brain of the inverter. It measures parameters and generate control signals for the IGBT switches in the bridge circuit. This block is the main focus of this research. This block actually sets how much current should be generated. And since the inverter allows us to independently control active and reactive components of current being produced, it gives us freedom to introduce reactive component of current to grid to reduce Total Harmonic Distortions in grid current.

Figure 11-2 shows the Inverter Control Block that has been simulated in MATLAB 2018a.

11.3.3 Filter Circuit

This block filters out the switching ripples in inverter output voltage. RLC filter has been used in this block.

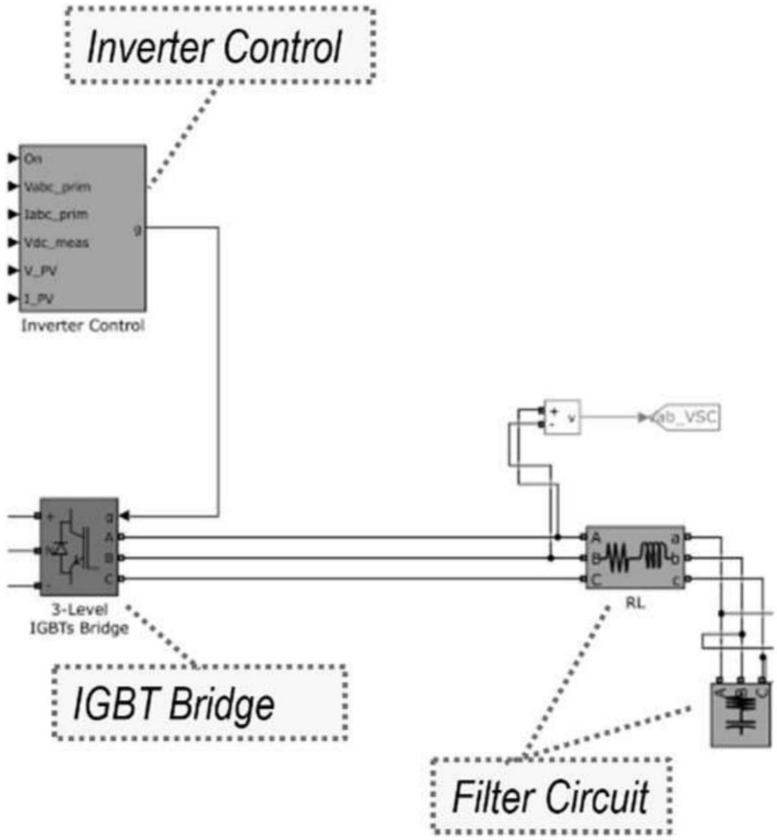

Figure 11-1 Inverter Simulated

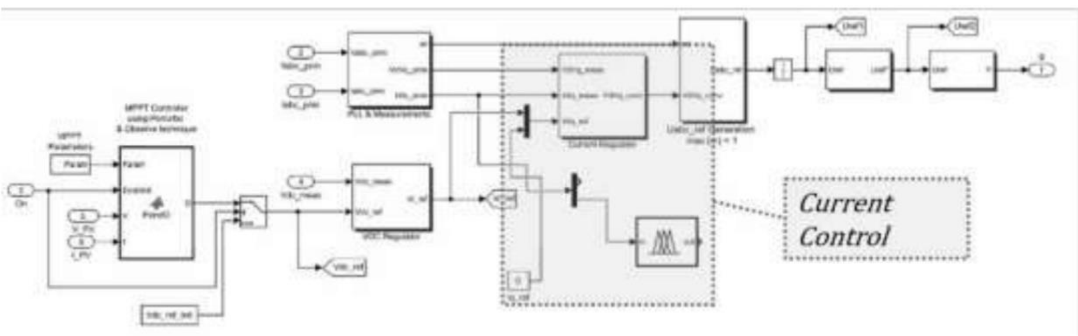

Figure 11-2 Inverter Control Block

11.4 Flow Charts

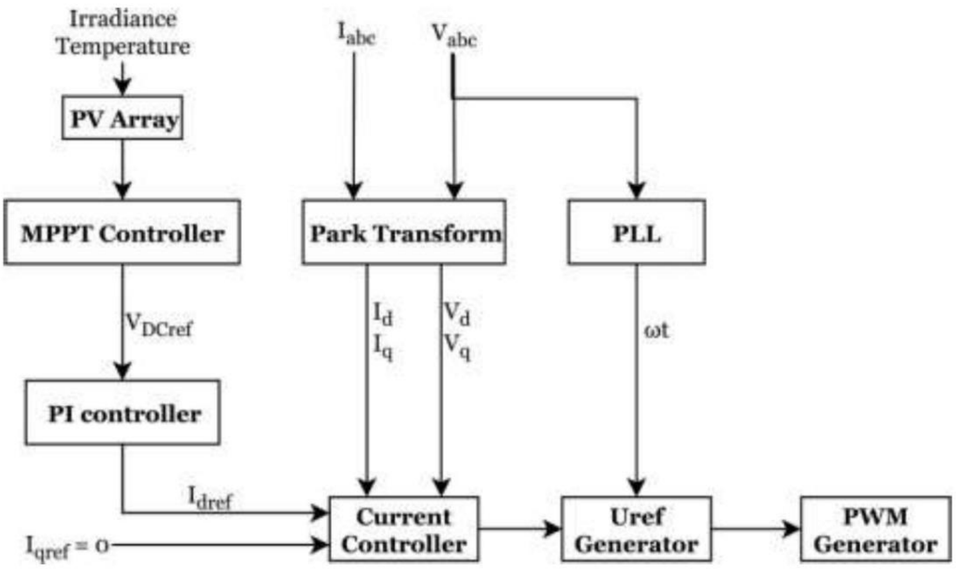

Figure 11-3 Flow Chart for Unity PF technique

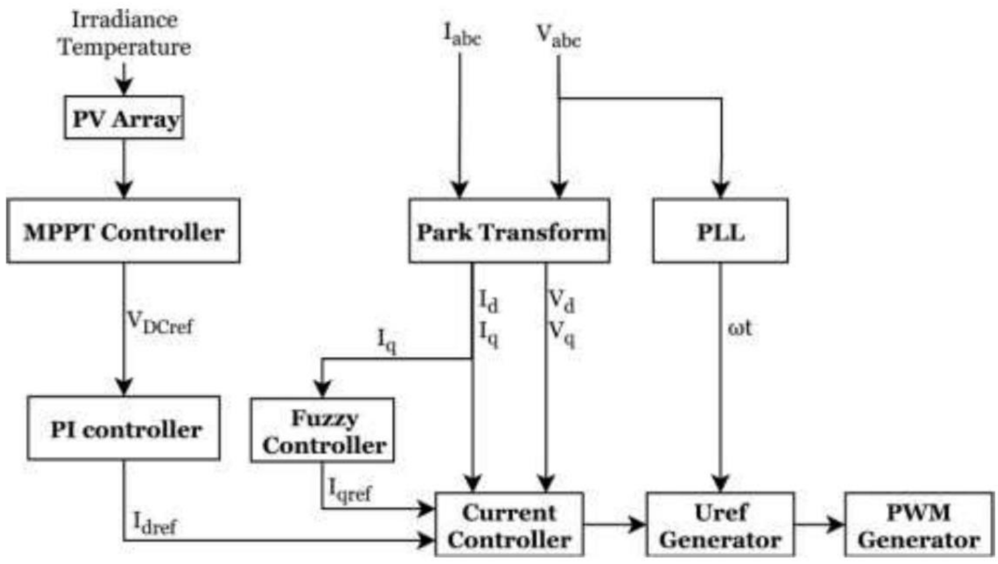

Figure 11-4 Flow Chart for Sugeno Fuzzy Control technique

11.5 Mathematical Modeling for common components

11.5.1 Mathematical Model – Idref

- MPPT takes voltage and current variables from PV array and generate Vdcref.
- Voltage regulator compare it to Vdcmeas.
- $\frac{Vdcmeas\text{-}Vdcref}{Vdcnom}$ is given to the PI controller in Voltage regulator.
- It generate the active current reference. Idref.
- Here, for the PI controller Kp=2 and Ki=400 for the PI controller.

Figure 11-5 shows the mathematical model implementation of Idref generation in MATLAB 2018a.

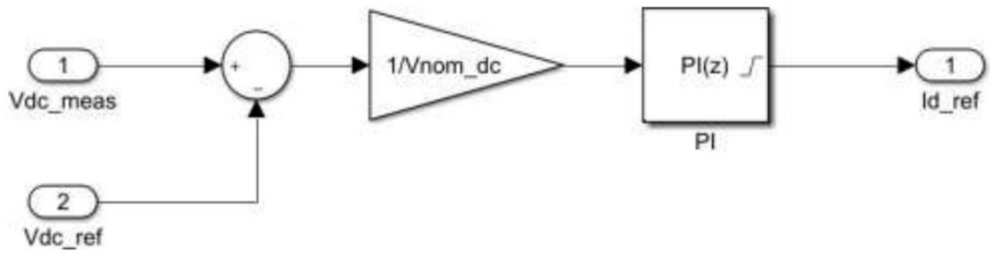

