JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING

GRADUTE PROGRAM IN ELECTRICAL POWER ENGINEERING

Design of Grid Connected Rooftop Solar PV System

(Case Study: Dire Dawa Industry Zone)

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A thesis submitted to faculty of electrical and computer engineering, Jimma institute of technology in partial fulfillment of the requirements for the degree of masters of Science in electrical power system engineering

Advisor:- Dr.Kinde Anley (PhD)

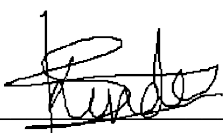Co-advisor:- Mr.Mengistu Fentaw (M.Sc.)

Jimma, Ethiopia

February 2021

Declaration

I, the undersigned, declare that this thesis entitled " DESIGN OF GRID CONNECTED ROOFTOP SOLAR PV SYSTEM (CASE STUDY: DIRE DAWA INDUSTRY ZONE " is my original work under Jimma Institute of Technology, Faculty of Electrical and Computer Engineering, Graduate program of power system engineering and has not been submitted by any other person for an award of a degree in this or any other University, and that all resources of materials used for this thesis have been acknowledged and a list of references is given.

Reta Degefa _____ _____16/02/2021_____

This thesis has been submitted for examination with my approval as university advisor.

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i

Acknowledgment

First of all, I would like to thank the Almighty God for his love shown on the cross to save me. I Am thankful for his provision of Grace to complete the thesis work. Secondly,I wish to express my deepest gratitude to my advisor, Dr. Kinde Anley for his guidance and support in shaping the outlook of this thesis. He provided invaluable insights that have guided my thinking and understanding. I would like to extend my appreciation to my co-advice Mr. Mengistu F. for his encouragement, advice, feedback and helpful comment on my research work for editing this thesis work. Next to that, I would like to thank Dire Dawa Sebian substation SCADA team for their kind and help in providing necessary data and I am also thank the managers of each factories in Dire Dawa industry zone for their special help in my data collecting. I am grateful to the Faculty of Electrical Engineering at the Jimma Institute of Technology for providing me the excellent work environment during my study. Let my acknowledgment extend to my classmates, friends, instructors and colleagues in and outside the university. I would like to appreciate all for their friendship and support during my stay at Jimma University. I would like extend by thanks those who encouraged me and showed me great affection throughout this thesis work, my sincere thank is here, Thank you all. Finally, I would like to thank My wife Roman Girma for her love, encouragement, pray and help to finish this thesis and want to say may God bless our newborn baby (Rabbirra) by all health and wisdom abundantly.

Reta Degefa

Contents

List of Tables

List of Figures

Nomenclature

CO_2 Carbon-dioxide

AC   Alternative Current

BSc   bachelor's degree in science

CCM   continuous Common mode

CSI   Current Source Inverter

EEU   Ethiopian Electric Utility

F   frequency

KVA   Kilo Volt Ampere

KWh   Kilowatt hour

LCOE   levelized cost of energy

MoWIE   Minister of Water, Irrigation and Electricity

MPP   Maximum Power Point

MPPT   Maximum Power Point Traking

MSc   Master's degree in science

PR   Performance Ratio

SCADA   Supervisory Contol and Data Acquisition

THD   Total Harmonic Distortion

V   Voltage

Abstract

Dire Dawa is one of the industry center in Ethiopia. Due to expansion of industry in Dire Dawa and around the city electric demand is increasing. Distribution Generation have advantage over central generation by minimizing transmission line loss. Solar photo-voltaic(PV) system is becoming a promising energy sources because of its advantages. But the solar installation need large area to install the panel and other components which, is not available near load center because of its cost. When looking for land far from the load center it costs transmission line and line losses which is unwanted. Dire Dawa industry zone have many industries in it. Each factories have big buildings with large roof area which can used to install solar PV system. The other problem is when grid is connected with solar PV system it should be in the standard. The purpose of this research is to design a grid connected roof top solar PV system for Dire Dawa industry zone. To address the objective, data gathering were done in Dire Dawa industry zone and by using the collected data the grid connected solar PV system were designed in PVsyst software. Secondly, the research was focused on designing the component of grid connected rooftop PV system, such as solar PV, DC-DC converter, NPC inverter, filter and their controllers. Finally, the signal analysis were done by Matlab/Simulink. In addition to that, the rooftop mounted and ground mounted PV system were compared by the investment cost and transmission line cost.

The result shows, the performance ratio is 84.2% and the total investment cost for Dire Dawa industry zone is 320 million ETB to generate 8545 KW peak power generated on the rooftop of the site by the levelized cost of energy(LCOE) it become $0.99\frac{ETB}{KWh}$ for this design. The simulation result of Matlab/Simulink also shows that the inverter output active power follows the trend of PV DC power, which depend on the value of solar irradiance and temperature values. When it come to the reactive power it is not dependent on irradiance and temperature value, so the value of inverter reactive power can control at any desired value and at any time of day or night. The harmonic analysis also done and the quality of the grid is not disturbed. When there were a power interruption, the stand-alone solar PV system take the load and supply it. The comparative study shows rooftop solar PV system have more advantage than ground mounted solar PV system by transmission line loss and installation cost reduction in case of Dire Dawa industry zone.

Chapter 1

Introduction

1.1 Background

There are electrical energy losses from production centers to consumption places. About 5%
of the energy produced in power plants with an efficiency of $30\% - 40\%$ is wasted. In addition, in the transmission system between 4% and 5% of electrical energy is wasted and at
the end of the distribution network about $10\% - 15\%$ is wasted. The production of electrical
energy consumption was elevated near the consumption place [1]. Integrating PV system into
national grids can reduce transmission and distribution line losses, increase grid resilience,
lower generation costs, and reduce requirements to invest in new utility generation capacity
[2]. Over recent years, the production and installation of PV power plants have seen a huge
increase all over the world. The level of penetration continues to grow, with approximately
100 GW of generated power has been added by 2019 only, which makes PV systems contribute to about 55% of the newly added renewable energy capacity across the globe. This
high growth of PV power plants generation and integration is anticipated to be maintained
in the future [3]. Since Ethiopia is located near the Equator, the solar resource potential is
significant. The yearly mean average daily radiation reaching the ground is $5.2\frac{kWh}{m^2 day}$. But up
to this year there was a little solar power where harvested in Ethiopia. In the other way, the
National Electrification Plan has a target of achieving a universal electricity access(100%)
rate by 2025, and to achieve this from the current electrification rate, in addition to expanding on-grid electricity access, the Minster of Water, Irrigation and Electricity MoWIE and
Ethiopian Electric Utility (EEU) have decided to pursue the deployment of solar PV mini-
grids with energy storage system (ESS) and diesel generator backup for villages that are far
away from substations [4]. To achieve this plan it need to focus on the distribution generation
around the load center like, Dire Dawa industry zone, to minimize the transmission line loss
for on grid also.

1.2   Problem Statement

The energy demand in Dire Dawa are increasing from time to time, because of the new factory installed in the city and also in Dire Dawa industry zone. In the future the shortage of energy will be going to happen because, still other big factories are plan to be installed in the future. So there is a need of additional power which can support the grid in the future. When electrical load increase, the transmission and distribution losses also increase otherwise, it need additional transmission line to supply the demand with high cost. To minimize the loss of transmission line the generation station should near to the load center. Dire Dawa industry zone have many industries in it and still other factories are being installed in the industry zone. The building in industry zone have large roofs which, make them suitable for solar system installation. Solar energy is the promising energy source in now time, because of the cost of PV panel is decreasing and the other case it is a clean energy source. But such power renewable energy source need large area to install the PV panel and other accessories. When one looks for the land in urban area its cost is expensive, when one go far to find the cheapest land he/she should deforest the large area for the setup, the land which is used for farming or cattle, in addition to transmission loss which is another problem again. Even if we get the land, installing solar power on the ground between the buildings the efficiency of the PV were affected by shading loss. But in urban, their is an available area on the roof of each buildings. Specially Industries in Dire Dawa industry zone have big buildings with large roof areas. Secondly connecting the solar PV system should be synchronized with grid, otherwise the grid quality will affected so, the grid connected rooftop solar PV should control properly. The purpose of this research is to design a grid connected rooftop solar PV system for Dire Dawa Industry Zone.

1.3   Objective

1.3.1   General Objective

The objective of this research work is to Design a grid connected rooftop solar PV system for Dire Dawa Industry Zone.

1.3.2   Specific Objective

1. To make assessment on the roof area of Dire Dawa industry Zone.

2. To design the grid connected rooftop solar PV system by PVsyst Simulator for the available rooftop area and Identify the power it could generate for the site.

3. To model the grid connected solar PV system and control the reactive power at the desired value.

4. Make comparison between rooftop mounted and ground mounted solar PV system

1.4 Significance of the Research

- It can minimize the power interruption problem in Dire Dawa Industry Zone and use as back up when the grid power is interrupted.

- It will improve the power factor for the Dire Dawa Industry Zone.

- It's known that solar energy is the clean energy. So, in case of decreasing of deforestation and minimization of the emission of greenhouse gas it can contribute a significant benefit for Ethiopia and the world.

- This research will have benefit for Ethiopia to increase the usage of solar power and to collect the full potential of solar energy that can supply the Reactive Power to the grid.

1.5 Scope of the Study

- In the design a weight of PV panel on the roof of the building is not considered.

- The simulation will be done by using PVsyst 7.1 and MATLAB/Simulink Software

1.6 Methodology

To address the listed objective of this research the first work is to collect the necessary data from the selected site and the utility (in our case the Sabian substation and SCADA control). After collecting and analyzing the necessary data, the next work will be identify the site temperature and Irradiance and then, by using the Area of rooftop of each factory design the grid connected rooftop solar PV system for Dire Dawa Industry Zone will be proposed. Nextly, each grid connected solar PV system components, i.e. solar PV, DC-DC converter, inverter, filter and the grid was designed by the use of Matlab/Simulink software. Under this section the power controller is designed. Finally the signal analysis for the inverter output voltage and current will be done. The total methodology of the research is shown in the figure 1.1.
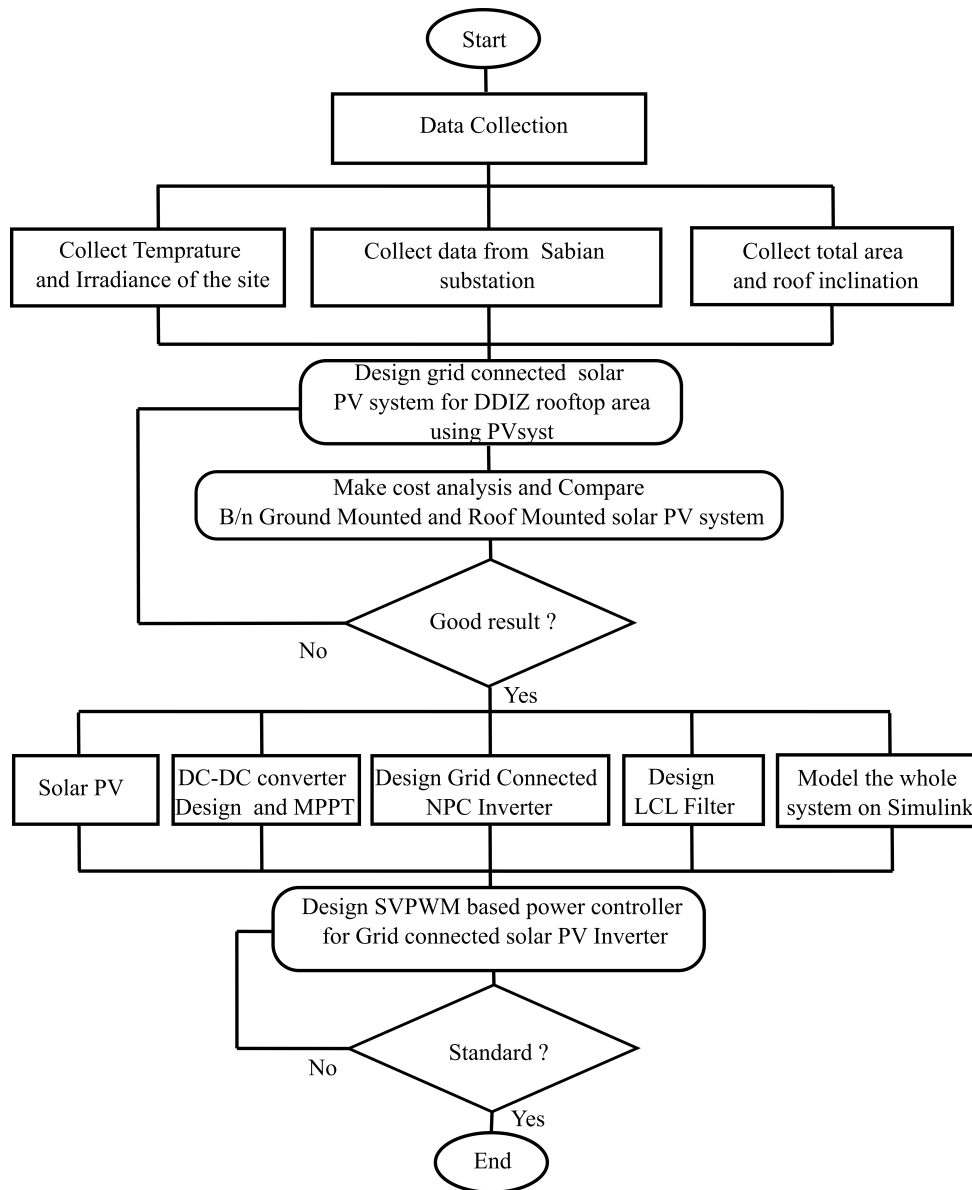
FIGURE 1.1: Research methodology

1.7   Organization of the Thesis

The thesis is organized into six chapters which are briefly summarized as, Chapter Two:- Deal with the solar usage of our country, The component of grid connected PV system and review of literature on the PV system modeling and design. Chapter Three:- Assessment of rooftop PV in Dire Dawa Industry Zone, the analysis of survey data with discussion and PVsyst software base design. Chapter Four:- Present Mathematical modeling of 3 level grid connected NPC Inverter and three level space vector PWM, Design the power controller and LCL filter and finally simulate the whole system by Matlab/Simulink. Chapter Five and Chapter Six:- dealing with Result and Discussion, finally about conclusion and Recommendation

Chapter 2

Theoretical Background and Literature Reviews

2.1   Ethiopia and Solar Energy

Ethiopia has made significant progress towards increasing electrical access over the last three decades. The 44.98% of Ethiopian population have access to electric power in 2020 [5]. This progress is coming by big effort. For instant, since 1996 to 2010 as observed on the following table 2.1, the electric progress and demand of the electricity is high [6]. After such significant

TABLE 2.1: Progress of Ethiopia towards electricity access [6]

S.No	Quantity	Percentage
1	Installed Power Capacity has increased	15%
2	Electrical grid network length has increased	16%
3	the number of electricity customers has increased	12%

achievement, Ethiopia's electrification rate still stands at less than 45 % in 2020 [5]. Due to the dependence on biomass for cooking, CO_2 emissions in Ethiopia have increased from 5.1 million tons in 2005 to 6.5 million tons in 2010. Ethiopia is endowed with various renewable energy resources. Ethiopia receives an average solar radiation which is more or less uniform and it may vary seasonally, from $4.55 - 5.55 \frac{KWh}{m^2}$ per day and with a location from $4.25 \frac{kWh}{m^2 day}$ in the extreme western lowlands to $6.25 \frac{KWh}{m^2 day}$ in Adigrat area [6].   As much solar energy the country is endowed with, only 450 kW of photo-voltaic panels are installed as of 2004 with half of it being for telecommunication purposes. The Ethiopian government has recently developed some programs that aim at the potential use of solar cells for different purposes [6].   The National Electrification Plan has a target of achieving a universal electricity access rate by 2025. To achieve 100 percent electrification rate from the current electrification rate of less than 45%, in addition to expanding on-grid electricity access, the MoWIE and Ethiopian Electric Utility (EEU) have decided to pursue the deployment of solar photovoltaic mini-grids with Energy Storage System (ESS) and diesel generator backup for villages that are far away from substations [4]. Minister of Water, Irrigation and Electricity (MoWIE) and EEU have identified over 250 villages throughout the country that are far away from on-grid
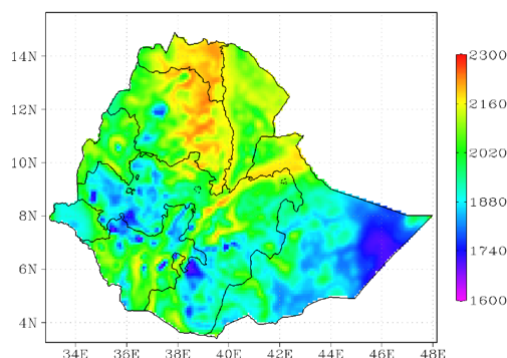
FIGURE 2.1: Ethiopian Solar radiation distribution (Ethiopian Ministry of Water and Energy June 22, 2013

substations and need to be connected via solar photo-voltaic mini-grids and EEU want to launch pilot projects in different regions and demographics of the country to determine the technical, financial and operational feasibly of mini-grids. Metahara solar power plant is one of the examples with the capacity of 100 MW which will be fed into the National Grid at the End of the Project. The Metahara Solar PV power plant, which will supply electricity to the Ethiopian national grid, will be one of the largest solar power facilities in Africa [7].

2.2   Components in Grid Connected PV Systems

A grid connected photo-voltaic system is dependent on several components in order to function. In addition to the solar modules, which convert solar radiation to DC current a photo-voltaic system consists of several components which ensures safe and efficient operation of the system. Grid connected Solar PV system should fulfill the international standards. Some international standard were listed on table 2.2. To connect the solar PV system to the grid each component of the system should controlled and selected properly. The figure 2.2 shows the component of grid connected solar PV system.

TABLE 2.2: Grid standard(Code)

The Standard	Parameter	THD (%)
IEEE 1547	Current	<5 %
	V<1 KV	<8%
IEEE 519	V<69 KV	5 %
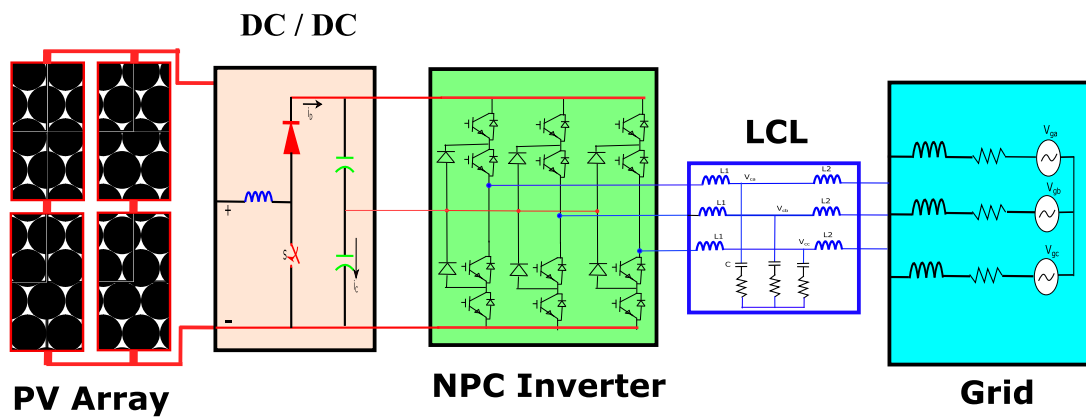
FIGURE 2.2: Component of grid connected PV system

In the following sub-sections, each component of the grid connected PV system observed on the above figure will be discussed. The first section was about the solar system and PV operation

2.2.1 PV System

The solar cell is the fundamental component of the PV system as it converts sunlight to DC current. As the operating voltage of a single solar cell is relatively low, several cells can be connected in series in order to form a solar module. Assembly of PV cells, mostly with 36 cells, connected in four parallel rows connected in series with an area ranging from 0.5 to 1 m^2 are called PV modules. Several modules assembled structurally and connected in series electrically are called panels. Assembly of several panels, electrically connected in series, is called arrays, and several arrays, electrically connected in parallel, to produce power is called PV generator figure 2.3. PV cells are not exactly alike, so does the assembly of modules and assembly of arrays. These assemblies of inequalities of cells, modules, and arrays cause mismatch losses. Shades and faults in arrays and the inequality of irradiation in cells cause voltage and current inequalities in the modules and arrays, causing overheating and damage to the modules. External factors such as temperature, shades, and imperfect cell surfaces cause deterioration of cells. Therefore, the cells are adequately encapsulated in a metal frame usually of aluminum and a rear supporting substratum of glass, metal, or plastic.

2.2.1.1 Solar Radiation

The amount of electricity produced by a photo-voltaic system will depend on the amount of irradiation that the PV modules receive. An assessment of solar radiation and isolation at
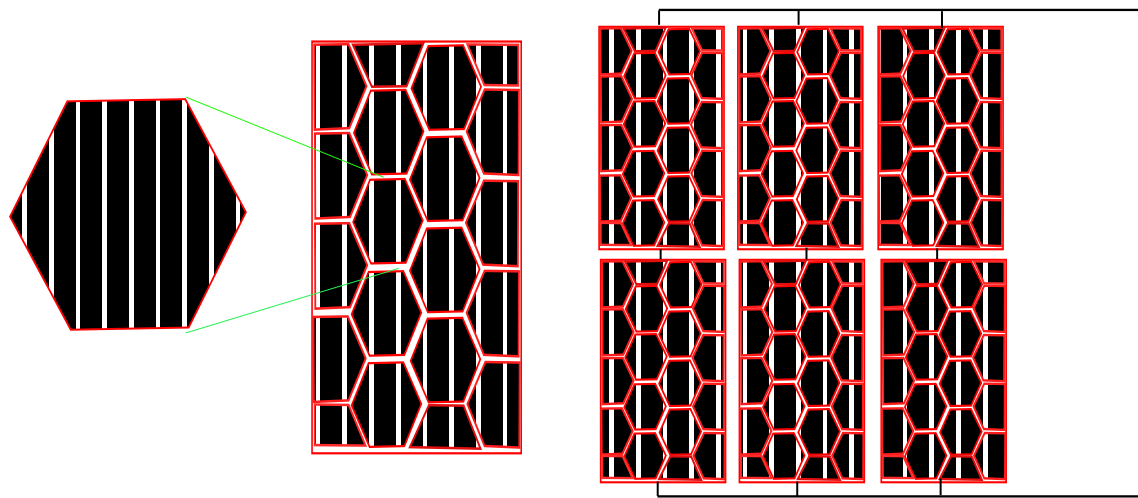
FIGURE 2.3: PV Cell, module and array

the intended installation site is therefore of great importance for the optimization of a photo-voltaic system. At the edge of the earth's atmosphere, the solar irradiation has approximately the same value at a plane that is perpendicular to the direction of the sun. The average irradiation value is [8].

$$S_0 = 1367 \pm 2W/m^2 \tag{2.1}$$

where S_0 is also known as the solar constant.

W is watt

m is meter

However, at the earth's surface the irradiation will vary significantly, mainly due to atmospheric effects, latitude, season of the year and the time of day

2.2.1.2   Season of the Year and the Time of Day

The earth uses 365 days to orbit the sun and 24 hours to rotate around its own axis. At a given place, the solar irradiation will therefore arrive from different directions at different times of the day and year. The motion of the earth around the sun is tilted by 23.45^0 to the equator. In the Northern hemisphere, the Earth will be tilted away from the sun in the period from autumnal equinox to vernal equinox, and tilted towards the sun from vernal equinox to autumnal equinox. The declination angle, δ, is 23.45^0 at summer solstice, -23.45^0 at winter solstice, and 0^0 at the two equinoxes [7].