Figure 11-5 Idref Generator

11.5.2 Phase Lock Loop – PLL

Voltage ($Vabcprim$) of three phase at Primary windings of transformer is measured.

$$\frac{Vabcprim}{Vnom\_prim\sqrt{\frac{2}{3}}}$$

$Vabcprim$ is given to a PLL module to extract the frequency ωt.

Figure 11-6 shows the implementation of Phase Lock Loop in MATLAB 2018a.

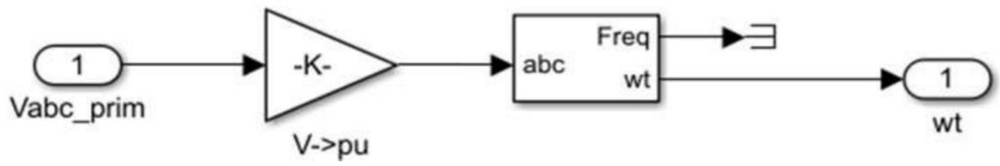

Figure 11-6 Phase Lock Loop

11.5.3 Park Transform

Voltage ($Vabcprim$) and Current (I$abcprim$) of three phase at Primary windings of transformer is measured.

$\frac{Vabcprim}{Vnom\_prim\sqrt{\frac{2}{3}}}$ .... (i) $\frac{IabcprimVnom\_prim}{Pnom\sqrt{\frac{2}{3}}}$ .... (ii)

A Park Transformation is perform on (i) at ωt to generate Vdprim and Vqprim.

A Park Transformation is perform on (ii) to generate Idprim and Iqprim.

Figure 11-7 shows the implementation of Park Transformation in MATLAB 2018a. Two separate Park Transformation blocks are used; one each for voltage and current.

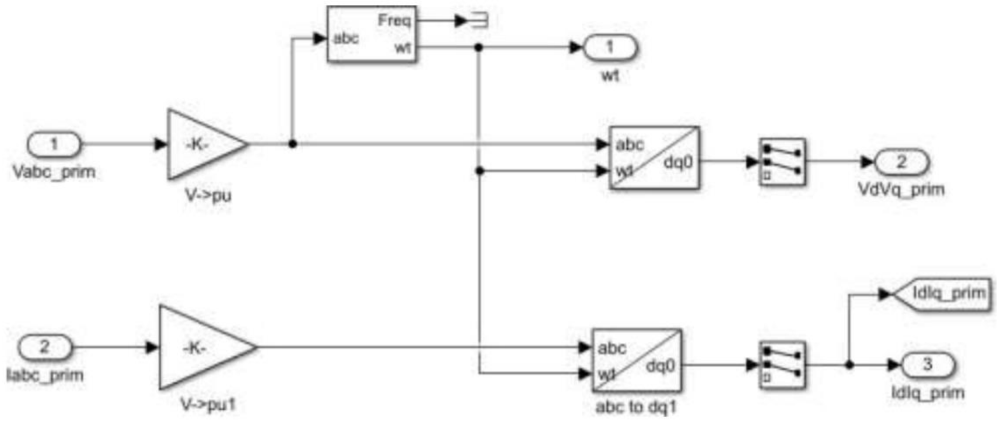

Figure 11-7 Park Transformation

11.5.4 Production of Uref

$$Vdconv = Vdmeas + [(Idref - Idmeas) \times (Kpconv + \frac{KiconvTs}{z-1})] + Idref(Rff-Lff)$$

$$Vqconv = Vqmeas + [(Iqref - Iqmeas) \times (Kpconv + \frac{KiconvTs}{z-1})] + Iqref(Rff+Lff)$$

$$\vec{U} = \frac{2\sqrt{2}Vnomsec}{\sqrt{3}Vnomdc} \times (Vdconv + jVqconv)$$

$$\vec{U} \longrightarrow |U| \angle \theta U$$

$$Uref = |U| \sin(\omega t + \theta U - \frac{\pi}{6})$$

This Uref is given to PWM generator module. The PWM generator module generate pulse signals for H-bridge module.

Figure 11-8 shows the mathematical model implementation of Uref generation in MATLAB 2018a.

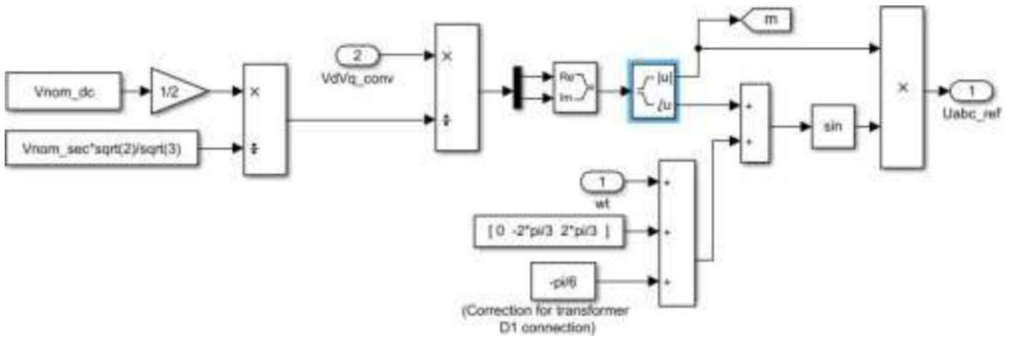

Figure 11-8 Production of Uref

11.6 Unity PF Control

in Unity PF inverter controllers the reactive current reference is set to zero (shown in the figure 11-9 in wide border box).

It simplify the inverter control and reduce the expenditure of circuit.

Setting the reactive current reference to zero means that the inverter shall not cater for any reactive power demands.

The graph shows the grid current output of inverter in this control setting.

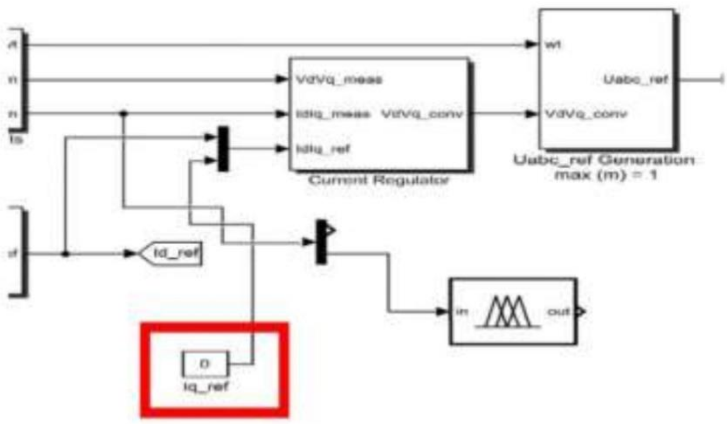

Figure 11-9 Unity PF Control Block

Figure 11-10 shows the simulation result of output grid current produced using Unity PF technique in MATLAB 2018a. The current is produced at solar irradiation of 200W/m^2. The current has 7.21% Total Harmonic Distortion. Current waveform is jittery.

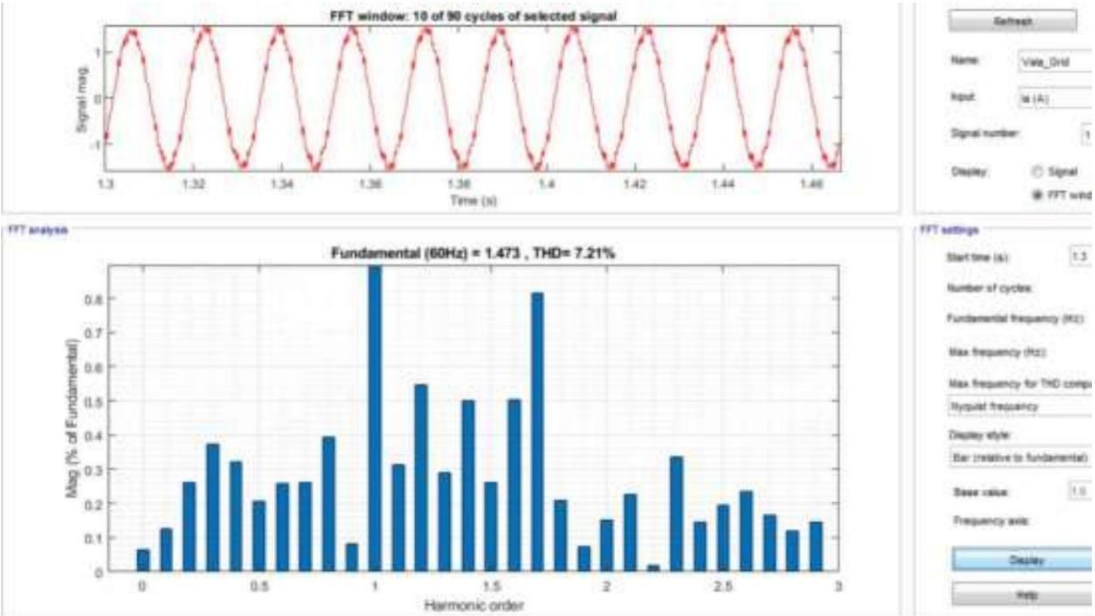

Figure 11-10 Unity PF output waveform

Figure 11-11 shows the expanded view of the simulation result of output grid current produced using Unity PF technique in MATLAB 2018a. The current is produced at solar irradiations of 1000W/m^2, 800W/m^2, 600W/m^2, 400W/m^2 and 200W/m^2. The waveforms and Total Harmonic Distortion values for each irradiation are shown in the circles in the magnified view.