The variation in declination angle through the year is illustrated in figure 2.4. The change
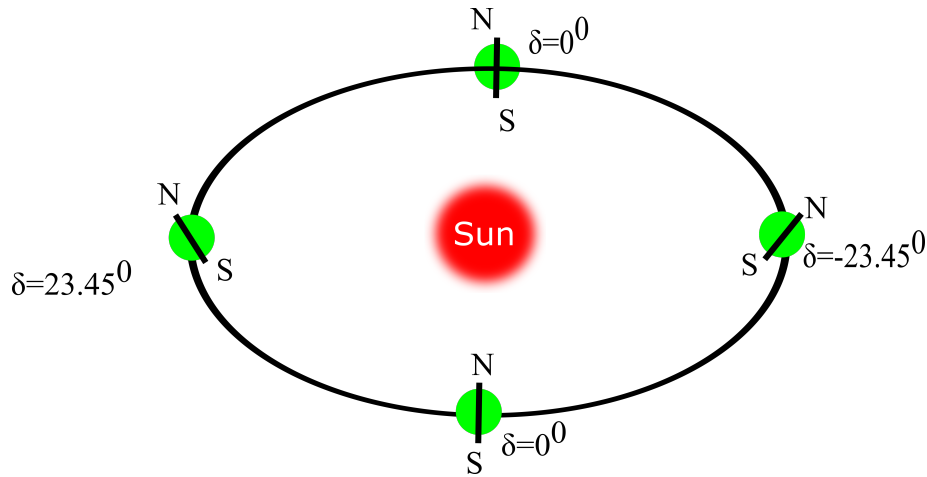
FIGURE 2.4: The Earth's declination angle for different times of the year

in path of the sun during the day is described using the hourly angle, ω_s, which is the angle between the meridian of the site and the meridian of the sun. This angle is by definition 0^0 at solar noon. The hour angle can be calculated using (2.2). Note that the hour angle is negative in the morning and positive in the afternoon.

$$\omega_s = (L_t - 12) * 15^0 \qquad (2.2)$$

where

L_t is the local time in hours.

ω_s is hour angle

2.2.1.3   Latitude and Solar Elevation Angle

The *Phi* latitude of a site determines the highest elevation angle of the sun throughout the year on a daily basis. The highest elevation is not constant throughout the year, and in the northern hemisphere the elevation will be the highest at the solar midday the summer solstice. The elevation of the sun is denoted h_s. The following relation is given between h_s, φ, δ and ω_s [3]. Equation (2.3) shows that the solar altitude varies depending on three factors: The time of year, which is expressed through the declination angle, δ , the site location, through the latitude, φ , and the time of day represented in the hour angle, ω_s.

$$sin(h_s) = sin(\varphi)sin(\delta) + cos(\varphi)cos(\delta)cos(\omega_s) \qquad (2.3)$$

When the latitude, the hourly angle and the angle of decline of a given site are known,
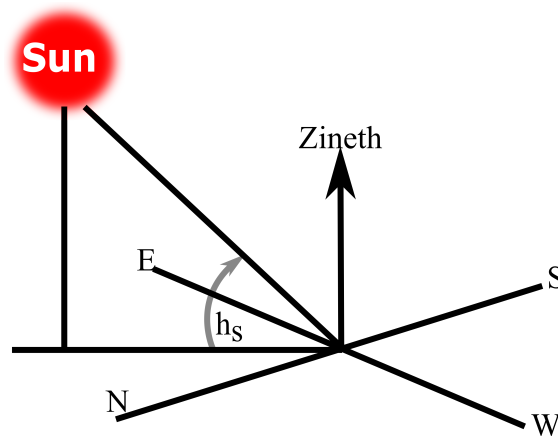
FIGURE 2.5: The elevation angle h.

the extraterrestrial irradiance for the location at a given moment can be calculated using the equation.

$$G_{ex} = S_{ex} sin(h_s) \tag{2.4}$$

where G_{ex} is the extraterrestrial irradiation on a horizontal plane $\frac{W}{m^2}$ and S_{ex} is the instantaneous solar constant varying between 1322 and 1414 $\frac{W}{m^2}$ depending on the time of year.

2.2.1.4 Module Orientation

The irradiation on a solar module will be a function of two angles: The tilt angle, β, of the module, and the azimuth angle, γ. The angle of inclination is the angle between the modulus and the horizontal plane. Various mathematical definitions of the azimuth angle exist, from those In this thesis the azimuth angle is defined as the angle between the south and the orientation of the module. Note that the azimuth angle by this definition is negative in the east direction. Figure 2.6 illustrates two concepts. The two angles must be chosen in such a way that the solar modules receive the greatest possible amount of irradiation.

2.2.1.5 Optimum Tilt Angle for a PV System

There are many different approaches suggested for the identifying of the optimum tilt angle of a solar module. A general rule of thumb is that the tilt angle should be equal to the latitude of the site location.

$$\beta_{opt} = \varphi \tag{2.5}$$

For instant, the Latitude of Dire Dawa is 9.62 so the optimal tilt angle of PV panel is equal to $\beta_{opt}Dire = 9.62^0$ At very northern latitudes, this approach will significantly reduce the
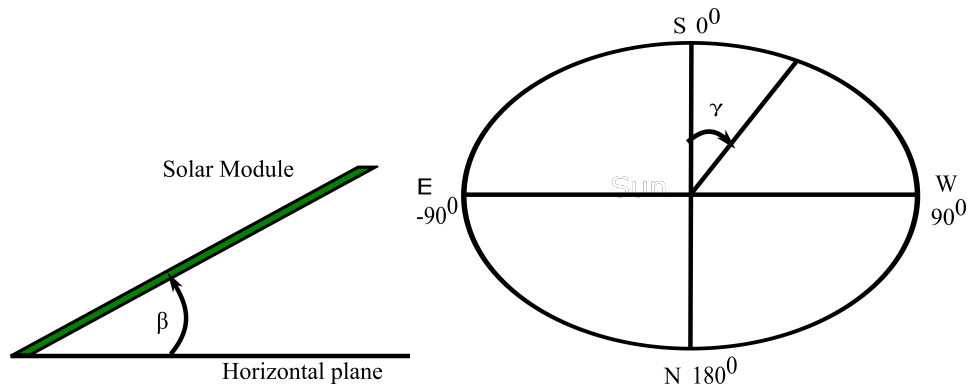
FIGURE 2.6: The tilt angle(the left) and azimuth angle(the right)

amount of diffuse radiation received by the module, and a lower angle of slope may therefore be desirable. However, a large angle of inclination will increase production during the winter because the path of the sun is lower and a greater fraction of the direct irradiation will strike the module. On horizontal surfaces, the angle of inclination of the modules will also influence the distance between the lines, since shading effects between modules should be avoided. An increase in the tilt angle of the β module will also increase the distance required between the module lines to avoid reciprocal shadows between the lines.

2.2.1.6 Optimum Azimuth Angle

The solar modules should be oriented directly towards south, as the sun in the Northern Hemisphere is at its highest altitude when in south. This can also be deviated from (2.3), as the hour angle ω_s is zero when the sun is in south, which means that $cos(\omega_s) = 1$.

However, a change in the azimuth angle of the modules of 20^0 or less will have a minimal effect on the energy generated by the system citepTsion . The optimum azimuth angle may also change in some cases because of local weather conditions when photovoltaic systems are located close to mountains or in a valley [9].

2.2.1.7 Irradiation on a Plane as a Function of Tilt and Azimuth Angle

The total amount of irradiation that hits a plane is given by the equation

$$H_p = t_f(\beta, \gamma, \frac{D}{G})H_G \tag{2.6}$$

where t_f is the transposition factor between horizontal and inclined irradiation, and $\frac{D}{G}$ is the ratio between diffuse and overall irradiation. When designing a PV system, a maximum H_p value is desirable and transposition is not only dependent on the angle of inclination

and azimuth of the plane; the scatter ratio is also important because the amount of scatter radiation is most important horizontally. Therefore t_f is a site-specific parameter that is not only determined based on module geometry.

2.2.1.8   Performance Ratio

The performance ratio (PR) is used to indicate the installation quality of a system though it doesn't necessarily quantify the amount of energy generated. Literature suggests that a low PR system located at a good irradiation site is highly likely to produce more energy than a high PR system located at a lower irradiation site. The findings of another study proved that the higher the PR, the higher the conversion rate of solar energy into electrical energy [9]. The PR of a solar PV system is determined as follows:

$$PR = \frac{E_{system}}{E_{ideal}}$$

where, E_{system} is the actual measured grid energy in kWh and E_{ideal} is ideal energy output of the solar PV system that would have been obtained in kWh if the system suffered no losses. E_{ideal} is determined as follows:

$$E_{ideal} = P_{systemSTC} \frac{G_t}{G_{STC}}$$

where G_t is the measured Plane-Of-Array irradiance or G_{PI} in $\frac{kWh}{m^2}$, G_{STC} is the irradiance at standard test conditions i.e. $1 \frac{kWh}{m^2}$, and $P_{systemSTC}$ is the rated DC output power of the solar PV system in kW under standard test conditions. The orientation of the PV modules and that of the device that measures the solar irradiation must be the same, so that they get exposed to the same temperatures and same solar isolation [9].

2.2.2   Grid Connected Inverter

It's known that inverter is type of power converter which converts DC to Ac power. There are many classification of inverter. Mainly the inverter is classified depending on the output phase number (i.e.single phase and three phase). In other case the inverter can also classified by the type of source (i.e. current source, impedance source and voltage source). Under those classifications the inverter divided into multilevel or two level inverter. If the inverter was connected to Grid, the third classification will come which is depending on the availability of transformer so-called transformer and transformerless. All the above classification has its

own advantage and disadvantage. So somebody can select depending on its need. The next topic will discuss on three phase grid connected inverter.

2.2.2.1 Three Phase Inverter

Inverter can be classified in to different parts based on the kinds. Inverter in terms of Phase can be classified into two single phase and three phases, inverter also can classify in to two based one grid connection Mechanism Transformer connected and Transformerless connected Inverter. Let discuss the different between three phase Transformerless inverter and Transformer inverter. There are two way of connection the PV inverter to the grid. The first one is with transformer grid tied inverter. This method has high cost, and not efficient but it doesn't have galvanic problem and leakage current. It can separate the common ground. When we connect renewable energy sources to the utility grid, there exists power quality and
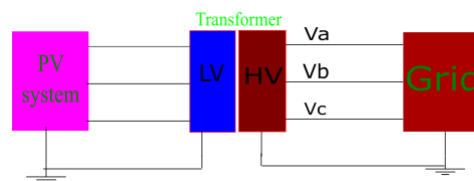
FIGURE 2.7: Transformer based Inverter

synchronization problem. The inverter output parameters must be synchronized in phase and frequency of the utility network. For achieving this synchronism, we require a control technique called phase lock loop. Pole Lock Loop is a closed-loop technique, and it produces an output signal which is synchronized in phase and frequency of the input reference signal.

2.2.3 PV Syst Overview

PVsyst is a software package developed at the University of Geneva by Andre Meroud. It can be used for the study, sizing and data analysis of complete PV systems including grid connected, stand-alone, pumping and DC-grid PV systems. It incorporates a database of meteorological data from various pre-defined stations of Meteonorm and PV systems components. The software currently has reached version 7.0.1 starting from version 2.21 with many improvements at each version [8]. For this study, PVsyst software version 7.1.0 is used. The model implemented by the software and sizing principles will be discussed briefly in the following sub-sections.

2.2.3.1   PV Module Model Implemented in PVsyst

For the purpose of describing the operation of a PV module, Shockley's simple one diode model primarily developed for a single cell is used. Its generalization to the whole module implies that all cells are considered rigorously identical. The equivalent circuit of the model is as displayed in figure 2.8 [8]. The main expression describing the general one-diode model
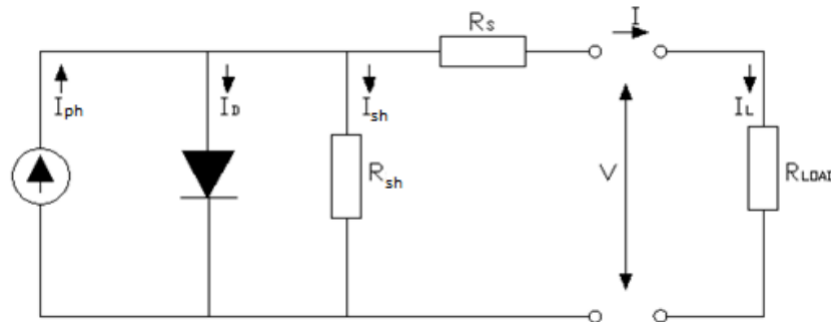
FIGURE 2.8: Equivalent circuit for one diode model of a PV cell (Source: PVsyst software's user manual)

is written as (2.7).

$$I = I_{ph} - I_o(exp^{q\frac{V+IRs}{Ncs\gamma*kTc}} - 1) - \frac{V + IRs}{R_{sh}} \tag{2.7}$$

2.2.3.2   Array and Inverter Sizing in PVsyst

Inverter sizing in PVsyst has the following considerations:

1. The nominal power (Pnom) of the inverter is defined as the output AC power. The corresponding input power is $P_{nom}DC = \frac{P_{nom}AC}{Efficiency}$

2. The P_{nom} of the array is defined for Standard Test Conditions (an irradiance of $1000\frac{W}{m^2}$ and temperature of 25_oC) which is very rarely or never attained in real conditions.

3. The power distribution is dependent on the plane orientation. For example, a facade will never receive more than $700 - 800\frac{W}{m^2}$ depending on latitude.

4. The maximum power is not significantly dependent on latitude but rather on altitude. On clear days and perpendicular to the sun's rays, it is only dependent on the air mass.

5. Many inverters accept a part of overload specified by a P_{max} parameter, during short times (dependent on the temperature of the device). This is not taken into account in the simulation which may reduce the calculated overload loss.

6. When over-sized, the inverter will operate more often in its low power range, with decreased efficiency.

In PVsyst, the inverter sizing is based on an acceptable overload loss during operation, and therefore involves estimations or simulations in the real conditions of the system meteorological data, orientation and losses) taking the following into account.

Overload Behavior:- With all modern inverters, when the P_{mpp} of the array overcomes its $Pnom_{DC}$ limit, the inverter will stay at its safe nominal power by displacing the operating point in the I-V curve of the PV array (towards higher voltages). Therefore, it will not undertake any overpower and there will not be power dissipation, overheating and supplementary aging. But the potential power of the array will not be produced.

Loss Evaluation:- The energy loss is the difference between the P_{mpp} potential power and the $Pnom_{DC}$ limit effectively drawn. The PVsyst criteria for an acceptable sizing are as follows:

- $3 > OverloadLoss > 0.2$ inverter slightly undersized, warning
- $Overloadloss > 3$ inverter strongly undersized, prevents the simulation

These criteria lead to $P_{nom}Ratio = \frac{P_{nom}(Array)}{P_{nom}(Inv)}$ of the order of 1.25 to 1.3 for most well-oriented systems. PVsyst also allows modifying these design parameters in order to consider strongly over sized PV arrays. The next step is the determination of a number of modules in series and a number of strings in order to approach the desired power or available area based on the following requirements [8].

- The minimum array operating voltage (at maximum module operating temperature, 60^0C by default) should be above the minimum inverter's operating voltage (V_{min} of MPPT range).

- The maximum array operating voltage (at minimum module operating temperature, 20^0C by default) has to stay below the maximum inverter's operating voltage (V_{max} of MPPT range).

- The maximum array absolute voltage (V_{oc} at minimum temperature, -10^0C by default) has to stay below the absolute maximum inverter's input voltage.

- The maximum array absolute voltage (V_{oc}) should not overcome the maximum system voltage specified for the PV module.

2.2.3.3   System Losses in PVsyst

System losses can be defined as all events which reduce the energy output of a PV array as compared to nominal power stated by the manufacturer for Standard Test Conditions (STC). Several of these loss sources are not directly measurable. In PVsyst, array loss parameters are initially set to reasonable default values, and these values can be defined depending on the PV system to be designed. The factors that diminish the energy output include thermal losses, ohmic losses, module quality losses, light induced degradation losses, array mismatch losses, soiling loss, array incidence loss and unavailability loss [8].

2.3   Literature Review

Growth in the energy demand coupled with aging infrastructure and increasing concern over environmental impact is driving the development of Distributed Generation (DG) systems that support Renewable Energy Sources (RES) like solar, wind, thermoelectric, fuel cell etc. Increases in cell efficiency and reduction in total system costs, including ease of installation, has made photo-voltaic energy systems not only affordable, but in some markets cheaper than energy from conventional sources [10, 6]. However, PV cells produce low, direct-current (DC) voltage as compared with the high-voltage alternating current (AC) grid and thus require power electronics for step up, DC/AC conversion and maximum power point tracking (MPPT) for efficient operation. This generally requires multiple power converter stages to accomplish. Many of the common PV inverter topologies are two-staged with an energy buffer, such as DC-link capacitor [4]. The first stage performs MPPT, boosts the PV voltage and transfer the PV power to the energy buffer, the energy buffer is followed by second inverter stage to connect the system to the utility grid [7]. Let see some literature on the Grid connected inverter in two steps. The first section talks about solar PV system modeling by PVsyst software and secondly grid connected inverter power control based literature.

Rachit, on their study Grid connected photovoltaic system for the load of Madan Mohan Malaviya University of technology is designed using the PVsyst software. By the help of PVsyst software PV system configuration, output electricity and system losses are analyzed. The whole study is focused to designing a grid connected photovoltaic system for Madan Mohan Malaviya University of technology, Gorakhpur, India. By this accurate size of the

grid connected PV system is determined and suitable PV mode and inverter are selected. It is founded that 2000 PV panels of 250W solar panel and 10 grid tie inverter of 50kW are the optimal solution for supplying the load throughout the year. From the proposed system 901.44 MWh electricity could be generated in a year and available to the grid. Performance ratio of the system is about 83.1 % [11].

Ashok, study to calculate performance parameters of existing system as well as performance of identical sized, totally on-grid system, simulated using PVsyst in Tribhuvan University Teaching Hospital, Maharajgunj, Kathmandu to fulfill its own load demands and reduce the electricity bill of the building. The detailed On-Grid solar PV system is modeled, and performance parameters such as Performance Ratio, Specific Yield and Capacity Utilization Factor as defined. Using PVsyst, the performance parameters are found to be performance ratio 83.5% and Specific Yield 1728 $\frac{kWh}{kWp}$ respectively [12]. Chong Li, in his paper study to establish the performance of 8 kWp grid-connected photovoltaic (PV) power systems based on different PV module technologies in Nanjing, China. The study focuses on performance assessment of grid-connected PV systems using typical PV modules installed on location. The yearly average energy output, PV module and system efficiency, array yield, final yield, reference yield, performance ratio, monthly average array capture losses, and system losses of seven PV module technologies are all analyzed. The results show that grid-connected PV power system performance depends on geographical location, PV module types, and climate conditions such as solar radiation and ambient temperature [13]. Mahachi, in his article an overview of the losses in a solar PV system is given and the findings of the loss analysis of an operational 75 MWP solar PV plant in South Africa are shown. The calculated losses are then used to improve the PVsyst model for the solar PV plant and finally the PVsyst model and the improved PVsyst model for the solar PV plant are compared to the measured data from the operational 75 MWP solar PV plant in South Africa [14]. In all above four literature, the design of Solar PV system by using PVsyst software to analysis the performance ration solar PV system, Optimizing the Component and comparative study parformance of different PV module on the different climate condition. But cost analysis and rooftop solar PV system in Dire Dawa Industry Zone were not done.

Ahmed, Done the performance analysis of rooftop and ground-mounted PV systems and it is carried out to determine the most feasible configuration in hot urban areas. The PV modules are placed at a particular tilt angle to receive the maximum amount of solar irradiance and

operate at maximum efficiency, but the tilted PV modules cause mutual shading among the parallel arrays, which decreases their efficiency. From the results of this paper, it is concluded that the rooftop PV system is clearly a much better option than the ground-mounted PV in regions with hot climates [15]. But in this literature the transmission line cost were not considered. In Grid connected Solar PV system the other concern were the quality of the Inverter output. Sheril, have been demonstrated that the voltage, current and frequency of the grid connected photovoltaic system could be synchronized and controlled by using phase locked loops and stationary reference frame technique. But the active and reactive power flow from the output of inverter to the grid has not been controlled. Since the two powers are not being controlled independently, the stability and efficiency cannot be improved [16]. Another researchers, Binh et.all, presents a control algorithm for a single-phase grid-connected photo-voltaic system in which an inverter designed for grid-connected photo-voltaic arrays can synchronize a sinusoidal current output with a voltage grid. The active and reactive power are sequentially controlled by load angle and by inverter output voltage magnitude besides a maximum power point tracker always finds optimal power of the PV array in use. The controller feeds maximum active power into grid at unity power factor, whereas it also allows the adjustment of reactive power injected into the grid [17]. But, the grid feed to the industry zone were three phase and design of single phase for three phase connection will lead to voltage unbalance. The other problem in grid connected solar PV system is the quality of the signal of voltage and current.

While various authors have addressed the subject of yield and performance of solar power farms in different locations of the world to meet the technical and global standard, none has been conducted in Dire Dawa. This study therefore fill this gap by investigating the key performance parameters of the site. Secondly, this paper is going to do the the whole design of grid connected PV from site parameter determination, DC-DC converter and three phase grid connected PV inverter , and finally control the reactive power flow of rooftop grid connected inverter. This thesis work combine the two steps of design. The first step were to observe the capacity of the Dire Dawa industry zone to the generation of PV power on the roof of the given site and the second step is focus on the design of the grid connected rooftop PV system and controller to connect to the grid within standard. Finally the comparison of rooftop PV system and Ground mount PV system will conducted.

Chapter 3

Assessment of The Site and Design Grid Rooftop Solar PV system using PVsyst

3.1 Need Assessment of Rooftop PV

3.1.1 Introduction

This section have two sub topics. The first topic deals with data gathering method and tools; the second is data interpretation and analysis and in the next section the solar power will be designed using PVsyst software.