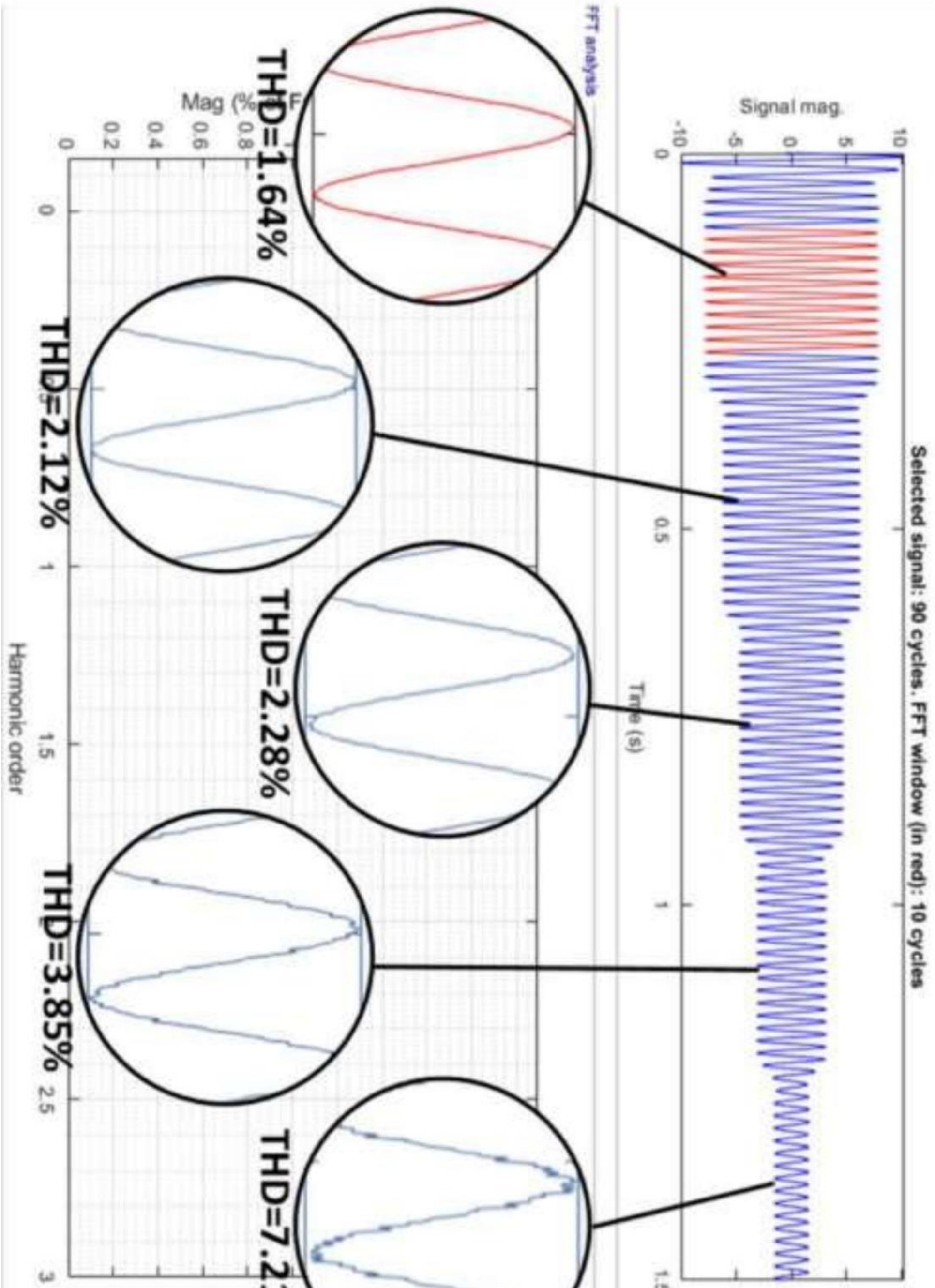

Figure 11-11 Unity PF output waveform – zoomed

11.7 Sugeno Fuzzy Logic Control

Sugeno Fuzzy logic controller has been use to generate reactive current reference (shown in figure 11-12 with the wide border box in figure).

The algorithm continuously adjusts the current reference according to the varying conditions.

The graph shows the grid current output of inverter in this control setting.

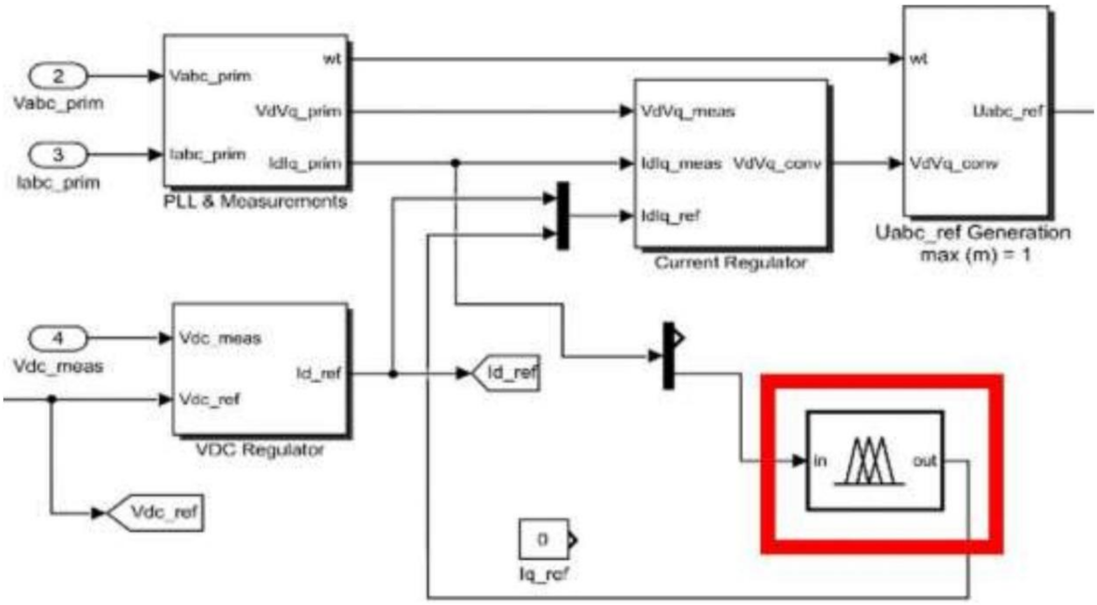

Figure 11-12 Sugeno fuzzy logic control block

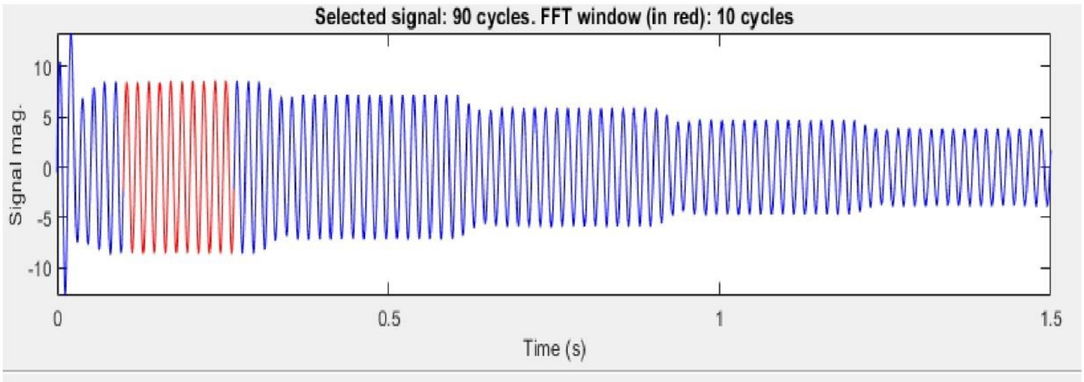

Figure 11-13 Sugeno fuzzy logic control output waveform

11.8 Membership Functions

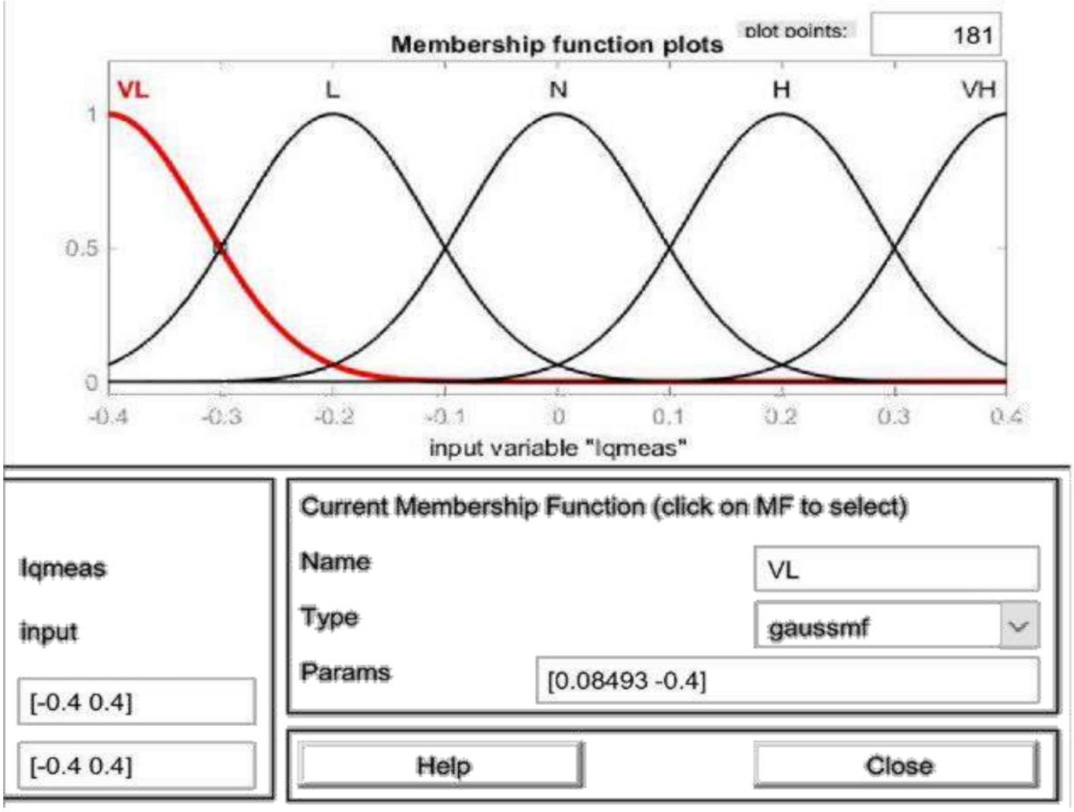

Figure 11-14 Membership functions

Gaussian membership functions have been used. Five membership functions are used for one variable. All membership functions are equidistant.

Membership Pnemonic	Description
VL	Very Low
L	Low
N	Normal
H	High
VH	Very High

Table 3 Fuzzy Pnemonics

Iq-Iqref	VL	L	N	H	VH
Iq					
VL	VL	VL	L	N	H
L	VL	L	L	N	H
N	VL	L	N	H	VH
H	L	L	N	H	VH
VH	L	N	H	VH	VH

Table 4 Membership Control Rule Table

Figure 11-15 shows the simulation result of output grid current produced using Sugeno Fuzzy Logic Control technique in MATLAB 2018a. The current is produced at solar irradiation of 200W/m^2. The current has 2.69% Total Harmonic Distortion. Waveform of current is much smoother as compared to that in Unity PF technique.

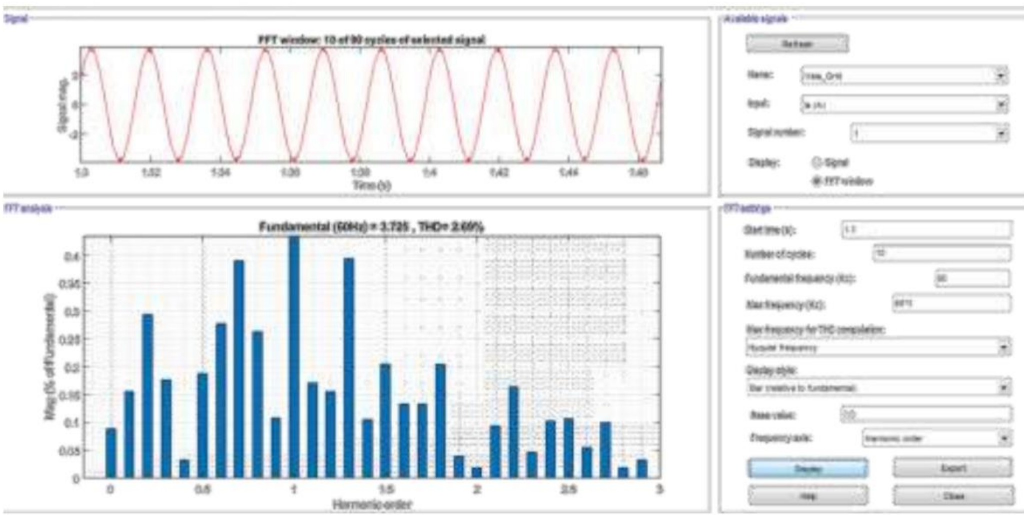

Figure 11-15 Fuzzy Control Output Waveform

Figure 11-16 shows the expanded view of the simulation result of output grid current produced using Sugeno Fuzzy Logic Control technique in MATLAB 2018a. The current is produced at solar irradiations of 1000W/m^2, 800W/m^2, 600W/m^2, 400W/m^2 and 200W/m^2. The waveforms and Total Harmonic Distortion values for each irradiation are shown in the circles in the magnified view. Inverter with the Sugeno Fuzzy Logic controller is performing better at all values of solar irradiation. But the difference is more apparent at lower values of solar irradiation. At 200W/m^2 the difference of THD is 7.21% – 2.69% =4.52%.