3.1.2 Method and Tools

The method of collecting data is used by tools like data Survey, Interview and Observation to assessing the capacity electric power production from solar PV system on the roof top of each factories in Dire Dawa Industry Zone. This involves screening the site and the roof of buildings in question in order to evaluate solar availability of the Site and the capacity of each buildings. Dire Dawa industry zone have many factories but some of them were closed and not operating. Thus, in Dire Dawa industry zone for 20 Factories the survey paper distributed. Following this, The Grid Connected Inverter based Solar System will be Designed by selection of components and detailed system sizing using the latest version PVsyst 7.0.1

3.1.2.1 Study Area

This research study was intended to find Solar Energy Need Assessment and Rooftop Area of Dire Dawa industry zone. The survey was focused on the factories in the Dire Dawa industry zone. Dire Dawa industry zone is the industry zone which is situated in [9.62 N,41.80 E] in coordination in the town of Dire Dawa. Major factories were established at Dire Dawa such as Cotton Textile, Vera Food Complex Factory, National Cement and Ture Cement. The major industrial park begins production. The large industrial park kicks off production. In addition to these large and complex factories in Dire Dawa industry zone has more than 16 factories were collected. Dire Dawa has a warm semi-arid weather. Dire Dawa has a
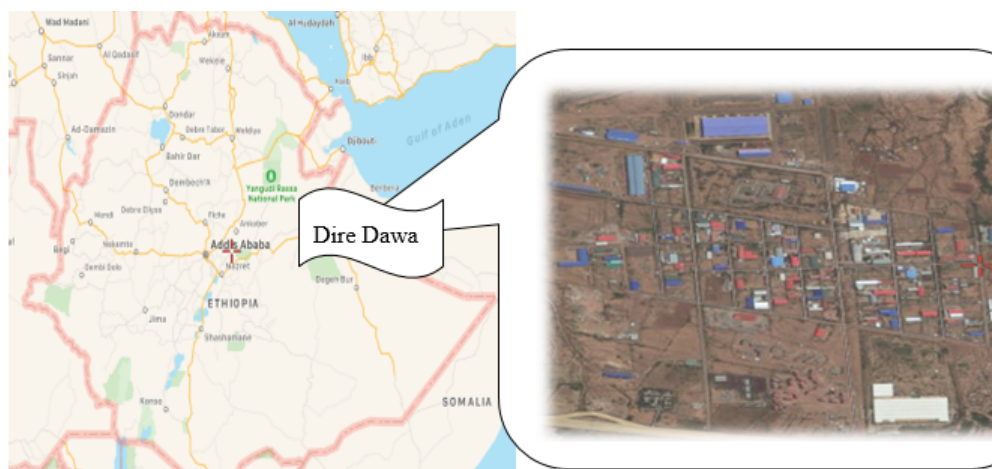
FIGURE 3.1: Dire Dawa industry zone

mid-arid warm climate. The Dire Dawa has an average annual temperature of approximately 25.9^0C. Dire Dawa's average maximum temperature is 32.8^0C whereas its average minimum temperature is 18.1^0C. The region has two rainy seasons, a small rainy season from March to April, with a more pronounced rainy season extending from July to August. The total average annual precipitation the region receives from both seasons is approximately 583 millimeters or 23.0 inches.

3.1.2.2 Source of Data and Data Gathering Instrument

In orders to collect the necessary information data sources were employed Person which was assigned by the factory Manager or the manager itself by using multiple data gathering instruments like questionnaires, and interview. An assessment of the site was conducted from $Tir, 22^{th} - nehase, 29^{th}2012$ E.C. In order to collect the necessary data, the methodology for observing, interviewing and collecting data by questionnaire was used. The use of various tools made it possible to look at the situation in depth. The details of each data collection instrument are presented in this manner:

Interview:- For the case of interviews' free response and flexibility that cannot be obtained by other data gathering instruments and procedures semi-structured interview, which consisted of experience of the Industry with PV system and why don't they use solar energy until now were carried out for each factory.

Questionnaire:- Questionnaires were also used to gather appropriate information from industries. Open and closed questions were distributed and collected among respondents.

Of the 20 questionnaires delivered to the target population, 17 were returned by the industries. The analysis was subsequently conducted using responses from Industries.

Observation:- In the data collecting time I observe that all buildings have two sides tilt and the northing of the building were also two types. One is the tilt direction of the building is in the direction of east and west. And the second type was tilted to north and south direction.

Secondary Data:- Secondary data such as the meteorological state of the city of Dire Dawa, solar radiation and other design parameters were collected from NASA and the PVsyst simulator.

3.1.3   Data Interpretation

3.1.3.1   Data From Sabian SCADA station

Dire Dawa city take power from national grid, the eastern region transmission line which start from Koka Power Station to Hurso, then from Hurso to Dire Dawa city with 250 KV. Dire Dawa Sabian Substation took this 250 KV High Voltage and convert to 132 KV and give to Shell Substation. After this 132 KV transmission line arrive Shell substation it converted to 15 KV and distribute to the city by five bus bars as shown on the figure 3.2 . In addition to these five bus bars from the Shell substation with are referred to as $R2 - DTU$, $R3 - DTU$, $R4 - DTU$, $R5 - DTU$, $R6 - DTU$ respectively, Sabian Substation also have a bus bar with a distribution voltage of 15 kV which is referred to as $R1 - DTU$. The $R1 - DTU$ busbar was designed to supply the power of Dire Dawa industry zone($R1 - G4$), Melka (Dire Dawa Industry Park) ($R1 - G3$) and the community (Papa and Boron)($R1 - G5$) with 3 distribution lines respectively. But this bus bar is not working now so it took power from $R2 - DTU$ Bus bar as observed in figure 3.2. In addition to this $R1 - G4$ (Dire Dawa industrial area distribution line) is out of service per major issue since $Hidar, 5, 2012E.C$. To solve this problem they Shunt the line with $R1 - G5$. From that time the Dire Dawa industry zone took the power from $R1-G5$. Therefore the data collected by the EEU_{Sabian} sub-station is $R1-G4$ and $R1-G5$. Dire Dawa industry zone is 7 km far from Sabian Supply Station. Data collected from the Sabian sub-station indicate that there are many factors that affect power quality. The first factor is the complexity of a distribution system. For instant, if the fault occurs on the bus bar $R2 - DTU$ it directly affects the distribution line of the industry zone of Dire Dawa. The next factor is, since the $R1-G4$ distribution line which only provides the industrial area is out
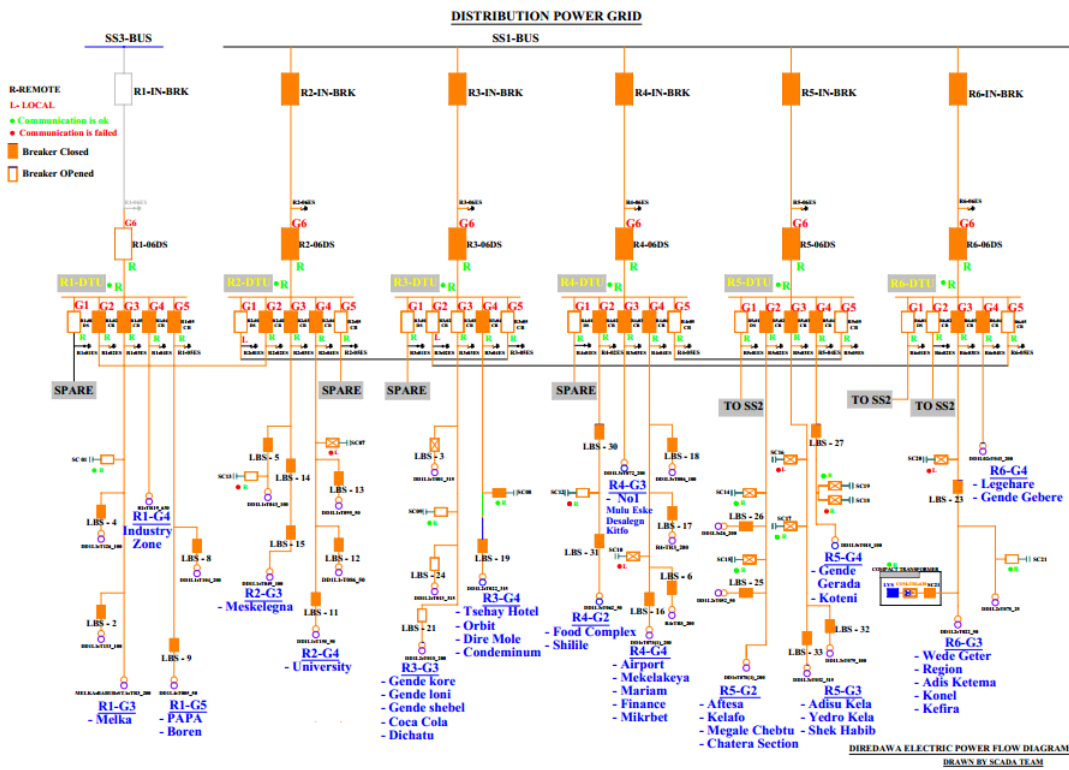
FIGURE 3.2: Electric distribution single line diagram of Dire Dawa city

of service and replaced with $R1 - G5$ which covered the large residential house. In addition, as a result of the distribution system is old insulation on the pole is cracked and fail at each rainfall and the pole itself is weak and fails repeatedly. The main power interruption is the

FIGURE 3.3: Interruption data of industry zone(from SCADA)

forced interruption that takes 83% of the total interruption and the remain, 17% is operational

interruption as shown in figure 3.4 (the left side). In the right side of the figure figure 3.4 it shows that the duration of the interruption in day thermal starting from nine months of total data. In general, from the above data, we can conclude that there is a power failure problem in the industrial zone of Dire Dawa. In the following section we will see the data collected from Dire Dawa area of the industry itself.
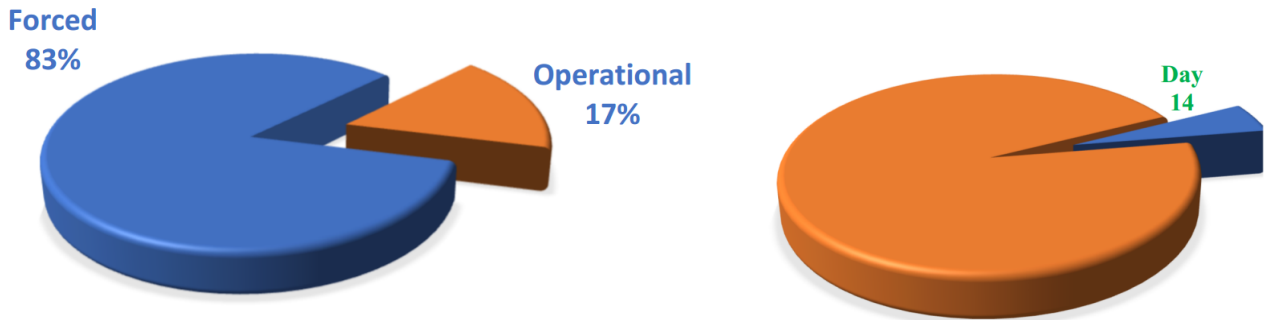
FIGURE 3.4: Forced interruption data of industry zone(from SCADA)(left) and Power interruption duration of Dire Dawa industry zone from 270 Days

The figure 3.5 shows the peak load of the Dire Dawa industry zone distribution feeder in month.
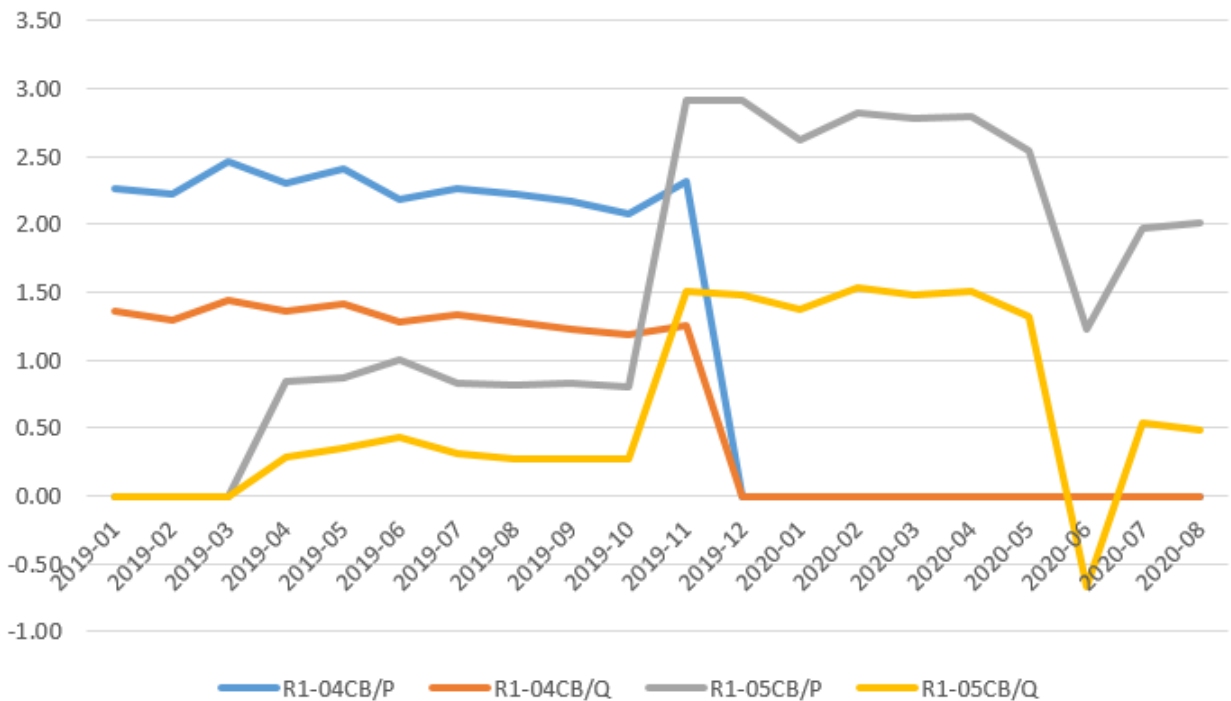
FIGURE 3.5: Electrical load of the Dire Dawa industry zone

3.1.3.2   Respondent Personal Informations

The respondents were well educated, 6.25% respondents have MSc, 87.5% have BSc and the rest 6.25% have Diploma. The specialization was 43.75% is in electrical engineering, 37.5% in other engineering, 17.75% is in Natural and social Science. The respondents were well informed about the factory 18.75% was employees, 43.75% team leaders, 18.75% production manager and 18.75% general manager.

3.1.3.3   Energy Source and Power Interruption Problem in Dire Dawa industry zone

According to the evaluation of the data, all factories in the Dire Dawa industrial area use electrical energy as a primary source and only one factories use an additional solar water heater to boil water for its production process. The energy source for the Dire Dawa industrial zone is the electricity from the national grid(Sabean substation). Each factory takes the power according to its capacity and converts to 1000 V (6.25%), 600 V (6.25%) and 380 V (100%) the voltage level to be used for their production. 6.25% of plants use less than 50 KVA, 31.25% use $51KVA - 100KVA$, 50% use between $101 - 500KVA$, 6.25% use between $501KVA - 1MVA$, and 6.25% use again between 1MVA - 24MVA. From the collected data, the utility (network) electrical power reliability is 50%. 31.5% the power grid is generally reliable, but most of the time that is not the case. 18.75% of the the electricity system was reliable most of the time, but sometimes the system was unreliable. 18.75% respondents replied the grid power is reliable most of the time but sometimes the system was not reliable. Because of the grid power reliability problems,43.75% of the factories product is significantly affected. 18.75% were affected moderately, 25% of the factories were affected by minor and 12.5% factories were not affected by grid power interruption. From the data it observed that the effect of power interruption is depends on the type of product. The effect of power interruption on the product is depend on the power interruption and the duration of interruption. The number of interruption per month were 6.25% said the interruption per month is less than 5, 12.5% of the respondent answer that the interruption is between 6 to 10 per month. 6.25% respondent estimated between 11 to 20 per month, 31.25% respondents were estimate the interruption between 30 to 40 per month, 18.75% factory estimate the interruption between 41 to 100 per month and the other 25% factories estimate the interruption between 101 to 200 interruption per month as shown in appendix B: table 4. The respondent answer about number of interruption per month were depends on the type of product and the working culture of the company, some factories work in two or three working shift. From the

above information some factories are very sensitive to power interruption and on other side some factories even don't notice the interruption of the power, because of the small interval of it. The other question for respondent was if the other power problem on their factories. All respondents were answer that voltage dip problem 100% and in addition to that poor power factor problem 12.5% as shown appendix B: table 3.

3.1.3.4   About Solar Energy

On the questionnaire the other question for responder were about solar energy. From the response, 93.75% of the them believe that PV could solve their power problem and 6.25% of the factories believe it could solve the problem, but not significant. From all factories 56.25% of them plan to install in near future and 43.75% of them are not. All of them believe in the benefit of rooftop PV installation system is the solution for their problem. But non of them were not using PV electric power only one factory use solar heater for boiling water. 62.25% haven't ground surface area to install solar power, 31.25% have but not enough to install solar power, 6.25% have enough surface but the place was held for expansion planning in the future for the factories as shown in appendix B: table 6. The building of factories were the same type of houses design which is known as two sided roof house. and the orientation of building are the in the south to north direction and the other were in the west to east direction. 31.25% of the building have less than 10^0 of roof tilt, 62.5% have between $10^0 - 15^0$ roof tilt and 6.25% have greater than 20^0 roof tilt. the roof area of all factories were listed in the table 3.1.

In the above discussion we observe that there is an interruption problem in Dire Dawa industry zone electric power supply and secondly we observe as there is need for solar installation but they don't have enough area on the ground surface to install solar panel and finally we observe that there is huge area on the top of each factory roof. In the next section we will design rooftop solar system for Dire Dawa industry zone by using PVsyst software.

3.2   Design of Rooftop PV for Dire Dawa Industry Zone

3.2.1   Introduction

From previous section the area of the Industry zone, the tilt angle and the direction of the tilt were observed. By using those data in this section the grid connected Roof top PV was designed by using PVsyst 7.1.0 simulator.

TABLE 3.1: Rooftop area of each factory

Name of Factories	Area(M^2)
Abshir flour factory	900
Arken Jute Product	1500
Ayan Nail Factory	3,000
Dire Steal	11,000
Free Spring Water	2517
Hire Flour Factory	1018.224
Kromoto	2030
New Wave Industry	950
Ries Eng'g/CAT/	500
Royal Foam	2000
Shamu1	5500
Shamu2	500
Shamu3	400
Ummy Flour Factory	1494.4
Urji Soap & Detergent	1600
Vita Spring Water	3800

3.2.2 Simulation by PVsyst Software

The PVsyst software offers two stages of PV system design, Which is preliminary design and project design. The preliminary design involves evaluating the performance of the system using monthly weather data and some general parameters of the system without specifying actual system components. In this study, only the project design stage is used, as the preliminary design provides a rough estimate of system performance and cost.

3.2.2.1 Project Design

The first stage of the project design is the project designation, which includes the geographic site definition, associated hourly meteorological data, and albedo parameters as shown on figure 3.6. The dialog used to specify the project parameter so that PVsyst takes into account the effect of reflected diffuse radiation, the albedo values for the site must be given as input. The albedo values used in these simulations had a default value of 20% as shown on the figure 3.7.

3.2.2.2 Temperature Effect

In Ethiopia, the angle between the sun shines and the vertical line when the sun is at tropical (southern) Capricorn is greater than the angle when the sun is at tropical (northern) cancer. Taking into account only the position of the sun, the value of solar radiation on the land of
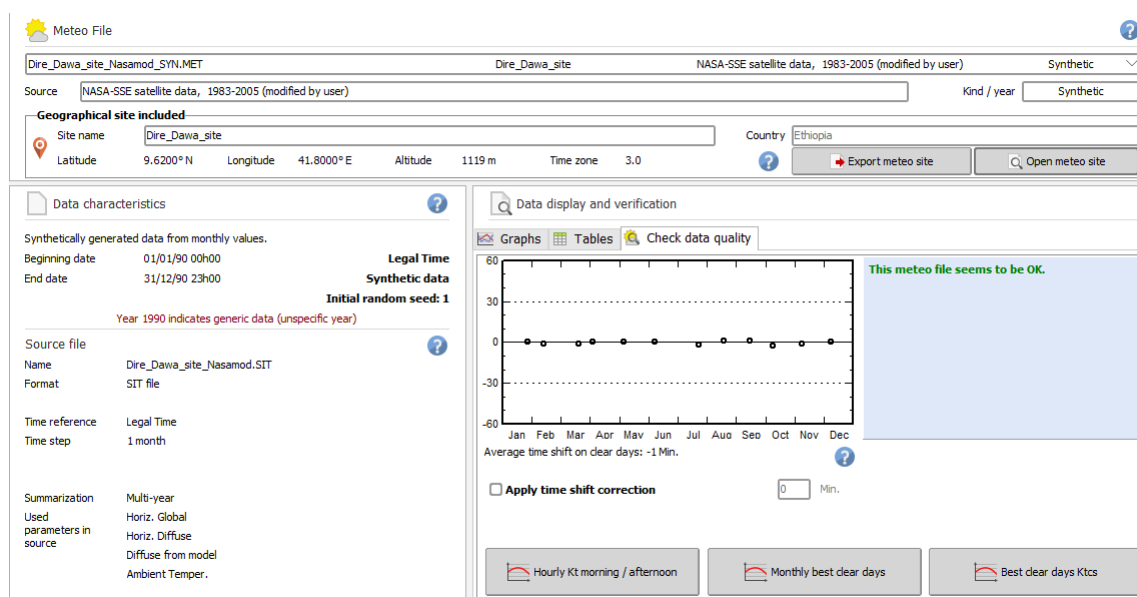
FIGURE 3.6: Site location and data from PVsyst

FIGURE 3.7: Project setting for albode

Ethiopia as of December 21st (Tropical Capricorn) must be less than the value of radiation as of June 21st (Tropical Cancer). By contrast and the observation of the local residence, the rainy season is in the months of June to September in Ethiopia. This is an exact match to NASA data. Between September and March is the dry season, there is more sunshine during this season. Therefore, this information obtained from NASA can help in comparison with the result produced by the software, the actual observation and the investigation of the local residence. Consequently, the irradiance and temperature result obtained from the site were compared with respect to NASA in figure 3.8and figure 3.9. The table 3.2 shows the site data generated by PVsyst software. Where GHI is the Global horizontal Irradiance, HDI is the horizontal diffusion Irradiance and Temp is the temperature(^{0}C)

TABLE 3.2: Dire Dawa industry zone site data generated by PVsyst

	Jan	Feb	Mrch	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
GHI	5.9	6.34	6.29	6.1	6.27	6.03	5.83	5.86	6	6.06	6.07	5.8	6.04
HDI	1.34	1.5	1.89	2.13	1.96	1.95	2.03	2.12	2.03	1.73	1.36	1.26	1.78
Temp	20.4	22.1	24.6	25.5	26.6	24.8	22.4	22.3	23.8	23.7	21.7	20.2	23.2
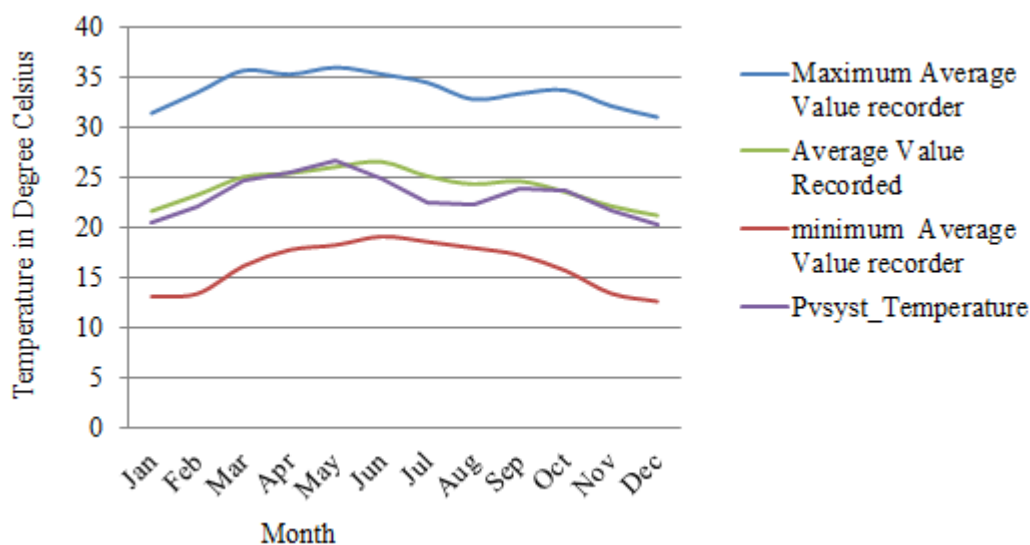
FIGURE 3.8: Dire Dawa city temperature value at 2 meters(NASA meteorological data for past 38 years)