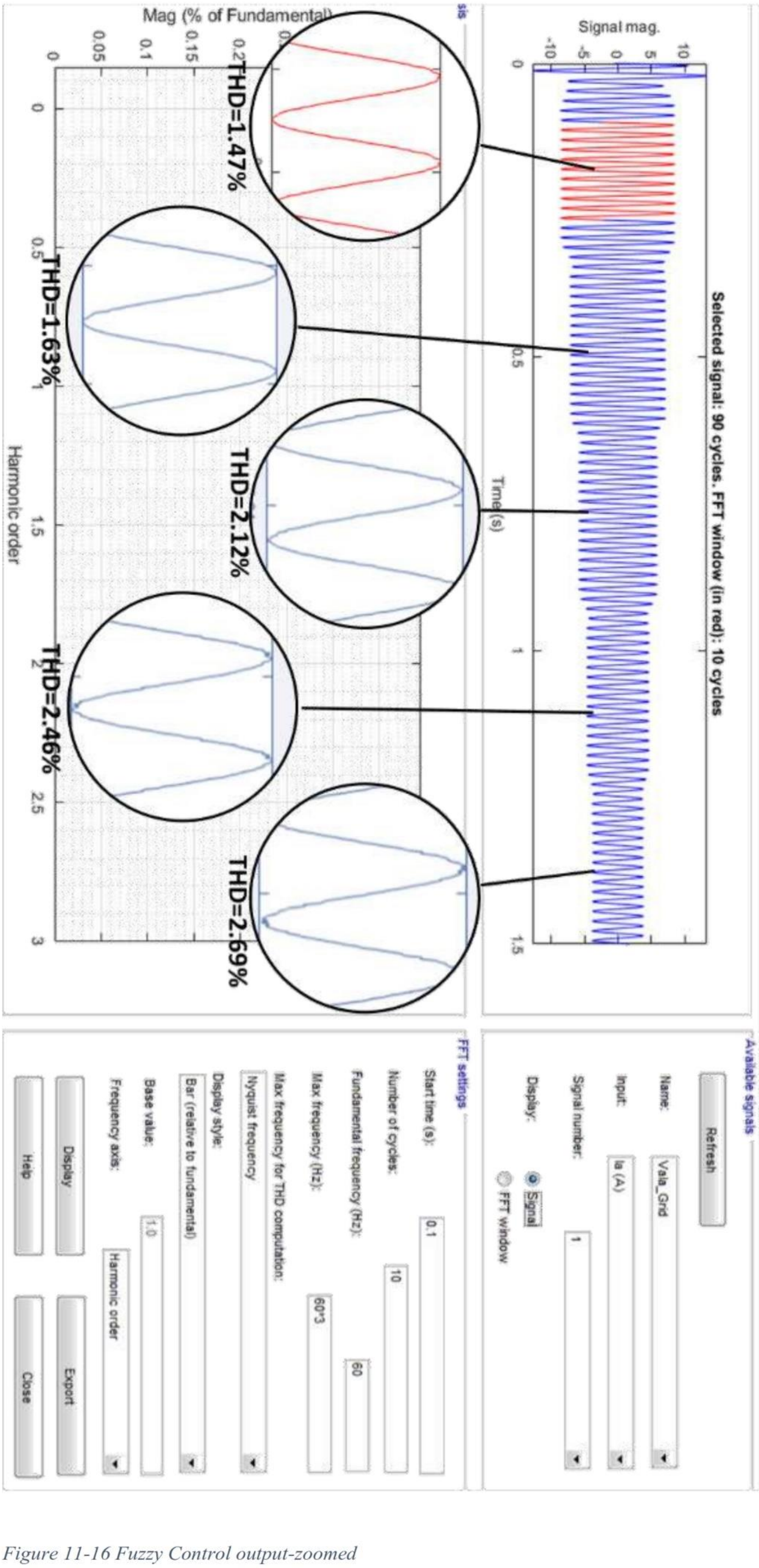

Figure 11-16 Fuzzy Control output-zoomed

12

Simulation Results

12 Simulation Results

This section discusses the simulation results. Figure12-1 shows the variation in grid current with variation in solar insolation for both techniques. The solid line shows the graph for the fuzzy logic controller inverter. And the dashed line shows the graph for the Unity PF inverter. Inverter with the proposed technique is performing better at all values of solar irradiation. But the difference is more apparent at lower values of solar irradiation. At 200W/m^2 the difference of current is 3.86 – 1.5 = 2.36A. Higher amount of current is being produced from lower solar irradiation. The reactive power demand has been fixed at 3 MVAR.

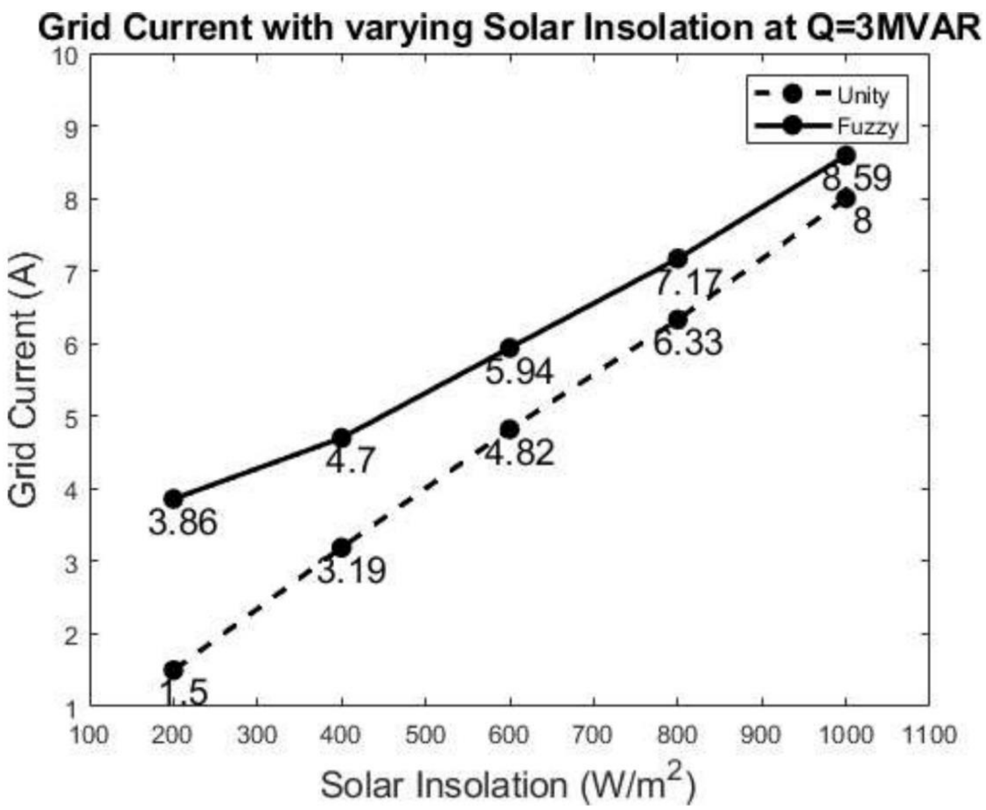

Figure 12-1 Grid current and solar insolation

Figure12-2 shows the variation in the Total Harmonic Distortion in the grid current with variation in solar insolation for both techniques. The solid line shows the graph for the fuzzy logic controller inverter. And the dashed line shows the graph for the Unity PF inverter. Inverter with the proposed technique is performing better at all values of solar irradiation. But the difference is more apparent at lower values of solar irradiation. At 200W/m^2 the difference of THD is 7.21% – 2.69% = 4.52%. Standard deviation is also calculated for both curves. The lower values of standard deviation mean a more uniform performance throughout the range of solar irradiation. The reactive power demand has been fixed at 3 MVAR.

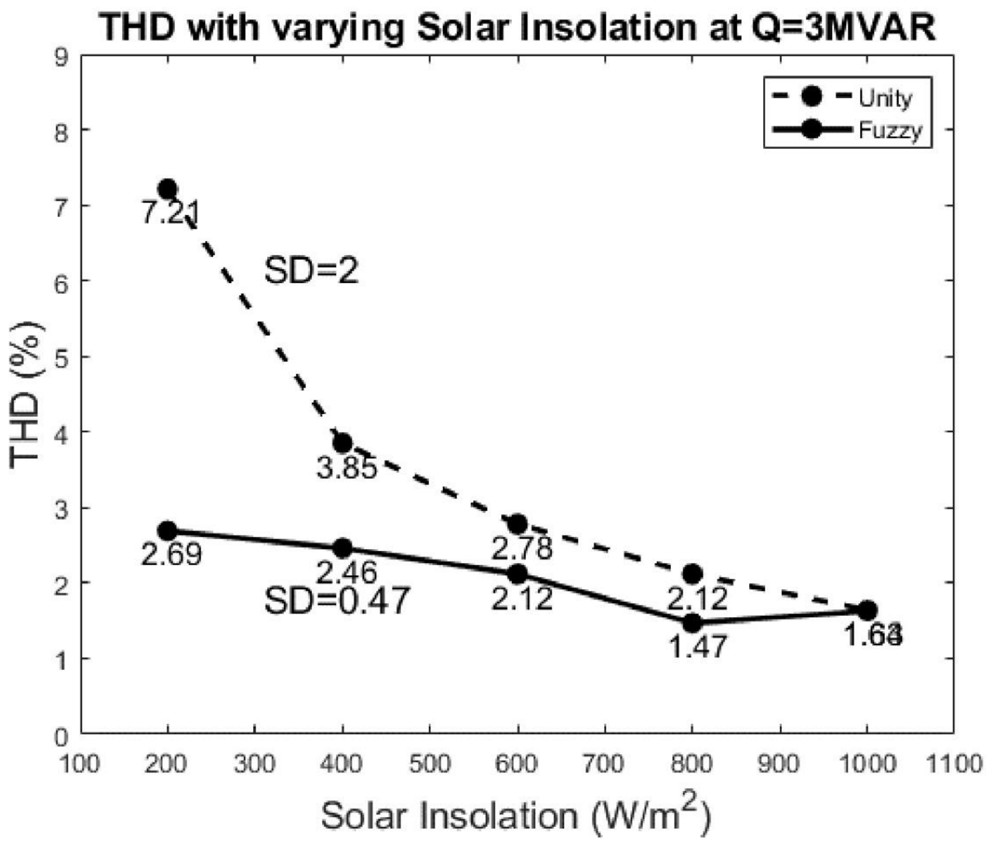

Figure 12-2 THD and insolation

Figure12-3 shows the variation in the Total Harmonic Distortion in the grid current with variation in reactive power demand. The solid line shows the graph for the fuzzy logic controller inverter. And the dashed line shows the graph for the Unity PF inverter. Inverter with the proposed technique is performing better at all values of reactive power demand. But the difference is more apparent at higher values of reactive power demand. At 3MVAR the difference of THD is 3.85% – 2.46% = 1.39%. Standard deviation is also calculated for both curves. The lower values of standard deviation mean a more uniform performance throughout the range of reactive power demand. Solar irradiation is fixed at 400W/m^2.