The efficiency of photovoltaic technologies depends very much on the temperature, because the temperature of the modules increases, the efficiency of the photovoltaic cells decreases. Photovoltaic modules convert only $10\% - 25\%$ of solar energy into electricity, so the vast majority of incoming energy is converted into heat. The efficiency of crystalline silicon cells is reduced by 0.4 degrees Celsius for each temperature increase. For amorphous silicon cells, the effect is dependent upon a specific production process and is estimated at half that amount. The temperature difference between the PV and the environment depends on the intensity of the irradiation and may be as high as 40 ^0C. In summer, the high daily mean temperature of Dire Dawa can reach 42 ^0C, therefore the PV temperature can rise to about 73 ^0C see figure 3.10. To prevent this temperature increase, the integration of photovoltaic networks must be done in such a way that the heat can be well dissipated. In order to allow the cooling of the PV laminate by natural convection, it is recommended to create a space of air between the PV and the structure of the building at the rear. In this design, the vented roof with natural ventilation is assumed to be used.
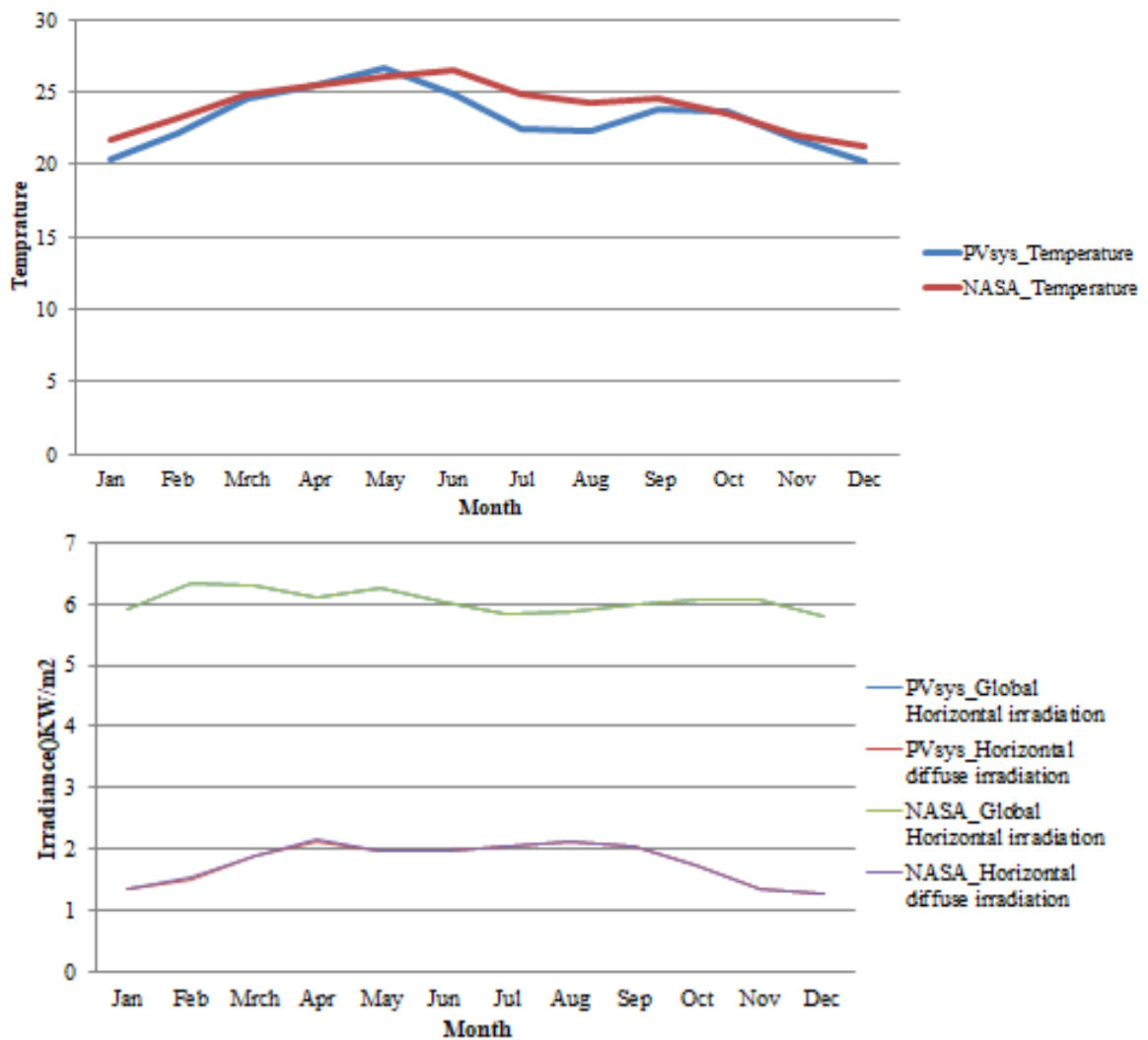
FIGURE 3.9: Compression between PVsyst generated and NASA meteorological Data of temperature and irradiation respectively

FIGURE 3.10: Project setting for operating temperature

Lower temperature for absolute voltage limit: This is the absolute bottom temperature of

the cell to determine the maximum possible voltage of the grid, ideally it should be the

minimum temperature never measured during daylight on the site under consideration. The default value is -10^0C [8]. For this study a value of 1^0C was taken considering the lowest recorded temperature of Dire Dawa city in the past 30 years as described in the figure 3.8.

Winter operating temperature for V_{mpp} design: This is defined as the winter minimum cell temperature in operating conditions. The default value is 20^0C [8]. In operating conditions the temperature of building integrated PV modules may rise by 20-40^0C than the ambient temperature [8]. A value of average winter temperature of Dire Dawa City is 18.1^0C and by rise of 20^0C, the value of Winter operating temperature is become 38.1^0C which is taken as considering for this study during operation.

Usual operating temperature: This is defined as the summer usual operating conditions. The average daily temperature of Dire Dawa city is 25.4^0C. In operating conditions the temperature of building integrated PV modules may rise by 20-40^0C than the ambient temperature. Hence, a value of 45.4^0C was taken for this study.

Summer operating temperature for minimum V_{mpp} design: This is the maximum cell temperature in operating conditions [8]. The maximum average temperature of Dire Dawa is 33^0C. By considering a 40^0C rise in temperature of PV cells, a value of 73^0C was taken for the study.

The other parameters defined in the albedo setting are as follows.

Array maximum voltage: It is defined as the maximum admissible array voltage (Voc at minimum temperature) specified with PV modules. It is 1000V as per IEC standard.

Temperature coefficient of the open circuit voltage (muVoc): It is calculated by the one-diode model which allows the use of a derate factor muVoc specified by the manufacturer.

Limit overload loss for design: This parameter is used to limit the loss due to oversized PV array with respect to the inverter. For this study, the minimum value of 3% was used [8].

Other Limitations: This option is used for 3D shading analysis. Since the 3D shading analysis is not part of this study, the definition of these parameters was not performed.

3.2.2.3   Meteorological Data in PVsyst

In PVsyst, latitude and longitude are used as input data for the calculation of solar trajectories for a given site. This is accomplished by using the theory and equations described in the section (2.2.1.1). PVsyst makes it possible to import weather data in different formats. However, to carry out a simulation, the program requires hourly values for parameters like Global irradiance on the horizontal plane, Diffuse irradiance on the horizontal plane, Ambient temperature[8]. Figure (3.11) shows an example of solar paths calculated by PVsyst.
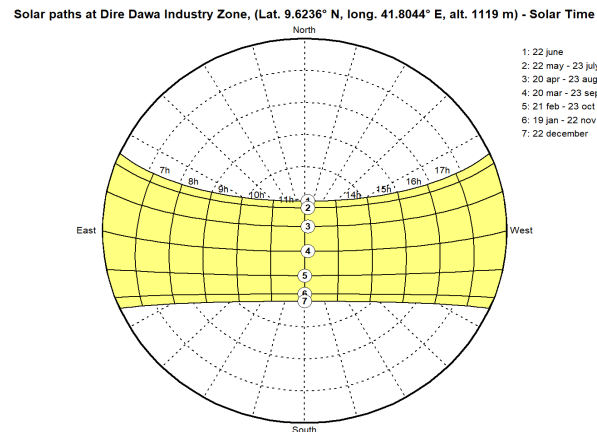
FIGURE 3.11: Sun path for different time by PVsyst

PVsyst has integrated mechanisms for the generation of diffuse irradiation data and wind speed data, so that the overall irradiation and ambient temperature are the data that should in any case be provided by the user. However, the outcome of the simulations will be more precise if all site parameters are available. As the meteorological data collected for this site consists of monthly average irradiation values and monthly average temperatures, the "Synthetic hourly data generation" function was used to generate hourly values for the irradiation and temperature data. Hourly irradiation values are constructed using a transposition mechanism that is closely linked to the solar geometry described in chapter two section 2.2.1.1, and the latitude and longitude of the site is therefore used as an input to calculate the solar path of each day. Daily values are then generated by means of probability matrices based on data from various weather stations or satellite data. Finally, the temporal values are generated using a Gaussian pattern. An example of hourly irradiation values generated for a day is shown in Figure 3.12.
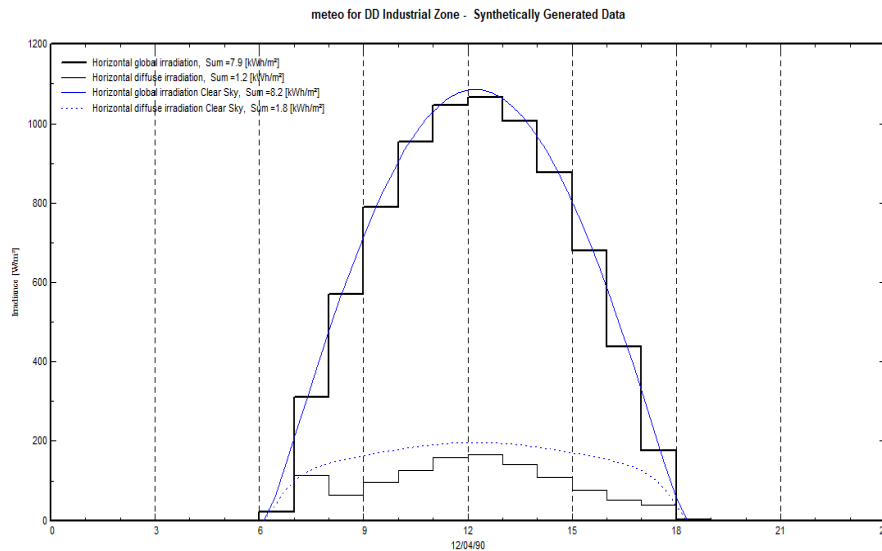
FIGURE 3.12: Solar radiation

3.2.2.4   Tilt and Orientation of Building Surfaces and Shading

One of the most important factors which influence the efficiency of PV systems is overshadowing. Hence, it is a necessity to examine a particular building for overshadowing due to neighboring buildings, trees and distant tall buildings. Currently, there are no shadings near the Building which can affect the performance of the PV. So for this particular study, it is assumed that there will not be shadings in the future. In the Northern hemisphere, the plane azimuth is defined as the angle between South and collector plane. This angle is taken as negative toward east, i.e. goes in the anti-trigonometric direction. Example: south plane, azimuth = 0^0, east plane, azimuth = -90^0. The uniform illumination of solar cells is a necessity for high energy output. It is clearly discussed that overshadowing reduces PV output. However, even partial shading from a tree branch, overhead cables running over the building or other things which might appear quite minor can reduce the electricity output significantly. The charge carriers which enable PV material to conduct electricity are only present in PV material when it is illuminated. Hence, the shading of one cell stops current generation causing the cell to become an electrical resistor [9]. In this study, an assumption was made that there would be no partial shading of PV modules. The integration of PV modules may sometimes be done on roof with different tilt and orientation which leads to the receipt of different levels of irradiance. Connecting modules of such surfaces in one series string would hold back the full generating potential of the modules that are receiving a higher irradiance since

the resulting current would be determined by the minimum, this being from the modules receiving least irradiation. In such cases, it would be a necessity to divide arrays into different zones, each zone composing arrays with the same tilt and orientation. In Dire Dawa industry zone all factories have two side roof styles as observed in illustrative figure on Appendix B: 1 , some factories have the North & South roof inclination and the other were oriented in the East & West direction. Hence, it is decided to divide the PV arrays into two zones, for each factories. The amount of light reaching the surfaces that will incorporate PV networks is considerably affected by the slope and orientation of the surfaces. Irradiance, which is the amount of light that occurs on a surface at a certain point in time, is a combination of direct and diffuse irradiation. Direct radiation depends on the position of the sun and the path of the sun plotting a range of angles throughout the day and year. Scattered radiation comes to the surface of the clouds. Insolation refers to the total amount of light energy received at a particular angle during a given period. For the northern hemisphere, the maximum annual photovoltaic power corresponds to a southern orientation and an inclination with respect to the horizontal equal to the latitude of the site[18]. figure 3.14 show the energy generate each day with respect of the irradiance which clearly shows that the irradiance of a sun on the PV panel is between $6\frac{KWh}{m^2 day} - 8\frac{KWh}{m^2 day}$ most of the time. So, this graph show as the strength of the site to generate the electric power. Figure 3.13 shows the performance ratio of the solar power for the site.
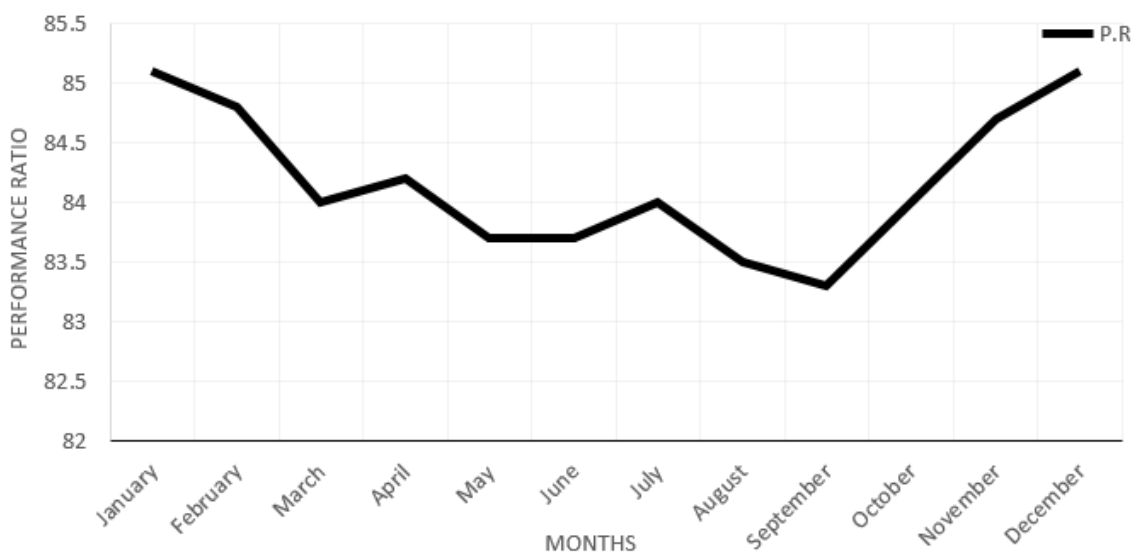
FIGURE 3.13: Performance ratio of the solar PV power system
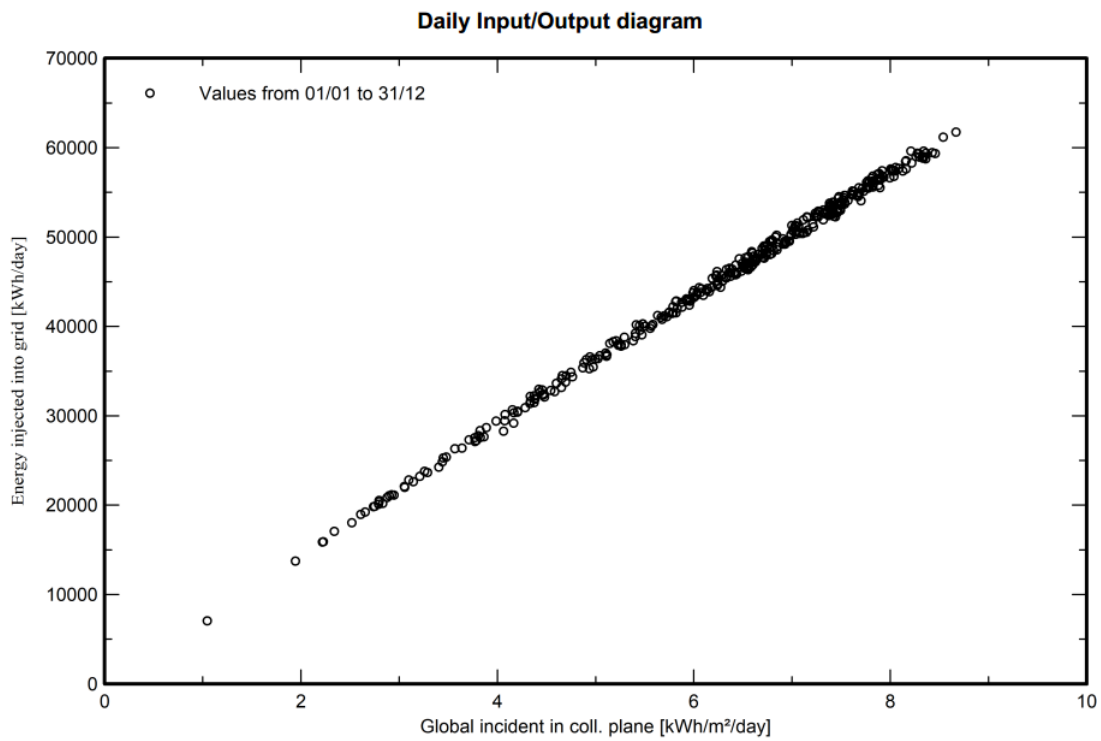
FIGURE 3.14: Daily input/output diagram

For our case the result of the simulation are shown in the table 3.3.

TABLE 3.3: Monthly and yearly result

	GlobHor	DiffHor	$T_{A}mb$	GlobI nc	GlobEff	EArray	$E_{G}rid$	PR %
January	177.3	55.77	21.31	199.4	197.5	1508	1449	85.1
February	177.4	49.40	21.99	192.4	190.4	1450	1394	84.8
March	200.0	62.36	23.60	204.5	202.7	1528	1468	84.0
April	181.3	76.12	24.67	176.8	174.9	1325	1272	84.2
May	195.2	72.9	26.74	182.3	180.0	1359	1303	83.7
June	182.9	71.52	27.58	167.8	165.7	1251	1200	83.7
July	185.2	81.99	27.23	172.7	170.7	1293	1240	84.0
August	184.6	74.65	27.37	177.6	175.9	1322	1268	83.5
September	176.3	59.31	26.06	177.3	175.6	1315	1261	83.3
October	195.7	60.14	24.52	206.7	205.3	1543	1483	84.0
November	186.4	47.52	22.15	207.0	205.7	1557	1498	84.7
December	179.8	49.01	21.53	204.5	203.1	1547	1488	85.1
Year	**2221.9**	**760.71**	**24.58**	**2269.2**	**2247.9**	**16998**	**16325**	**84.2**

Chapter 4

Design the components of Grid Connected Solar PV System

4.1 Solar PV Design

In this section design of the solar PV for 100 KW, by considering the design value is considered for one factory. To design the solar PV for the given value firstly the solar panel will be selected. In this case SunPower X-Series:SPR-X22-360 solar panel were selected for this design because of its efficiency (Table 4.1). PV modules are connected in a series to form strings, which are arranged in parallel rows. In order to conduct an impartial comparison between ground-mounted and rooftop PV systems, both the systems are designed for the same nameplate capacity. For this purpose, first the capacity of rooftop PV is calculated for the available rooftop surface area and then the same sized system is analyzed for the ground-mounted configuration. The desired AC power will be 100KW for our design.

TABLE 4.1: SunPower X-Series:SPR-X22-360

Nominal Power	360 W
Panel Efficiency	22.1%
Rated Voltage(Vmpp)	59.1V
Rated Current(Impp)	6.09 A
Open Circuit Voltage(Voc)	69.5 V
Short Circuit Current (Isc)	6.48 A
Power Temp Coef.	- $0.29\%/^0C$
Voltage Temp Coef.	- $167.4 \, mV/^0C$
Current Temp Coef.	$2.9 \, mA/^oC$
Temperature Operation Condition	- $40 - +85^0C$
Length x Width	1559 mm X 1046 mm
A_a	$1.630714 m^2$

$$Pdc = 100KW$$

To know the Number of panel for the given value

$$N_{module} = \frac{P_{dc}}{P_{each}} \tag{4.1}$$

35

$$N_{module} = \frac{100000}{360}$$

$$N_{module} = 278$$

lets take the panel equal to, $N_{module} = 280$

The panel were arranged by array of 5 series and 56 parallel numbers

$$V_{PV} = V_{MPP} * 5 = 295.5V \tag{4.2}$$

$$I_{PV} = I_{MPP} * 56 = 341A \tag{4.3}$$

The total area covered by the PV panel were calculated as follow ($A_a = 1.630714m^2$):

$$A_t = A_a * N_{module} \tag{4.4}$$

$$Area covered by PV panel = 1.630714m^2 * 280 = 457m^2 \tag{4.5}$$

where A_t is the Total area covered by PV panel, A_aArea each PV panel and $V = N_{module}$ is the number of PV module

4.2 Maximum Power Point Traking

MPPT techniques are employing to extract maximum power irrespective of environmental changes (temperature and pressure). Generally there are two ways of extracting the maximum power from the PV system: one is mechanical tracking and other is electrical tracking. Mechanical tracking consider as physical tracking. In this process the orientation of the PV system is changed according to the changes in the position of sun with some predetermined angle. The changes can also be made for the seasons of a complete year. The orientation changes are made with the help of some manual practice or with some automatic gear type arrangement. In electrical tracking the I-V curve is tracked by using some algorithms. PV parameters (voltage, current, temperature and irradiance) are sensed and fed in to the algorithm as per their requirement. The requisite MPPT technique computes the reference values for different parameters. The computed reference values are compared with the previous values at the converter end. Then, the present power at MPP is compared with the measured value. The differences between these values are minimized by changing the duty ratio of the converter[19]. The maximum power point tracking is the main part of the solar PV system.

It is the most important part in solar PV system which is used to extract the maximum power from the PV array. The output power of the PV array is influenced by solar irradiance and temperature. The most commonly used MPPT algorithms are Perturb and Observe Algorithm and Incremental Conductance Algorithm.