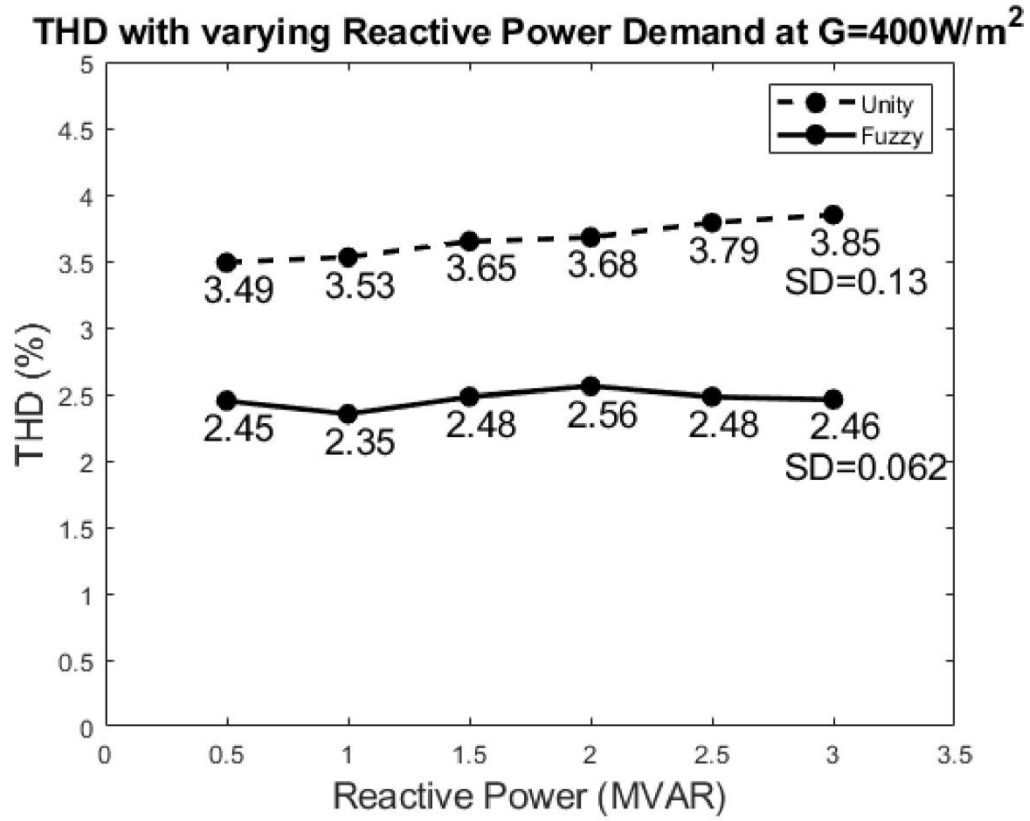

Figure 12-3 THD and reactive power

Figure12-4 shows the variation in the Total Harmonic Distortion in the grid current with variation in solar insolation for both techniques at 50% underload conditions. The solid line shows the graph for the fuzzy logic controller inverter. And the dashed line shows the graph for the Unity PF inverter. Inverter with the proposed technique is performing better at all values of solar irradiation. Standard deviation is also calculated for both curves. The lower values of standard deviation mean a more uniform performance throughout the range of solar irradiation.

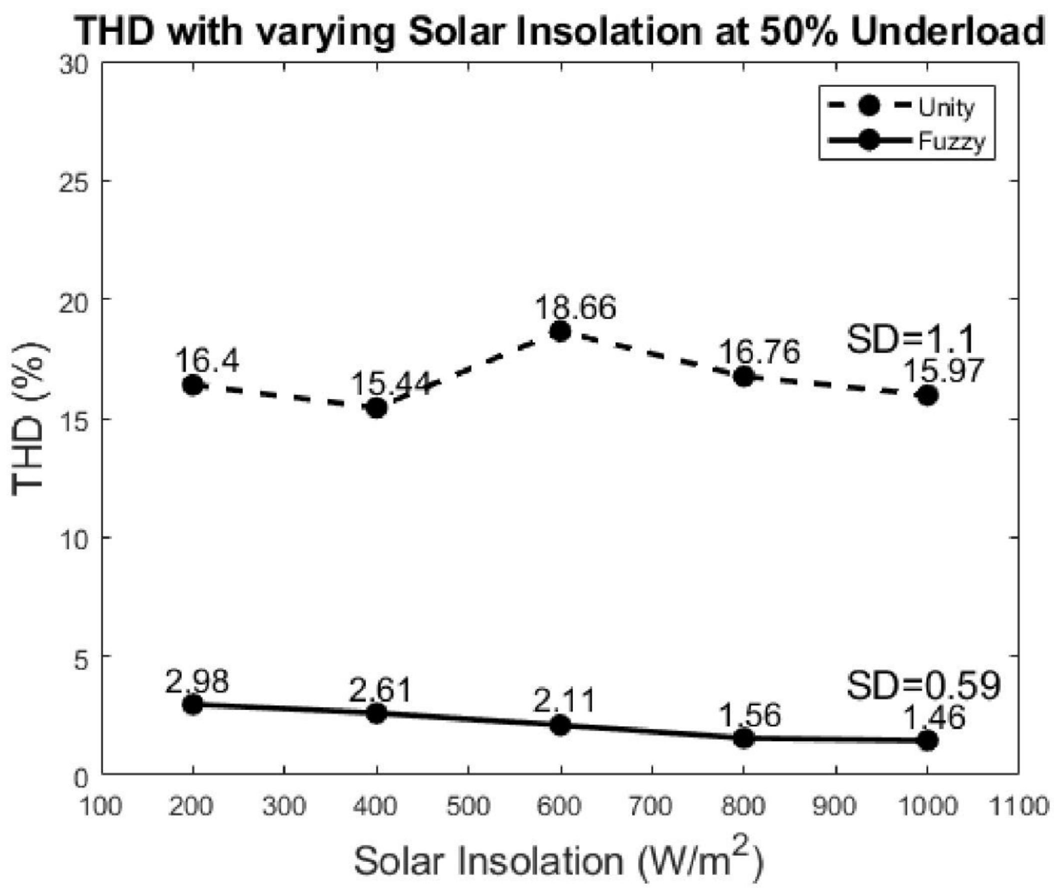

Figure 12-4 Underload conditions

13

Results Summary

13 Results Summary

Table 5 shows the summary of thesis results. The proposed technique is promisingand provides improved performance with lower THD at low irradiation and underload conditions. All values of THD of the proposed technique are well within the IEEE standard recommended limit of 5%. The table also shows comparison of thesis with a latest paper on THD reduction.

Conditions	**Unity**	**(Hossein,2019)**	**Fuzzy**	**Improvement**
THD@ 200W/m2, 3MVAR	7.21%		2.69%	4.52%
THD at underload conditions	15.44%		2.61%	12.83%
THD (@ 400 W/m2		5%	2.46%	2.54%
Research Parameters				
THD at varying Insolation		2 Levels	5 Levels	
THD with varying reactive load		NO	YES	
THD at underload conditions		NO	YES	

Table 5 Results Summary

Future recommendations:

In future this research can extended to simultaneous variation of parameters and hardware implementation.

14

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14 References

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