Perturb and Observe Algorithm is based on perturbation of a control variable, which is either the output voltage of PV array, or duty cycle of the DC-DC converter switches. For the first case, a perturbation is applied to output voltage of PV array and a PI controller, consequently, adjusts the duty ratio of the converter. In the case of direct duty cycle control, as the name suggests that a small perturbation is introduced in the duty ratio of DC-DC converter. A major advantage of Perturb and Observe algorithm is that it is simple and easy to implement. In an Incremental Conductance algorithm, the power (product of voltage and current) of PV array is differentiated w.r.t the PV array voltage and set equal to zero, and based on the value of the differential, the actual operating point is found. In this algorithm, unlike perturb and observe, PV array power doesn't have to be computed. This algorithm provides very good transient performance i.e., when atmospheric conditions are changing. Flowchart of Incremental Conductance algorithm is shown in figure 4.1. The basic idea of incremental
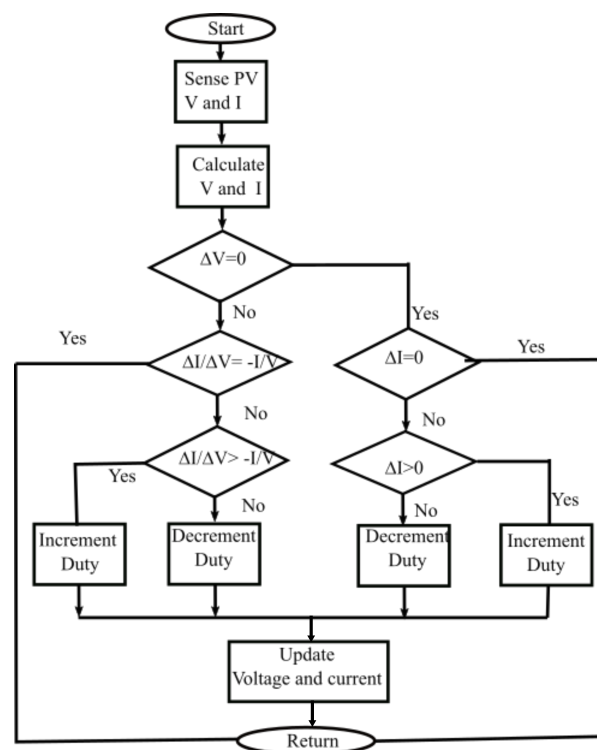

FIGURE 4.1: Incremental Conducting MPPT algorithm

conductance method is that the slope of the power at the MPP with respect to the voltage

equals zero. Also, the power is increasing with the voltage to the left of the MPP, and it is decreasing to the right of the MPP as shown on the figure 4.2. Simply, the slope of P-V characteristics curve is zero at the MPP, positive on the left of the MPP and negative on the right of the MPP [20, 21]. The main function of the MPPT in a PV energy conversion system
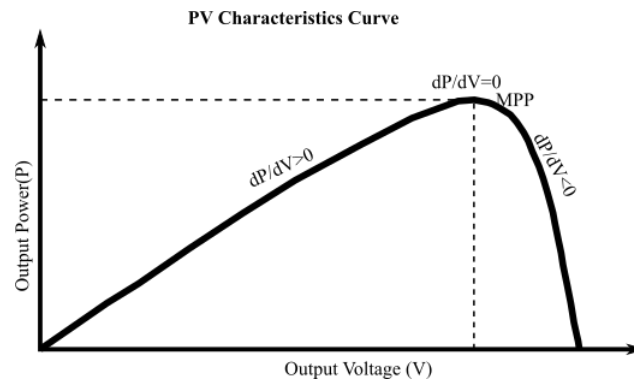
FIGURE 4.2: P-V curve shows Incremental Conducting Methods

is to setting continuously the system so that it extracts maximum power from the solar array in any case of weather or load conditions. Since the solar array has a non-ideal voltage-current characteristics and the conditions such as irradiance, ambient temperature, and wind that affect the output of the solar array are unpredictable, the tracker should deal with a nonlinear and time varying system. The conventional MPPT algorithms are using to obtain the maximum power point. Several algorithms can be used in order to implement the MPPT as follows: perturb & observe, incremental conductance, parasitic capacitance and constant voltage, but only the first two are the most frequently used. The incremental conductance algorithm has been chosen as a MPPT control strategy in this thesis work. This algorithm has advantages compared to perturb and observe as it can determine when the MPPT has reached the MPP, where perturb and observe oscillates around the MPP. The incremental conductance can track rapidly the increase and decrease of irradiance conditions with higher accuracy than perturb and observe. One disadvantage of this algorithm is the increased complexity when compared to perturb & observe. Using figure 4.2, the following equation can be analyzed:

$$\frac{dP}{dV} = 0 \qquad \text{at MPP}$$

$$\frac{dP}{dV} > 0 \qquad \text{at the left side of MPP}$$

$$\frac{dP}{dV} < 0 \qquad \text{at the right side of MPP}$$

The DC-DC converter is controlled by incremental conductance technique in order to achieve the maximum power point (MPP). The incremental conductance method is based on the

observation, the slope of the PV array curve is zero at MPP. In addition to this, the curve is increasing from left of MPP and decreasing from the right of MPP.

4.3 DC-DC Converter Design

$DC - DC$ converter is transform the level of voltage from small value to higher value and the reverse.Its called boost converter when average output voltage is higher than input voltage. Power stage also consists of a switch, diode,capacitor and inductor. Boost converter as shown in Figure 4.3, converts an unregulated source voltage, V_s, from the output of solar into a higher value and regulated load voltage,V_o. Let drive some necessary formula for our
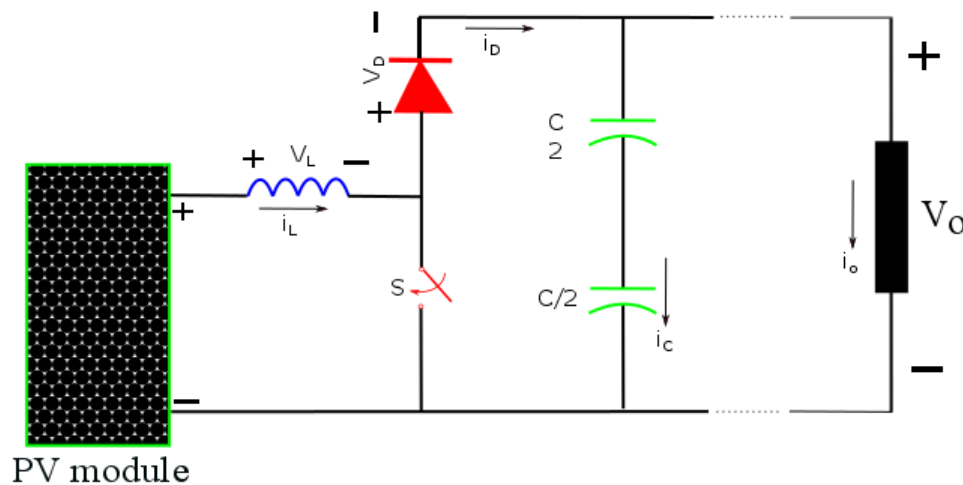
FIGURE 4.3: DC-DC boost converter

discussion. The function of boost converter can be divided into two modes, Mode A and Mode B. Mode A begins when Switch S is switched on at time t=0. The input current rises and flows through inductor L and switch S. Mode B begins when Switch S is switched off at time t=t1. The input current now flows through L, C, load, and diode. The inductor current falls until the next cycle. The energy stored in inductor L flows through the load.

For $0 < t < T_s$ the switch S is off as shown on the figure 4.4 (A) the inductor voltage and capacitor current equation can be derived:

$$V_L = V_P - V_0 \tag{4.6}$$

$$i_c = i_L - \frac{-V}{R} \tag{4.7}$$
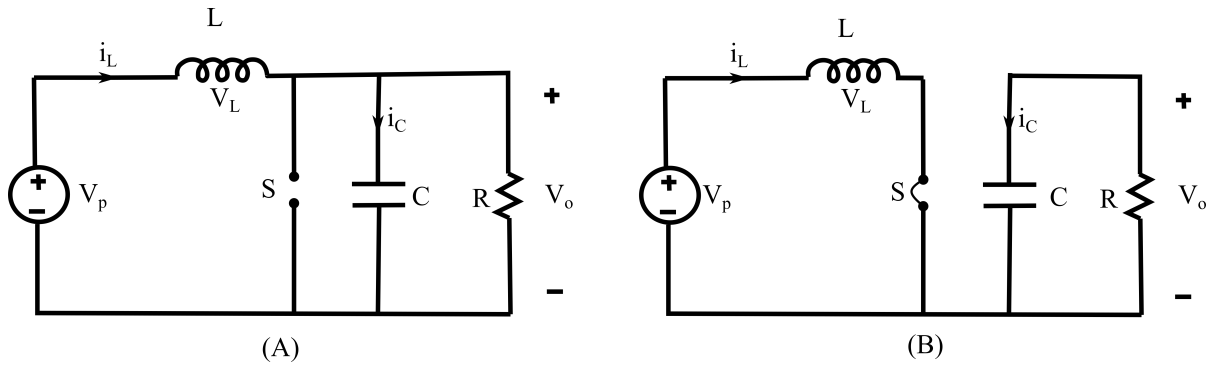
FIGURE 4.4: Circuit topologies in the boost converter

For $DT_s < t < T_s$ the switch S is on as shown in the figure 4.4 (B) the inductor voltage and capacitor current equation can be derived:

$$V_L = V_P \tag{4.8}$$

$$i_c = \frac{-V_0}{R} \tag{4.9}$$

The principle of inductor volt-second balance can now be used. By using the above four equations, the dc component or average value of the inductor voltage is

$$V_L = DV_P + D'(V_P - V_0) \tag{4.10}$$

By take $V_L = 0$ to zero, by considering $D + D' = 0$ and collecting terms, one obtains (4.11)

$$0 = V_P - D'V_0 \tag{4.11}$$

The second equation is obtained using capacitor charge balance. The dc component or average value of the capacitor current is

$$i_C = D\frac{V_0}{R} + D'(I - \frac{V_0}{R}) \tag{4.12}$$

The general formula for boost converter is shows in (4.13)

$$V_o = \frac{V_P}{1 - D} \tag{4.13}$$

where V_o is the out put of boost Converter, V_s is the solar panel output or the input of boost

converter, D is a duty cycle of switch for boost converter. To design the boost converter first we decided the output value, so the out put value is $V_o = 730V$ the PV Array output value is Varies between 301 V and 445 V depending on the value of Temperature 73^0C. If we have the unregulated solar output voltage value (V_P) and the the output Regulated DC voltage value (V_o) then, the duty cycle could be designed as follow.

$$V_s minimum = 301V$$

$$V_s maximum = 445V$$

From (4.13) the duty cycle value can simply calculated by rearranging the formula as follow.

$$D = 1 - \frac{V_s}{V_o} \tag{4.14}$$

By using (4.14) the value of duty cycle become $D_{min} = 0.32$ and $D_{max} = 0.59$ for the maximum and minimum value of source Voltage of boost input. Let design the filter for the boost converter by using the following parameters value

- P_{rate} =100 KW where P_{rate} is the boost rated power

- V_o=730 V where

- [$V_s min, V_s max$]=[301V, 445V]

- D_{min}, D_{max} =[0.39, 0.59]

For inductor current, $I_L = I_s$, where I_L is inductor current and I_s is source current. If we neglect the boost converter loss, the input power is equal to the output power of the converter. as shown in (4.15).

$$V_P I_P = \frac{V_o^2}{R} \tag{4.15}$$

Where R is load resistance. By rearranging the above equation we can get (4.17)

$$V_P I_L = \frac{(\frac{V_P}{1-D})^2}{R} \tag{4.16}$$

$$V_P I_L = \frac{V_P^2}{(1-D)^2 R} \tag{4.17}$$

Average Inductor current,

$$I_L = \frac{V_P}{(1-D)^2 R} \tag{4.18}$$

Inductor current, for I_{Lmax} and I_{Lmin}, Where I_{Lmin} is the minimum inductance current; I_{Lmax} is the maximum inductance current

$$I_L = I_L + \frac{\Delta I_L}{2} \tag{4.19}$$

$$I_{Lmax} = \frac{V_s}{(1-D)^2 R} + \frac{V_s DT}{2L}$$

$$I_{Lmin} = I_L + \frac{\Delta I_L}{2} \tag{4.20}$$

where L is boost inductance value $T = \frac{1}{f_{sw}}$ is the switching period; f_{sw} is 5000 Hz for this design

$$I_{Lmin} = \frac{V_P}{(1-D)^2 R} - \frac{V_s DT}{2L}$$

for CCM and Steady state condition,

$$I_{Lmin} \geq 0$$

$$I_{Lmin} = \frac{V_P}{(1-D)^2 R} - \frac{V_P DT}{2L} \geq 0$$

$$L_{min} = \frac{D(1-D)^2 TR}{2}$$

$$L_{min} = \frac{D(1-D)^2 R}{2f_{sw}} \tag{4.21}$$

To calculate the value of L_{min}(minimum inductance value) the value of R is needed.

$$R = \frac{(V_o)^2}{P_{rate}} \tag{4.22}$$

$$R = \frac{(730)^2}{100000} \tag{4.23}$$

$$R = 5.33\Omega \tag{4.24}$$

By using the above (4.21) can calculated as below. We took the value of D for minimum voltage value. i.e. D=0.54

$$L_{min} = \frac{0.54(1-0.54)^2 * 5.33}{2 * 5000}$$

$$L_{min} = 60.9e - 6H$$

The inductor value is selected L=70 μ H

4.4 Mathematical Modeling of Grid Connected PV Inverter and Controller

4.4.1 Mathematical Modeling of Grid Connected Inverter

In this section we are going to see and design the Grid connected NPC inverter for Dire Dawa industry zone. In a VSI system the active (P) and reactive (Q) powers can be controlled based on two distinct methods. The first approach is schematically illustrated in figure 4.5. In order to design the control system some simplifications can be done. the filter term with the capacitor and damping resistor can be neglected. The dynamics of the full LCL circuit including the specification for a damped resonance will be discussed later. Assume that the
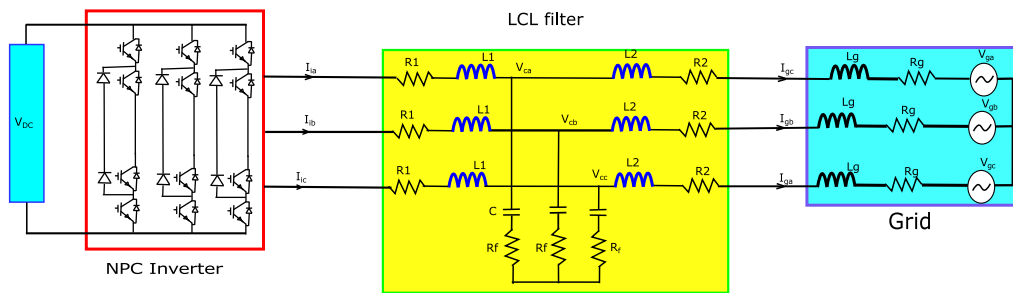
FIGURE 4.5: Three phase NPC inverter

AC system voltage in the VSI system of figure 4.6 is expressed as

$$V_{ga} = V_g sin(\theta) \tag{4.25}$$

$$V_{gb} = V_g sin(\theta - 2\pi/3) \tag{4.26}$$

$$V_{gc} = V_g sin(\theta + 2\pi/3) \tag{4.27}$$

where V_g is the peak value of the line-to-neutral voltage, $\theta = \omega t$, ω_g is the AC grid side frequency. Dynamics of the AC side of voltage source inverter system on figure 4.5 are described by the following differential equations:

$$(L_1 + L_2)\frac{di_g}{dt} = Ri_g + V_i - V_g \tag{4.28}$$

for our three phase system:

$$V_{ia} = (L_1 + L_2)\frac{di_{ga}}{dt} + Ri_{ga} + V_{ga} \tag{4.29}$$

$$V_{ib} = (L_1 + L_2)\frac{di_{gb}}{dt} + Ri_{gb} + V_{gb} \tag{4.30}$$

$$V_{ic} = (L_1 + L_2)\frac{di_{gc}}{dt} + Ri_{gc} + V_{gc} \tag{4.31}$$

or in matrix form Where L_1 is the inverter side inductor and L_2 grid side inductor

$$\frac{d}{dt}\begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} = \frac{1}{L}\begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix} - \frac{R}{L}\begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix} - \frac{1}{L}\begin{bmatrix} V_{ga} \\ V_{gb} \\ V_{gc} \end{bmatrix} \tag{4.32}$$

For simplicity, it is considered that $L = L_1 + L_2 + L_g$, $R = R_1 + R_2 + R_g$, where R_1 and R_2 resistances of first and second inductor respectively. where i_{ga}, i_{gb} and i_{gc} a grid 3 phase current and V_{ia}, V_{ib} and V_{ic} inverter voltage where V_{ga}, V_{gb} and V_{gc} grid voltage.
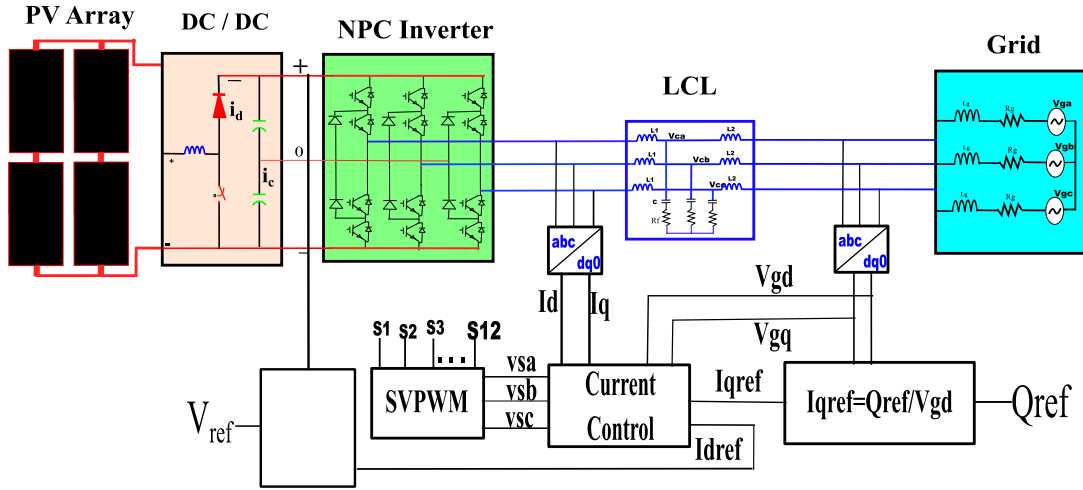
FIGURE 4.6: Power controller of grid connected NPC inverter

A common and often adopted approach in analyzing three-phase systems is to use a stationary or rotating frame. In fact the *dq* frame is synchronized with the angular speed ωt. It should be noted that the particular feature of the *dq* frame is that if a space vector with constant magnitude rotates at the same speed of the frame, it has constant *d* and *q* components while if it rotates at a different speed it has a time-variable magnitude (pulsating components). In the *dq* frame, differential equations for the current are dependent due to the cross-coupling terms $\omega_g I_{gd}$ and $\omega_g I_{gq}$ equations also have feed forward terms V_{gd} and V_{gq}.

$$\begin{bmatrix} V_{id} \\ V_{iq} \end{bmatrix} = R\begin{bmatrix} I_{gd} \\ I_{gq} \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} I_{gd} \\ I_{gq} \end{bmatrix} + L\omega_g\begin{bmatrix} -I_{gq} \\ I_{gd} \end{bmatrix} + \begin{bmatrix} V_{gd} \\ V_{gq} \end{bmatrix} \tag{4.33}$$

where I_{gd} and I_{gq} a grid dq form current and V_{id} and V_{iq} inverter voltage in dq form. where V_{gd} and V_{gq} a grid dq form voltage.

4.4.2   PQ controller for Three Phase NPC Inverter

The power control of the grid inverter is based on the *dq*-frame power theory and as a consequence on the definition of the power in a reference frame. Typically the voltage oriented control is based on the use of a *dq* frame rotating at ω_g speed and oriented such that the *d* axis is aligned on the grid voltage vector. The space vector of the fundamental harmonic has constant components in the *dq* frame while the other harmonics space vectors have pulsating components. The main purpose of the grid inverter is to generate or to absorb sinusoidal currents; thus the currents reference components in the *dq* frame are DC quantities.The reference current component i_d^* is controlled to manage the active power control; while the reference current component $i_q^* S$ controls the reactive power exchange and it is typically used to impress a desired power factor: The control scheme for the NPC inverter is applied in the synchronously rotating reference frame. The active and reactive power can be calculated using (4.34) and (4.35).

$$P_{dq} = \frac{3}{2}(V_d I_d + V_q I_q) \tag{4.34}$$

$$Q_{dq} = \frac{3}{2}(-V_d I_q + V_q I_d) \tag{4.35}$$

Assuming that the *d* axis is perfectly aligned with the grid voltage $V_q g = 0$, the active power and the reactive power will therefore be proportional to i_d and i_q respectively. The converter can be operated at unity power factor by setting the reference value of d-axis current to be zero. After decoupling Vd and Vq are transformed back into "*abc*" co-ordinates and these are used as the three reference wave-forms for the space vector PWM scheme

$$P_{dq} = \frac{3}{2}V_d I_d \tag{4.36}$$

$$Q_{dq} = -\frac{3}{2}V_d I_q \tag{4.37}$$

When we use solar power, we should utilize the maximum power which is DC power or we can called active power only. So we don't need to control the active power for PV instead we need to control only MPPT. The power PV module is depend on the irradiation and temperature directly.

PV is a DC power source. In this case, there is no reactive power associated with PV itself. When a PV is connected to a load via a dc/dc converter, the voltage and current of the PV can be changed by the converter, by this way active power can be control. The ideal case will be to draw out the maximum active power from the case, and such control will be known as MPPT. A DC/DC converter cannot inject or absorb any reactive power. Reactive power is a concept unique in AC power system. When an inverter is used, the reactive power can be injected into the grid by varying the magnitude and angle of the inverter voltage. Reactive power can be controlled by controlling the q-axis current. In a two stage system, PV panel is connected first to a DC/DC converter, then to an inverter. The DC/DC converter will perform the MPPT task to extract maximum active power from the PV. The inverter on the other hand still control the active and reactive power. However, in this case, the inverter is not doing the MPPT, but only injecting active power to the grid when controlling d-axis current to maintain a fixed DC-link voltage. At the same time, q-axis current is controlled to vary the reactive power. In this structure, the DC-link voltage of the inverter is maintained at a constant value all the time.

Let as discuss and model mathematically for each block of the figure 4.7 step by step. It has been discussed that the relationship between power and current in *dq* frame when the *d* frame is allied with *a* axis in the previous section so simply by controlling the current we can control the power. The *d* and *q* control loops have the same dynamics (in ideal case of DC values), so the tuning of the PI controller for the current is done only for the *d* axis. For the axis the parameters are assumed to be the same. As it can be seen from the current control block diagram, the voltage feed forward and the decoupling between the *d* and *q* axes has been neglected as they are considered as disturbances. So, as we observe in the following figure 4.7 the transfer function of the grid connected inverter could be.
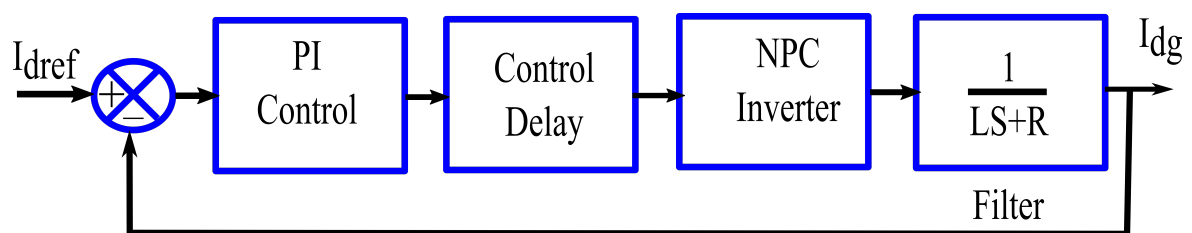
FIGURE 4.7: NPC grid connected inverter transfer function block diagram

The NPC inverter is modeled using its gain and delay time which is equal to 50 percent of time period of the carrier signal. Ts is the time period of LCL.

- Inverter transfer function can be expressed as below in the (4.38)

$$G_{inverter} = \frac{K_{PWM}}{1 + 0.5ST_{sw}} \tag{4.38}$$

where $T_{sw} = \frac{1}{f_{sw}}$ - switching period.

- Delay time of the controller can take as in the (4.39)

$$G_{delay} = \frac{1}{ST_s} \tag{4.39}$$

where $T_s = \frac{1}{f_s}$ -sampling time for the control system

- Current controller in PI form can express in the (4.40)

$$G_{pi} = K_p + \frac{K_i}{S} \tag{4.40}$$

- filter can express as below

$$G_{filter} = \frac{1}{LS + R} \tag{4.41}$$

Generally, the inverter current controller can have expressed as below first of all let multiply delay time and inverter transfer function

$$G_{c1} = G_{delay} * G_{inverter} \tag{4.42}$$

$$G_{c1} = \frac{K_{PWM}}{1 + 0.5ST_{sw}} \frac{1}{1 + ST_s} \tag{4.43}$$

$$G_{cl} = \frac{K_{PWM}}{1 + ST_i} \tag{4.44}$$

$$\tag{4.45}$$

where $T_i = 0.5T_{sw} + T_s$

$$G(s) = G_{pi} * G_{c1} * G_{filter} \tag{4.46}$$

$$G(s) = (K_p + \frac{K_i}{S})(\frac{K_{PWM}}{1 + ST_i})(\frac{K_f}{ST_f + 1}) \tag{4.47}$$

where K_f is $\frac{1}{R}$ and T_f is $\frac{L}{R}$

T_f and T_i are time values so we can write the above equation in the following form, where $T_t = T_f + T_i$ and $K = K_{PWM} + K_f$

$$G(s) = (K_p + \frac{K_i}{S})(\frac{K}{1 + ST_t}) \tag{4.48}$$

The proposed control technique has the purpose to control the active power injection and reactive power compensation for low voltage grids. For minimizing the order of the control system the Power loop gives the current reference for the first filter inductor, and finally, with this current loop the three-phase modulation is obtained. So, the whole control system is performed by a power and current control loops.

4.4.3 LCL Filter Modeling and Design

Some important constraints must be taken in consideration in the design of LCL filters, such as current ripple, filter size, switching ripple attenuation The reactive power variation seen by the grid because of the capacitor may gave a resonance that could lead to unstable operation of the system.

A LCL filter is more efficient than a simple inductor (L) because the latter has only attenuation of 20 dB/decade for all the range of frequency [22]. The switching frequency of inverter must be high enough for a correct attenuation of high current harmonics. The higher the switching frequency there are more losses. LC filters suffer from variability of resonance frequency over time like the grid inductance. Therefore, they are not appropriate for a weak grid. The following mathematical model can be used for the analysis of a LCL filter.The LCL
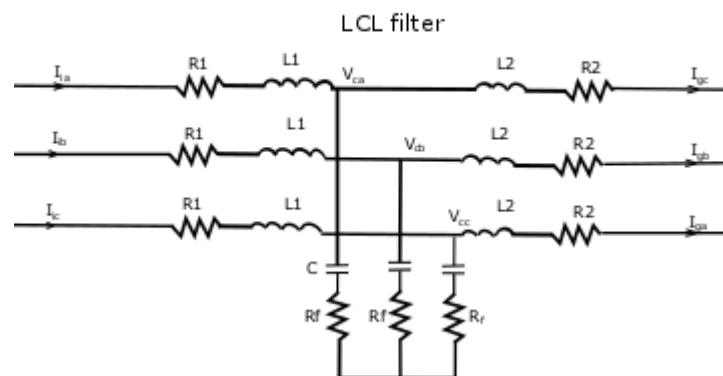

FIGURE 4.8: LCL filter

filter per-phase model is shown in figure 4.10, where L_1 is the inverter-side inductor,L_2 is the

grid-side inductor, C_f is the capacitor of LCL filter, R_f is the damping resistor, R_1 and R_2 are inductors resistances, V_i and V_g are inverter input and grid voltages.
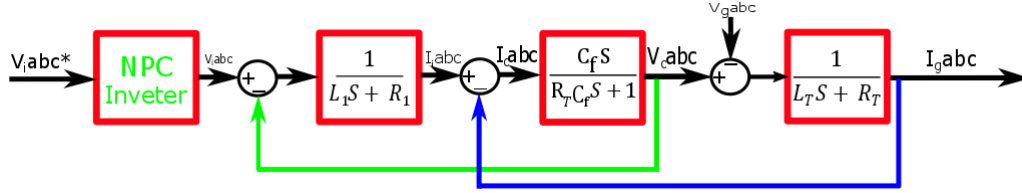
FIGURE 4.9: Filter transfer function
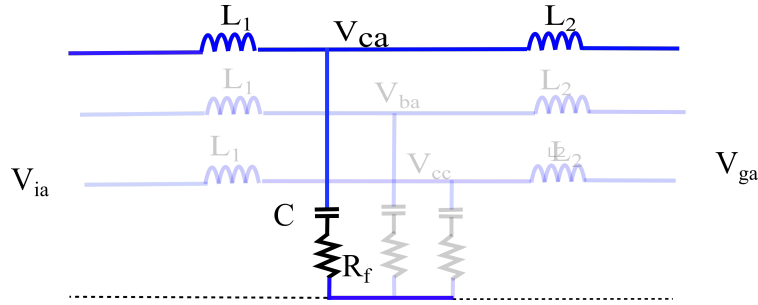
FIGURE 4.10: LCL filter for balanced three phase of phase "a"

The transfer function between grid current and inverter output voltage in stationary reference frame is shown as

$$\frac{dV_c}{dt} = \frac{(I_i - I_g)}{C_f} \tag{4.49}$$

$$\frac{dI_i}{dt} = \frac{1}{L_1}(V_i - V_c - R_f(I_i - I_g) - R_1 I_i) \tag{4.50}$$

$$\frac{dI_g}{dt} = \frac{1}{L_2}(V_c + R_f(I_i - I_g) - V_g - R_2 I_g) \tag{4.51}$$

where V_i inverter voltage, V_c filter capacitor voltage and V_g grid voltage and the rest is shown on the figure 4.10. After some manipulation of (4.49), (4.50) and (4.51) the final value will be

$$\frac{I_g(s)}{V_i(s)} = \frac{1}{L_T S} \frac{Z_{LCg}^2 (R_f C_f S + 1)}{S^2 + R_d C_f \omega_{reg}^2 S + \omega_{reg}^2} \tag{4.52}$$

$$Z_{LCg}^2 = \frac{1}{L_T C_f}$$

$$\omega_{reg}^2 = \frac{L_1 + L_T}{L_1 L_T C_f}$$

From the developed mathematical models, transfer functions of LCL filter can be derived. transfer functions are derived based on the three phase differential equations derived earlier,

but in these equations the inductors resistances are not considered. One of the extracted transfer function from derived state space equations is, $H_{LCL}(s) = \frac{I_g(s)}{V_i(s)}$. The grid voltage is assumed to be an ideal voltage source and it represents a short circuit for harmonic frequencies, and for the filter analysis is set to zero: $V_g = 0$. So,the transfer function of LCL filter without damping is:

$$H_{LCL}(s) = \frac{1}{L_1 L_T C_f S^3 + (L_1 + L_T)S} \tag{4.53}$$

$$H_{LCL}(s) = \frac{L_1 L_T C_f S + 1}{L_1 L_T C_f S^3 + C_f(L_1 + L_2)R_f S^2 + (L_1 + L_T)S} \tag{4.54}$$

The filter design approach has been explained step-by-step in the following subsection.

4.4.3.1   Design LCL filter

The procedure for choosing the LCL filter parameters requires the power rating of the converter, the grid frequency, and the switching frequency as inputs. The following parameters are needed for the filter design:

TABLE 4.2: Three phase grid connected inverter parameters

Grid		Inverter	
V_{ll}	380	$P_r(KW)$	100
$f_g(Hz)$	50	$f_{sw}(KHz)$	10
$R_g(ohm)$	0.001	V_{DC}	730
$L_g(H)$	0.001	V_{ph}	220
THD_g	< 5%	f_{res}	

- V_{ll}- line to line RMS voltage (inverter output)

- V_{ph}-phase voltage (inverter output)

- P_r- rated active power

- V_{DC} - DC bus voltage

- f_g-grid frequency,

- f_{sw}-switching frequency,

- f_{res}-resonance frequency.

The base impedance and base capacitance are defined below. Thus, the filter values will be referred in percent of the base values:

$$Z_b = \frac{V_{ll}^2}{P_r} \tag{4.55}$$

$$= \frac{380^2}{100000} \tag{4.56}$$

$$= 1.44\Omega \tag{4.57}$$

$$C_b = \frac{1}{\omega_n Z_b} \tag{4.58}$$

$$= \frac{1}{314.159 * 1.44} \tag{4.59}$$

$$= 2.2104 * 10^{-3} F \tag{4.60}$$

For the design of the filter capacitance, it is considered that the maximum power factor variation seen by the grid is 5%, as it is multiplied by the value of base impedance(Z_b) of the system:

$$C_f = 0.05 C_b$$

$$C_f = 110.2 \mu F$$

It is important to notice that factors higher than 5% can be used, since they will compensate the inductive reactance of the inductors on the filter and therefore the influence at the power factor of the system will be lesser than expected. The maximum current ripple(ΔI_{Lmax}) at the output of DC/AC inverter is [23]:

$$\Delta I_{Lmax} = \frac{2V_D C}{3L_1}(1-m)mT_{sw} \tag{4.61}$$

where,m - modulation factor. it can be observed that maximum peak to peak current ripple happens at $m = 0.5$, then

$$\Delta I_{Lmax} = \frac{V_D C}{6L_1 f_{sw}} \tag{4.62}$$

where L_1 inverter side inductor. A 10% ripple of the rated current(I_{Lmax}) for the design parameters is given by

$$\Delta I_{Lmax} = 0.1 I_{Lmax} \tag{4.63}$$

where :- $I_{Lmax} = \frac{P_r \sqrt{2}}{3V_{ph}}$

$$L_1 = \frac{V_{DC}}{6f_{sw}\Delta I_{Lmax}} \tag{4.64}$$

or simply the general formula could written as to calculate L_1 in the following steps.[23]

$$L_b = \frac{V_{ll}^2}{2\pi f_{grd}P_r}$$

$$= 4.58mH$$

$$L_1 = \frac{f_{grd}}{f_{sw}} \frac{L_b}{THD_i} \sqrt{\frac{\pi^2}{18}(\frac{3}{2} - \frac{4\sqrt{3}}{\pi}m + \frac{9}{8}m^2)}$$

where m=0.5 for this design.

$$L_1 = \frac{50}{10000} * \frac{0.046}{0.07} * \sqrt{0.37208}$$

$$= 0.2mH$$

THD_i is normally chosen to be between 5%- 15%, and for this study, was selected to be 7%. The grid-side inductance, L_2 is calculated as (4.65) and is dependent on a chosen RAF_{sw}, which is the ratio of grid current to inverter output current at the switching frequency.

$$L_2 = \frac{(RAF_{sw})^{-1}}{4\pi^2 f_{sw}^2 C_f} \tag{4.65}$$

RAF_{sw} is typically between 10% and 30% and is chosen to be 15% in this study. With the value of C_f calculated above, the resulting.

$$L_2 = \frac{1}{0.15 * 4 * (\pi)^2 * (10000)^2 * 110.2 * 10^{-6}} \tag{4.66}$$

$$L_2 = 15.32\mu H \tag{4.67}$$

The main objective of the LCL filter design is in fact to reduce the expected 10% current ripple limit to 20% of its own value,resulting in a ripple value of 2% of the output current [23]. In order to calculate the ripple reduction, the LCL filter equivalent circuit is firstly analyzed considering the inverter as a current source for each harmonic frequency

$$\omega_{res} = \sqrt{\frac{L_1 + L_2}{L_1 L_2 C_f}} \tag{4.68}$$

$$\omega_{res} = \sqrt{\frac{0.0002 + 15.32 * 10^{-6}}{0.0002 * 15.32 * 10^{-6} * 110.2 * 10^{-6}}}$$

$$\omega_{res} = 25252.65$$

$$f_{res} = 4019.08 Hz$$

It is necessary to check resonant frequency to satisfy Equation below. If it does not, the parameters should be re-chosen.

$$10 f_g < f_{res} < 0.5 f_{sw} \tag{4.69}$$

The value of f_{res} is satisfy the (4.69).

$$R_f = \frac{1}{3\omega_{res} C_f} \tag{4.70}$$

$$R_f = 0.1198\Omega$$

4.4.4   Three Level Space Vector PWM

There are many Modulations strategy that can used for three phase inverters. The most efficient method of controlling the output voltage is to incorporate pulse width- modulation (PWM) control within the inverters. The commonly used techniques are

- Multiple-pulse-width modulation

- Sinusoidal pulse-width modulation

- Space Vector Modulation (SVM)

From the above-mentioned method, space vector modulation has the ability to minimize the harmonics and have better efficiency than other methods. For a given magnitude (length) and position, V_{ref} can be synthesized by three nearby stationary vectors, based on which the switching states of the inverter can be selected and gate signals for the active switches can be generated. When V_{ref} passes through sectors one by one, different sets of switches will be turned on or off. As a result, when V_{ref} rotates one revolution in space, the inverter output

voltage varies one cycle over time. The inverter output frequency corresponds to the rotating speed of V_{ref}, while its output voltage can be adjusted by the magnitude of V_{ref}. For a three-level three-phase inverter there are 27 switching states. These states represent the connection to the different DC-link points. If there is a load connected to the output of these states the inverter will generate an output phase voltage. This can be calculated as follows:

$$V_{a0} = (2S_{1a} - S_{1b} - S_{1c}) + (2S_{2a} - S_{2b} - S_{2c}) \tag{4.71}$$

$$V_{b0} = (2S_{1b} - S_{1a} - S_{1c}) + (2S_{2b} - S_{2a} - S_{2c}) \tag{4.72}$$

$$V_{c0} = (2S_{1c} - S_{1b} - S_{1a}) + (2S_{2c} - S_{2b} - S_{2a}) \tag{4.73}$$

These are the line-to-neutral voltages, to receive the line-to-line voltage:

$$V_{ab} = V_{a0} - V_{b0} \tag{4.74}$$

$$V_{bc} = V_{b0} - V_{c0} \tag{4.75}$$

$$V_{ac} = V_{c0} - V_{a0} \tag{4.76}$$

There is requested to generate five levels of outputs, so the three-level can be created. These levels V are $2V_{DC}$, V_{DC}, 0, $-V_{DC}$ and $-2V_{DC}$ (for the line-to-line voltage). As for the two-
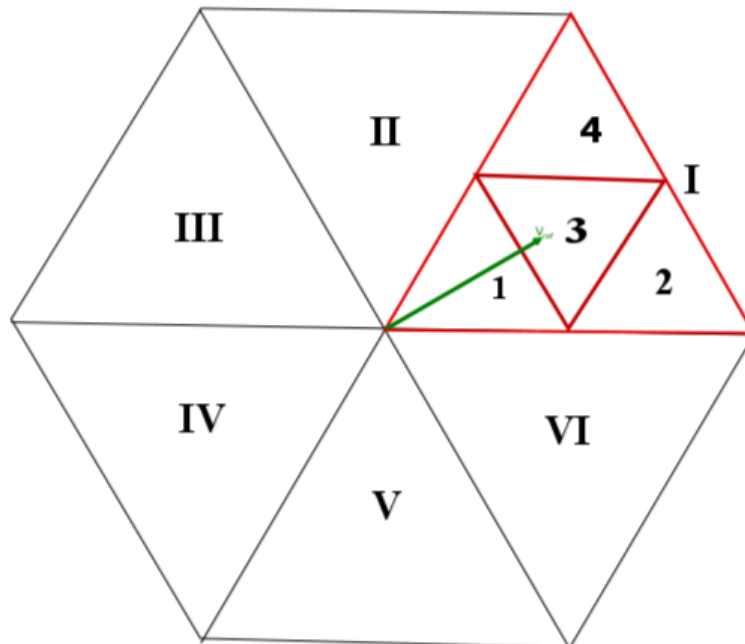

FIGURE 4.11: Sector of space vector

level inverter the reference vector is given with the help from three voltage vectors. For the

three-level converter each sector also is divided into 4 regions, specifying the output even more. Based on the magnitude the voltage vectors can be defined as:
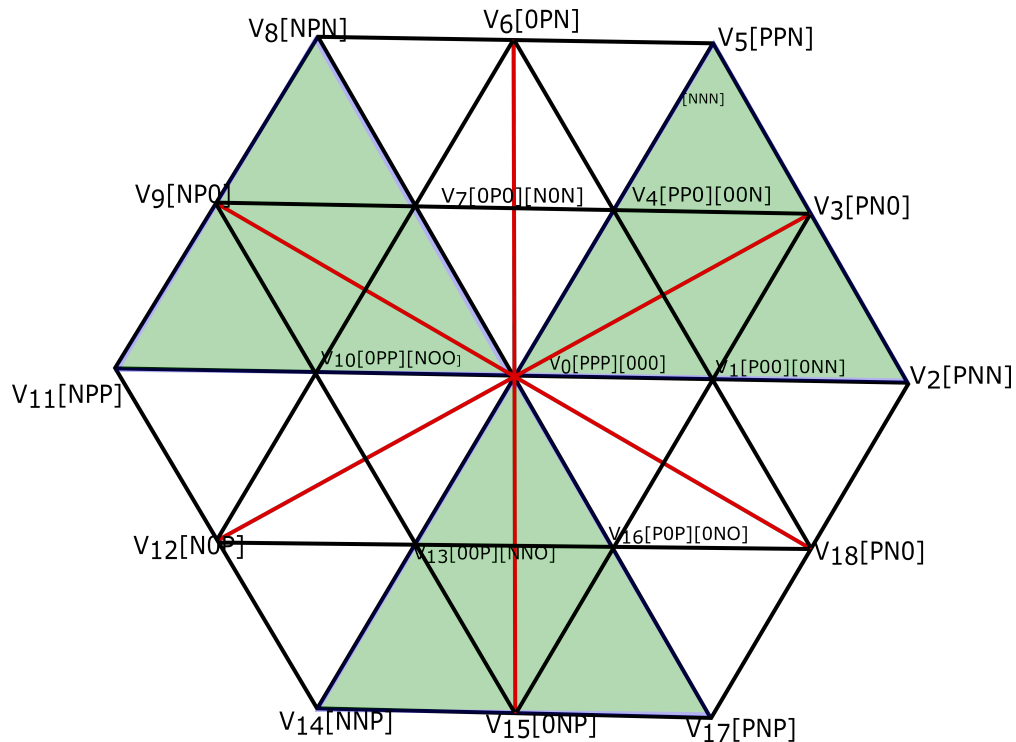
FIGURE 4.12: 3 Level SVPWM sectors with region

- Zero Voltage Vectors (ZVV): V=0 (redundant switch states)

- Small Voltage Vectors (SVV): V1, 4, 7,10,13,16 (redundant switch states)

- Medium Voltage Vectors (MVV): V3, 6, 9,12,15,18

- Large Voltage Vectors (LVV): V2, 5, 8,11,14,17

4.4.4.1 Grid Synchronization by PLL

The grid connected inverter can be synchronized with the grid by means of a PLL (Phase-locked loop). The phase of the output signal of the PLL is synchronized to the phase of its input signal. That is, it keeps the output signal synchronize with its reference input signal in phase and frequency. In a three-phase grid connected system, PLL is implemented using the clarke and Park transformations along with loop filters. The grid voltage Vgabc is converted in to rotating reference frame using the concept of different transformation methods. The

PLL gets locked by setting Vd* to be zero. The voltage-controlled oscillator acts as an integrator, whose input will be fed from the PI controller. The output frequency of the controller will be integrated to get the phase angle of the inverter.

4.4.4.2 Determining the Sector

α is calculated and then the sector, in which the command vector V* is located, is determined as;

If α is between $0^o \leqslant \alpha < 60^o$, then V^* will be in Sector A,

If α is between $60^o \leqslant \alpha < 120^o$, then V^* will be in Sector B,

If α is between $120^o \leqslant \alpha < 180^o$, then V^* will be in Sector C,

If α is between $180^o \leqslant \alpha < 240^o$, then V^* will be in Sector D,

If α is between $240^o \leqslant \alpha < 300^o$, then V^* will be in Sector E,

If α is between $300^o \leqslant \alpha < 360^o$, then V^* will be in Sector F.

4.4.4.3 Determining the Region in the Sector

The region selection is done as in [24]. The regions are given as: For that;

- If m_1, m_2 and $(m_1 + m_2) < 0.5$, then V^* is in Region 1,

- If $m_1 > 0.5$, then V^* is in Region 2,

- If $m_2 > 0.5$, then V^* is in Region 3,

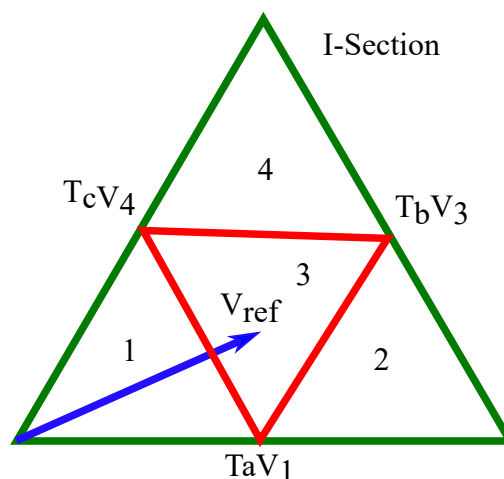- If m_1 and $m_2 < 0.5$ and $(m_1 + m_2) > 0.5$, then V^* is in Region 4.

FIGURE 4.13: Region 1 of three level SVPWM

4.4.4.4   Time Duration

To describe the reference voltage vector V_{ref}, the space vector transformations comes in hand:

$$V_{ref} = \frac{2}{3}(V_{a0} + V_{b0} * e^{(\frac{j2}{3}\pi)} + V_{c0}e^{(\frac{-j2}{3}\pi)}) \tag{4.77}$$

$$V_{ref} = Ve^{j(\omega_0 t - \gamma_0)} = V\angle\theta_0 \tag{4.78}$$

V_{ref} can be described with the three nearest voltage space vectors. This selection is based on the magnitude of the V_{ref} and its angle. For one cycle:

$$V_{ref} = T_1 V_x + T_2 V_y + T_3 V_z$$

T_a, T_b and T_c for Sector 1, Region 3 see figure 4.13. If V_2 is chosen as the reference axis (maximum magnitude as units) the voltage vectors on the axis can be described as:

$$V_x = V_1 = 1/2 \tag{4.79}$$

$$V_y = V_3 = \sqrt{\frac{3}{2}}e^{(\frac{\pi}{6})} \tag{4.80}$$

$$V_z = V_4 = 1/2 * e^{(\frac{\pi}{3})} \tag{4.81}$$

And the reference vector as :

$$V_{ref} = V_u e^{j\theta}$$

where $V_u = \frac{4}{3}V_{DC}$ V_{ref} in forms of the real and imaginary axis:

$$V_u(cos(\theta) + sin(\theta)) = 1/2T_1 + \sqrt{\frac{3}{2}}[cos(\frac{\pi}{6}) + jsin(\frac{\pi}{6})]T_2 + 1/2[cos(\frac{\pi}{3}) + jsin(\frac{\pi}{3})]T_3$$

Dividing the formula in real and imaginary part eases the calculations for the duty cycles:

Real part $1/2T_1 + \sqrt{\frac{3}{2}}cos(\frac{\pi}{6})T_2 + 1/2cos(\frac{\pi}{3}))T_3$

Imaginary Part $\frac{\sqrt{3}}{2}sin(\frac{\pi}{6})T_2 + 1/2 * sin(\frac{\pi}{3})) * T_3$

The duty cycles are then given in form of:

$$T_1 = 1 - 2(\frac{2}{\sqrt{3}}V_u)sin(\theta) \tag{4.82}$$

$$T_2 = (2(\frac{2}{\sqrt{3}}V_u)sin(\theta + \pi/3)) - 1 \tag{4.83}$$

$$T_3 = (2(\frac{2}{\sqrt{3}}V_u)sin(\theta - \pi/3)) + 1 \tag{4.84}$$

where :- $\alpha = \frac{2}{\sqrt{3}}V_u$

$$T_1 = 1 - (2\alpha sin(\theta)) \tag{4.85}$$

$$T_2 = (2\alpha sin(\theta + \pi/3)) - 1 \tag{4.86}$$

$$T_3 = (2\alpha sin(\alpha - \pi/3)) + 1 \tag{4.87}$$

In similar way the calculations for every sector and region can be calculated. Appendix C: 6.2 shows the Matlab code. Having the duration time for the vectors will give information about the duty cycle for each switch.

4.5 Inverter and Power Factor

The Grid connected Inverter can improve the power factor the factories. the following analysis will show how inverter can improve the power factror of the system. To show how the grid connected inverter can improve the the grid power factor let consider 15 KV bus connected inverter by the use of transformer. The inverter is near to the load so, we can use the following figure 4.14.
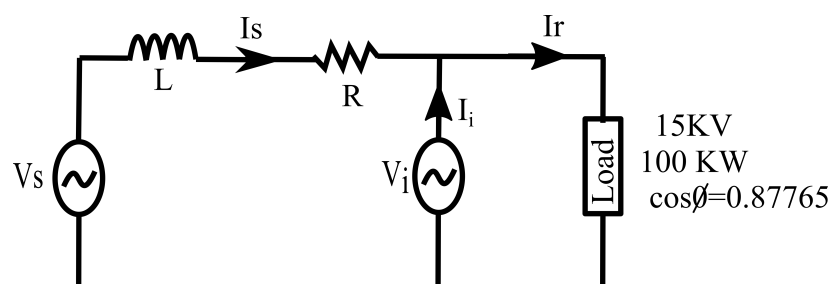

FIGURE 4.14: Inverter to improve PF

Inverter output Power is $Q_i = 40KVAR$, $P_r = 100KW$, $pf = 0.87765$

$$V_i = 15KV \tag{4.88}$$

$$I_i = \frac{0 + j40000}{15000 + j0} = 2.67\angle 90 \tag{4.89}$$

$$I_i = 0 + j2.67 \tag{4.90}$$

$$I_r = \frac{KW * 10^3}{V_r * cos\phi} \tag{4.91}$$

$$I_r = 6.67 - j3.64 \tag{4.92}$$

$$I_s = I_i + I_r \tag{4.93}$$

$$I_s = 6.67 - j0.97 = 6.74\angle - 8.27 \tag{4.94}$$

Voltage drop on the line by using AAC-50 for 7 KM.

$$Z = 4.872 + j3.625 = 6.07264\angle 38.651 \tag{4.95}$$

$$V_d = I_s * Z \tag{4.96}$$

$$V_d = 36.014 + j19.448 = 40.93\angle 28.37 \tag{4.97}$$

Sending voltage can calculated as below.

$$V_s = V_d + V_r$$

$$V_s = 15036 + j19.448 = 15036\angle 0.0741$$

Sending end power factor will be

$$phi = 0.0741 - (-8.2744) = 8.3485 \tag{4.98}$$

$$cos\phi = 0.9894 \tag{4.99}$$

Chapter 5

Result and Discussion

In this chapter the result of survey in chapter section 3.1, PVsyst simulation result in chapter section 3.2 and Matlab/Simulink study in chapter section 5.3 were discussed

5.1 PVsyst Simulation Result

Total area of rooftop is 38710 m^2 as discussed in chapter 3 which is used in the solar PV system on PVsyst. When we use this area to install the solar panel(i.e. Sunpower SPR-X22-360) we can generate the power of 8545 KWp DC power By using inverter(Dasstech 100KW) 8100 power can generate. The annual energy generated by grid connected rooftop solar PV system become 16325 MWh per year with 84.2% performance ratio. In PVsyst design using the optimal roof inclined and direction, by considering all roof area directed to the optimal orientation we can get the following result. The the whole simulation result is shown under appendix D: 6.2.

- The P$_{dc}$ is 8545 KWp

- The P_{AC} is 8100 KWac

- total Panel number is 23735, by the array of [5 x 4747]

- The total inverter is 81 each of 100KW.

- The parformance ration of the system is 84.2

- The total cost 320 Million

The figure 5.1 shows the the energy versus power injected into the grid.

5.2 Comparison of Ground Mounted and Rooftop Solar PV System

5.2.1 Economic Comparison

PVsyst software offers a tool used for economic evaluation of the system on the basis of the defined parameters and the simulation results. The procedure for the economic evaluation
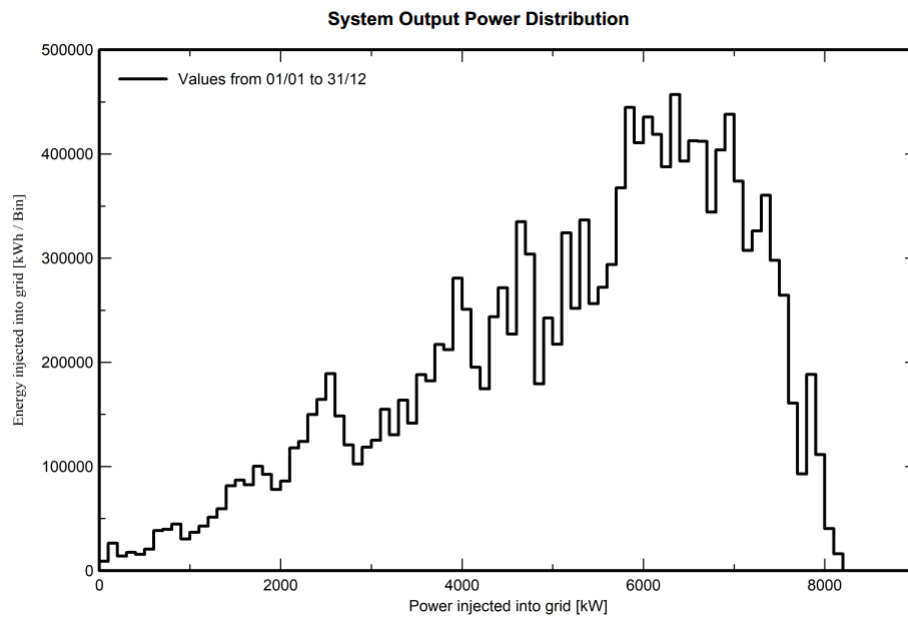
60

FIGURE 5.1: Grid injected power by PVsyst simulator

is described below. The first step was calculation of the investment. The number and type of system components (PV modules, inverters, etc.) were automatically updated from the simulation. After defining the component prices, PVsyst calculated the gross investment excluding taxes. The net investment, for the owner is the gross investment plus a tax percentage (VAT). However, for this study, the VAT was assumed to be zero. Following that, values for loan duration and interest rate were chosen and the software computed the annual financial cost, assuming the loan pay back as constant annuities. PVsyst takes the loan duration to be the expected lifetime of the system. This procedure is justified by the fact that, when purchasing a solar equipment the customer buys at a time the value of the whole energy consumed during the exploitation. The expected lifetime of the system was taken as 25 years. Figure 5.2 is show the cost breakdown of the Dire Dawa industry zone investment. Under this subsection the comparison of the cost between ground mounted PV system and Rooftop PV system will analyze. To make this comparison we need to take some consideration.

In case of rooftop PV system:-   all roof area were used for installing the solar panel only.

- Inverter and other accessories were installed in the factories power controlling house.

- No need of additional electrical engineer to operate and maintain the PV system, because each factories already have their own operator.

- No need of additional security guard for solar PV system.

- No additional transformer, the solar System connected to existing transformer.

- No additional cleaner

- installing cost is grater than ground mounted PV system

In case of Ground-mounted PV system:-

- Need land to install PV panel, Inverter and other accessories.

- Need of additional electrical engineer to operate and maintain the PV system.

- Need of additional security for PV system.

- Need additional transformer.

- Need transmission line

In the figure 5.2 (the left side) is show rooftop PV system cash flow with respect of years, the payback period for the investment is 5.6 year. The total ivestimant cost for rooftop PV system is 320 million Ethiopian Birr to generate $16325\frac{MWh}{Year}$ and levelized cost of energy(LCOE) is 0.99 $\frac{ETB}{KWh}$. The second Figure 5.2 (the right side) shows the Ground mounted PV system cash flow with respect of year, the payback period for the investment is 6 year. The total investment cost of ground mounted solar PV system is 338 million Ethiopian Birr to generate the same amount of energy and levelized cost of energy(LCOE) is 1.08 $\frac{ETB}{KWh}$. By considering the tariff in cost is equal to 3.5 $\frac{ETB}{KWh}$ or 0.09 $\frac{\$}{KWh}$ [25, 26].

5.2.2 Transmission line loss comparison

Comparison were done by considering the DC wiring loss and AC loss before Transformer of both system were equal. Secondly, the rooftop mounted PV system were connected to grid by using the factor's transformer. That means each factories have their own transformer in their factory, so their is no need of additional transmission line in this case. But in ground mounted PV system, assume the land were 1KM, 2KM, 5KM, and 10KM far from that Dire Dawa industry zone. The transmission line rated voltage were selected to be 15KV. For
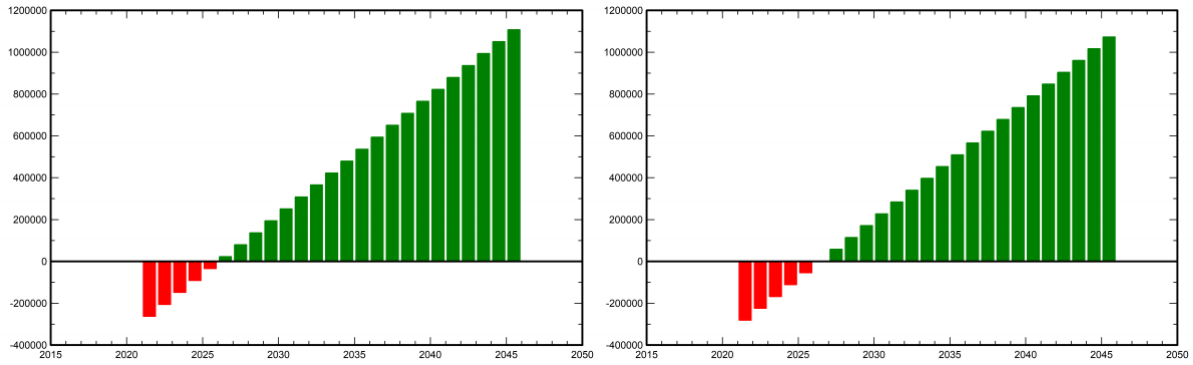
FIGURE 5.2: Cummulative cash flow comparison Ground Mounted and rooftop Solar PV system

transmission line the $AAC - 50$ wire were selected. The following calculation were discussed based on those values.

$$P_{ac} = 8000KW \tag{5.1}$$

$$V_{ll}rms = 15KV \tag{5.2}$$

$$R_{AAC50} = 0.6961\frac{\Omega}{KM} \tag{5.3}$$

$$\tag{5.4}$$

Transmission line loss can calculated by using equation (5.5) as below and where current of the transmission line were calculated by equation (5.5):

$$I_l = \frac{P_{ac}}{\sqrt{3} * V_{ll}rms} \tag{5.5}$$

$$I_l = 308AP_{loss} = 3 * I^2 * R \tag{5.6}$$

Transmission line efficiency were calculated by (5.8) and the net power were also calculated by (5.7).

$$P_{Net} = P_{ac} - P_{loss} \tag{5.7}$$

$$\eta_p = \frac{P_{Net}}{P_{ac}} * 100\% \tag{5.8}$$

Generally, the Ground mounted PV system have transmission line loss as shown on the above table 5.1. From the table we can observe that as transmission line increase, the transmission

TABLE 5.1: Transmission line loss

KM	P_{loss}	efficiency
1	198KW	97.5%
2	396KW	95.05%
5	990KW	87.4%
10	1980KW	75.25%

line efficiency decrease. But, the Dire Dawa industry zone rooftop PV system are installed near the load. So, transmission line is not needed.

5.2.3 Carbon Saved

The good advantage of solar PV system is a clean energy. the total CO_2 saved by the PV system were 20080.277 tons.
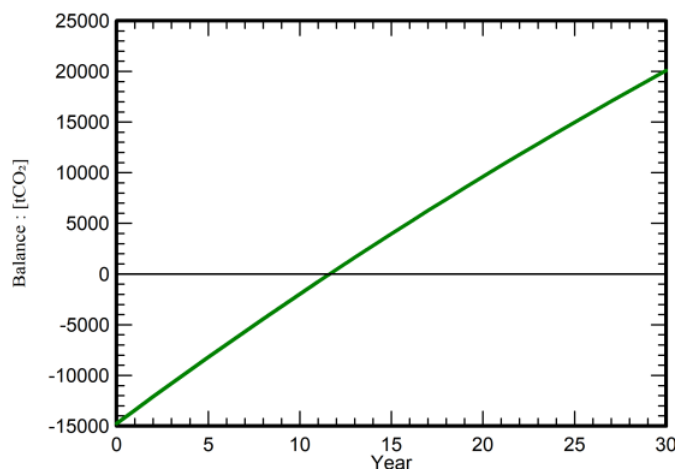

FIGURE 5.3: Carbon Dioxide saved by Dire Dawa industry zone rooftop solar PV

5.3 Simulation Analysis of Grid Connected PV Inverter Using Matlab/Simulink

In this section, an overall simulation in Matlab Simulink environment is designed, and the proposed three-phase grid-connected inverter system power control is modeled.

5.3.1 SVPWM

MATLAB/Simulink has special block which can use for three phase Pole lock loops, so simply by using the block it's possible to track the grid side voltage angle. In the figure 5.4 the three phase voltage, DC voltage and the grid angle are given to to the SVPWM block. By using the idea of Section 4.4.4.2 the first step determines the section in sector block on the figure. After determining the sector the next step is to determine the region in the each sector, for this case, reference voltage and switching angle is needed. This is done by the Matlab
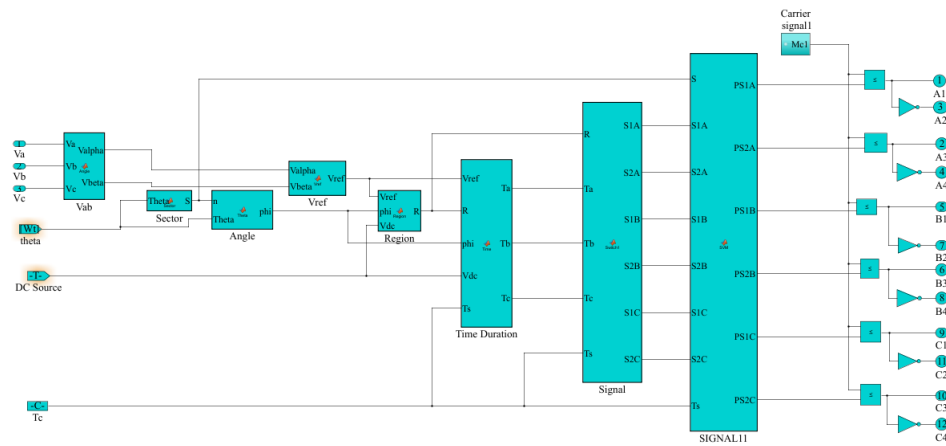
FIGURE 5.4: SVPWM design

code refound in the appendix C: 6.2 as described in section 4.4.4.3. The time duration block is calculating the duty cycle time of space vector as derived in section 4.4.4.4 and Appendix C: 6.2. The final stage is to generate the space vector carrier signal. By comparing the carrier signal with triangular signal the final SVPWM were generated as observed on figure 5.5.
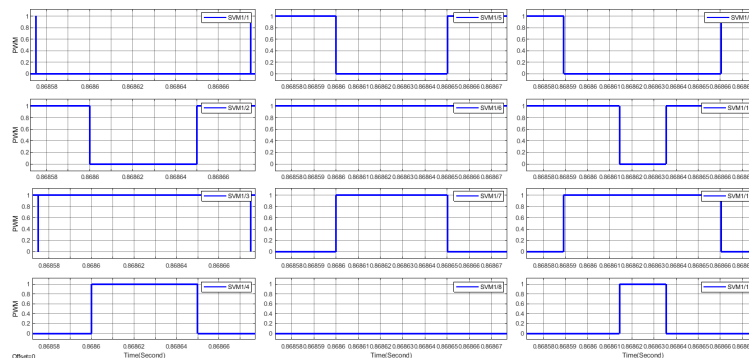

FIGURE 5.5: SVPWM for 3 Phase inverter(12 pulse)

5.3.2   Rooftop PV Inverter on Simulink

In the simulation, the grid connected PV inverter is based on the current control. But when the grid is disconnected by any means the inverter should supply the load by itself. To solve this problem the voltage control based inverter is designed. In the following subsection the standalone PV inverter and grid connected PV inverter will be discussed respectively.

5.3.2.1   Standalone Rooftop PV Inverter

In stand alone inverter the power control is not done, in this simulation the purpose of stand alone PV inverter is to maintain the voltage value at the desired value. The figure 5.6 and 5.7 shows the simulation of stand-alone PV inverter with result.
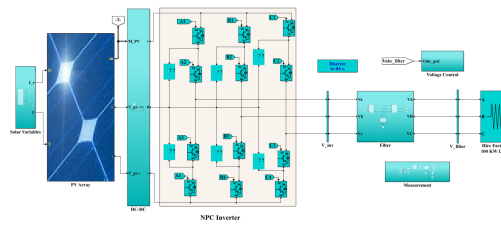
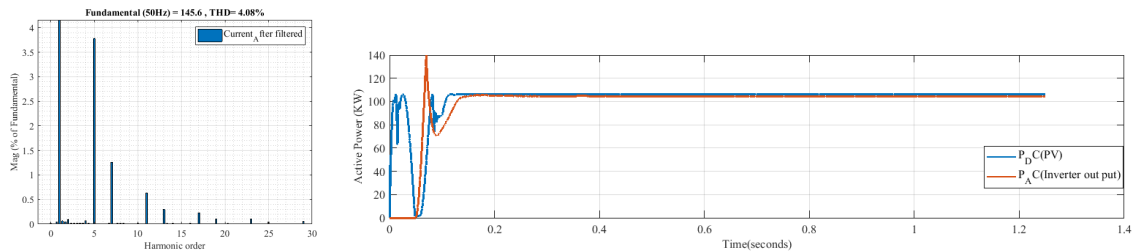FIGURE 5.6: Stand-alone PV inverter with voltage control

FIGURE 5.7: Stand-alone PV inverter current FFT analysis(left) and inverter power output with respect to PV power (right)

5.3.2.2   Grid Connected PV Inverter and Power control

The grid connected solar PV inverter has five components, DC source, Boost converter, Inverter, Filter and Grid. To integrate and synchronize with the grid frequency the controller should design properly. In this section the controller strategy was designed as based on the idea discussed in section 4.4.2.
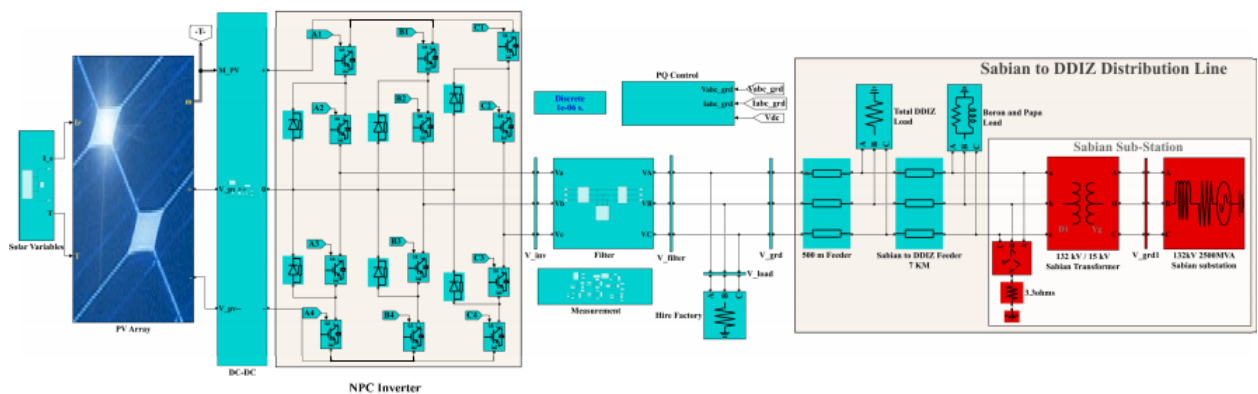
FIGURE 5.8: Full Matlab/Simulink of grid connected inverter power control

The PV panel is selected $SPR - X22 - 360$ sun power x-series mono-crystal solar panel which has the best efficiency with 22.1% By taking the output of PV array voltage which is uncontrolled and variation of temperature and irradiance, as shown in the figure 5.9 and give to DC-DC boost converter to step-up the voltage to the desired value and controlled voltage value (730 V). Boost converter design is discussed in previous section 4.3. To control the
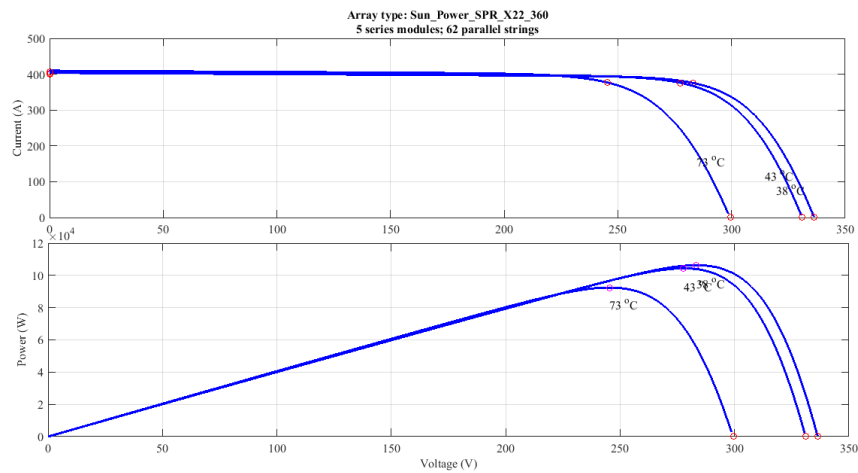
FIGURE 5.9: Solar MPPT and temperature in the 1000 irradiance value

boost converter the maximum power point tracking method is used to utilize the maximum power PV panel. The boost converter can control the voltage to the desired value, however the value of PV panel voltage varies as observed in figure 5.10, which is not constant and the boost output voltage with respect to its reference. This regulated value of Boost output
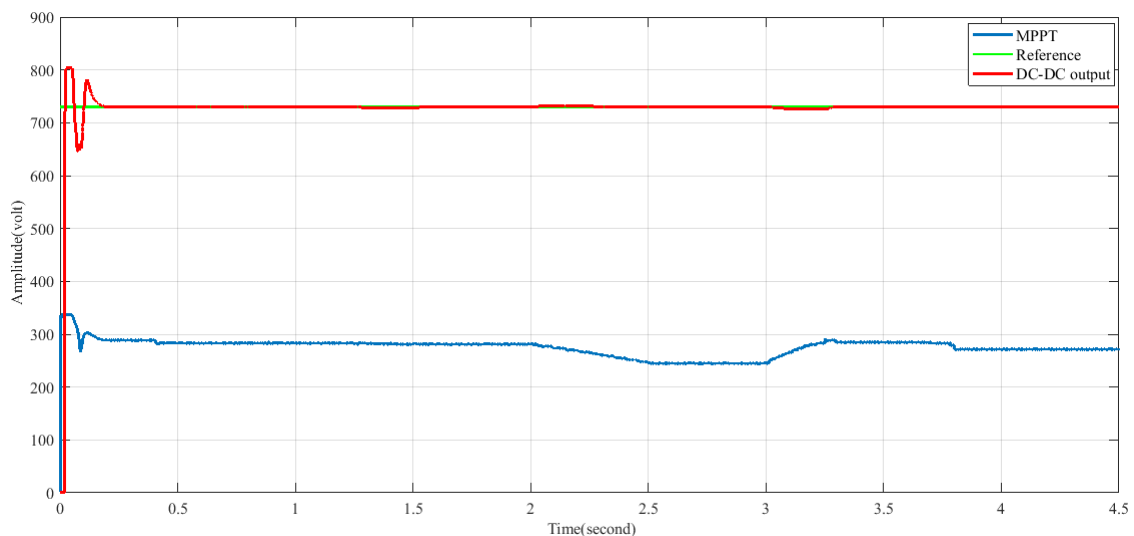
FIGURE 5.10: Solar PV MPPT output voltage value and DC-DC boost converter controller step response

Voltage value is given to the Neutral point clamped (NPC) three phase inverter. The NPC inverter controller is based on the ideology of the current controlled. As previously discussed in section 4.4.2 for dq-frame the d and q axis current and is directly proportional with active and reactive power respectively. So, by controlling the current we can control the active and reactive power separately. Figure 5.11 is the inverter active and reactive power control of the

above discussed system figure 5.8. The solar output power depends on the value of irradiation
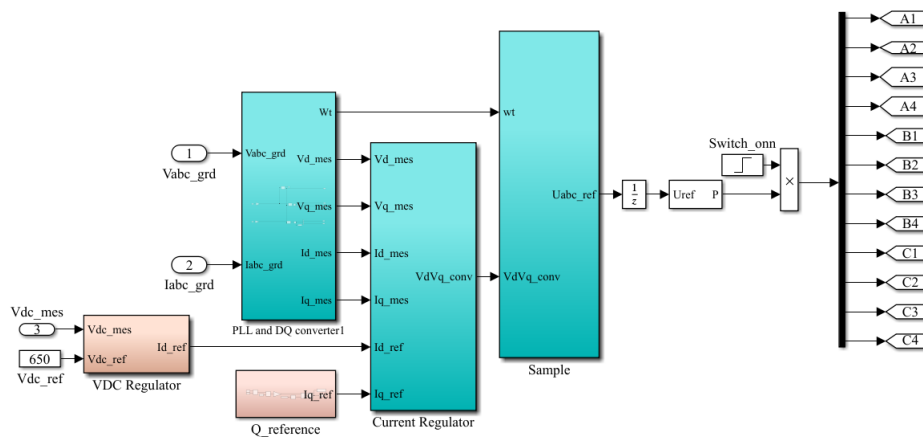
FIGURE 5.11: Inverter PQ controller

and temperature. For balanced system the voltage V_q is approximately equal to Zero. So by using equation (4.36) and (4.37) the reference power is converted into reference current in dq0 form. By taking the reference current and compare with grid current and multiply with PI controller the power were controlled as observed in the figure 5.11. After the inverter
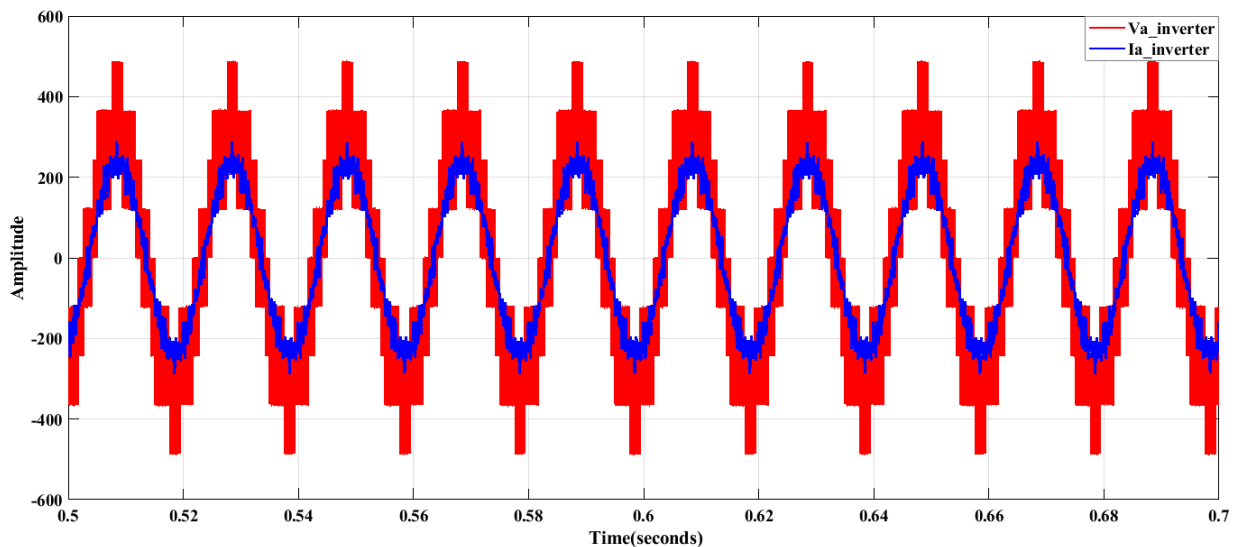
FIGURE 5.12: Inverter output voltage and current

output voltage is pass through the filter the three phase voltage and current become smooth as shown in the figure 5.13.
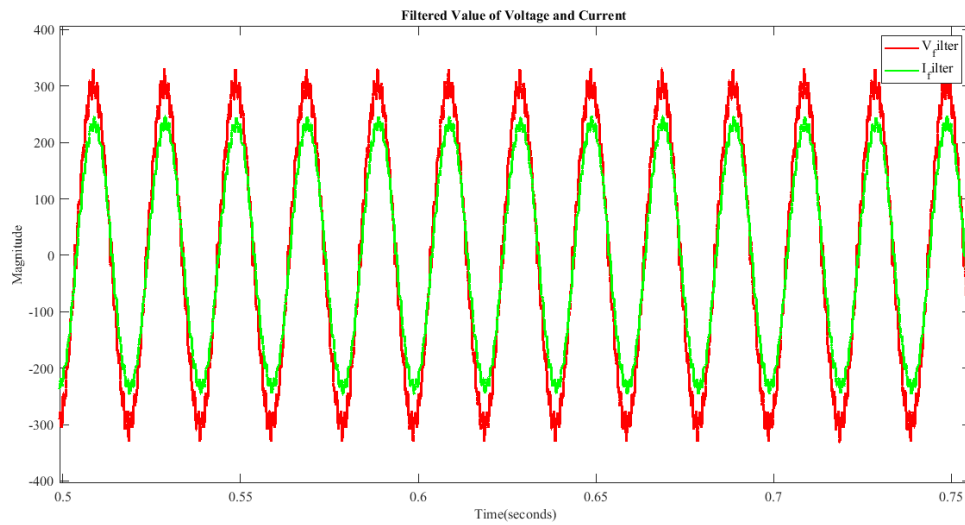
FIGURE 5.13: Inverter output voltage and current after filter

5.4 Power injection to the grid by Matlab/Simulink

5.4.1 Effect of Temperature

When Irradiance of the solar is constant and the temperature of solar panel increases the Active power is decreasing. As observed in the figure 5.14, 5.15 and 5.16. In another case also when the Temperature is constant and irradiance is decrease the active power is decreased. So we can conclude that the active power is directly proportional to Solar radiation and inversely proportional to temperature. But when we observe the reactive power it is not depend on both solar radiation and Temperature. By using this conclusion we can control our reactive power at any desired value at any time of day and night.
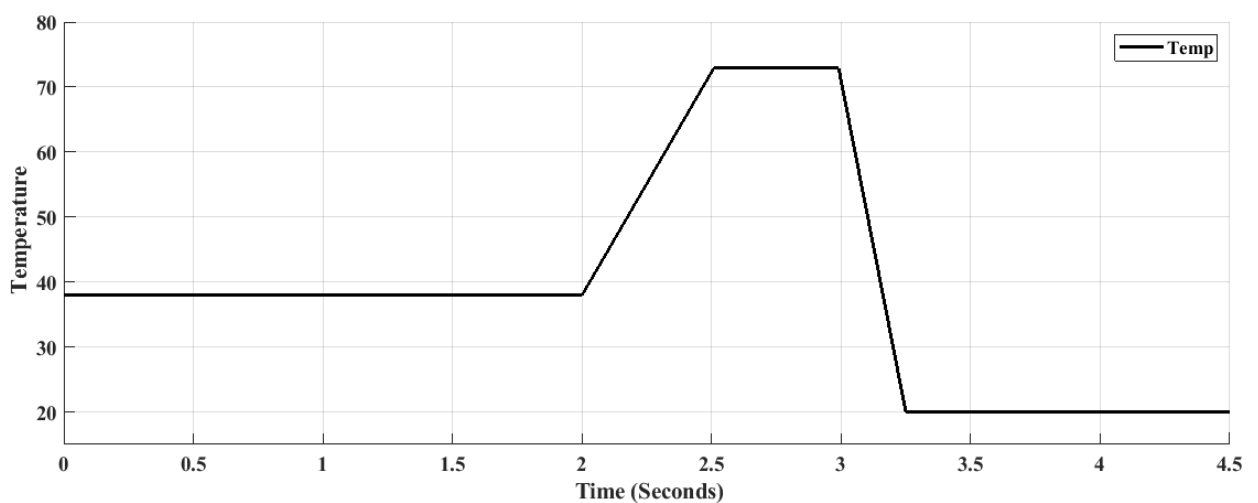
FIGURE 5.14: Temperature reference for the site
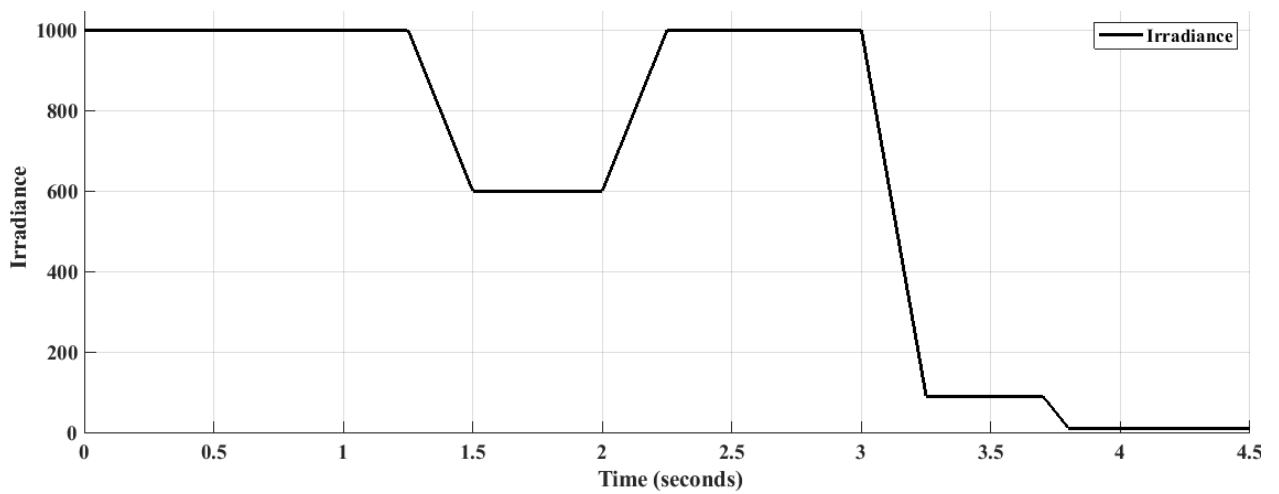
FIGURE 5.15: Solar radiation on the PV array

When the inverter is connected to the grid, capable of providing active and reactive power the system must behave in current-controlled mode. The simulation shows in Figure 5.16 show that the active power of AC-power is following the reference of DC-power controller can control. When we come to reactive power shown on the figure 5.17 the reference value
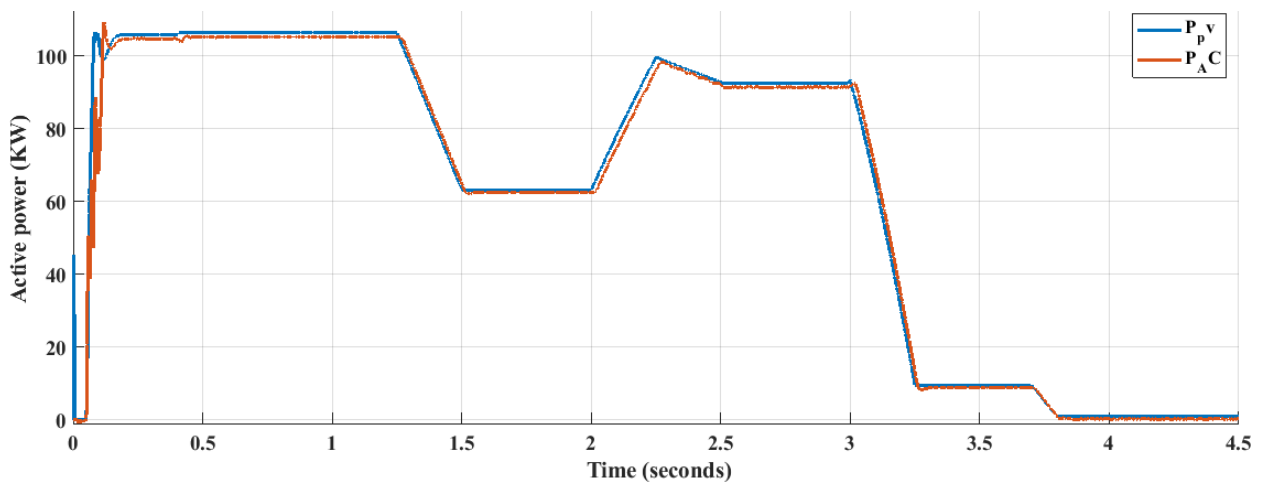
FIGURE 5.16: Active power of grid connected inverter

of 40 KVAr and -40 KVAr was given to the controller and we observe that the reactive power output is the same with the reference value. In the figure 5.17, we observe again that in the time interval from 3 second to 3.75 second the solar radiance is decreased from 1000 to 0 value and also the temperature decrease from the maximum value of 73^0C to the minimum value of 20^0C but the reactive value is not affected by both temperature and irradiance. The second section of the reactive power controller, which is from 3.75 second to 4.5 second, in this interval there is no light or we can consider it at night, But the reactive power is again not affected. The analysis of signal for the harmonic is observed in the figure 5.18. The Voltage
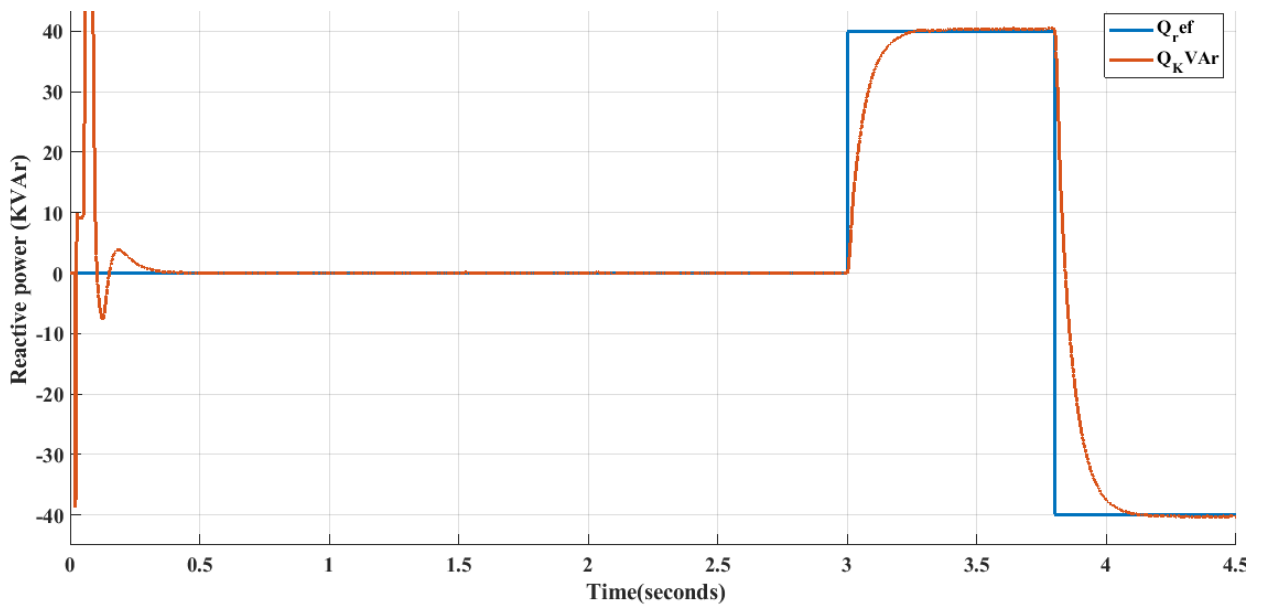
FIGURE 5.17: Reactive power of grid connected inverter
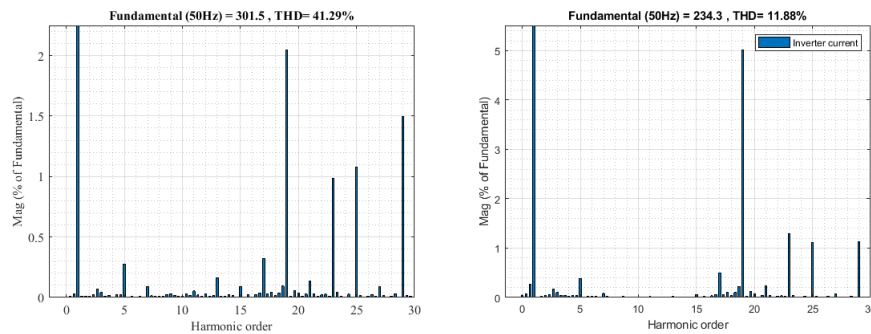
FIGURE 5.18: Inverter output voltage and current FFT analysis

inverter is synchronized with Grid voltage and the grid voltage and current is not disturbed by the inverter signal as observed in the figure 5.18, the THD of inverter voltage is 41.30%, the THD of inverter current is 11.98%. The THD of filtered inverter current is 4.56%, the
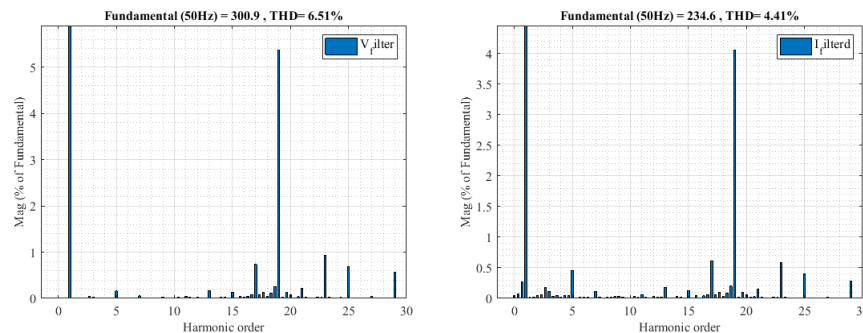
FIGURE 5.19: Filtered inverter output voltage and current FFT analysis

THD of the filtered inverter voltage is 6.69% as observed on the figure 5.19.

Chapter 6

Conclusion and Recommendation

The objective of this thesis were to assess the rooftop area of Dire Dawa industry zone and design the grid connected rooftop solar PV system. So, the thesis was divided into three sections, the first section was deal asses the rooftop area of the site to install the solar panel.

6.1 Conclusion

The Dire Dawa industry zone has series power interruption problem as discussed in section 4. The rooftop PV system is proposed and justified in chapter 3.1 that the rooftop solar installation can generate 16325 MWhr in in optimal orientation, with the performance ratio of 84.2%. The power controlled NPC inverter were designed in chapter 4 and the power of the inverter can controlled as given by reference value. The active power is controlled so that the AC-active power output is the same with DC-power and it depend on the value of solar radiation and temperature value. When come to reactive power the output follows the reference reactive power and it is not depend on the value of solar radiation. so, by using inverter we can improve the power factor of the system. The harmonic analysis of voltage and current was also done and the quality of the grid is not disturbed. For Dire Dawa industry zone grid connected rooftop solar PV power system was proposed, designed and discussed briefly. The rooftop PV is designed by PVsyst shown that there is enough capacity to install and use solar PV for Dire Dawa industry zone on their rooftop of each factory. The feasibility study was done and it shows that the return back time is 5.6 years. With PVsyst economic evaluation tools, the total investment cost for the Dire Dawa Industry Zone is 320 million ETB to generate 8545 KW peak power. The levelized cost of energy LCOE is become 0.99 $\frac{ETB}{KWh}$ for this design.

Each grid connected solar PV system were design and simulated. The 100 KW grid connected PV inverter which can control the active power and reactive power using Matlab/Simulink is designed. From this we observe the grid connected rooftop PV inverter can give and take the reactive power at any desired value even in the night time which make it suitable to compensate the power factor. The analysis shows that the addition of inverter can boost the power

factor from 0.87765 to 0.9894. The power controlled inverter were designed and the power of inverter can controlled as given by reference value. The harmonics analysis were done and the quality of grid is not described. The factory can get two advantages, when the grid voltage is exist they can save $16325000 KWH * 3.5\frac{ETB}{KWH} = 57,137,500\frac{ETB}{Annual}$ the bill payed for utility or when ever there is power interruption the stand alone rooftop solar PV system supply the factories load.

6.2   Recommendation

Government of Ethiopia should grant financial incentives to any power investor interested in investing in solar PV energy technologies. The future recommendation is the further research could be done on following cases:

- The wind,solar and diesel hybrid power generation or wind and battery base solar system hybrid system could design for Dire Dawa industry zone to supply the full load.

- secondly,i recommend the grid reconfiguration the minimize the power interruption and to minimize the voltage drop on the distribution line. Specially, Dire Dawa industry zone should have its own feeder .

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Appendix A:- Data Collecting Tools

A Questionnaire for Need Assessment of Rooftop grid connected PV

1. Introduction

My name is Reta Degefa and I am an MSc student in power system engineering program at Jimma Institute of Technology, Jimma University. Currently I am working on my master's thesis on evaluating the need assessment of solar energy that could be collected on the rooftop in Dire Dawa Industry zone. After the need assessment, Inverter with controller will be designed. For that, I am conducting a survey to collect data and understand the energy use among factories. Your support in filling up this questionnaire would greatly help me in my endeavor. Thank you in advance for your time and cooperation in this matter.

2. Personal Information

2.1. Please indicate your gender

            [A] Male   [B] Female

2.2. Which of the following best describes your occupation in the company?

            [A] Employee team Leader [B] Production Manager [C] General Manager

            [D] Company Owner   [E] Other (please specify) _____

2.3. What is your level of education?

            [A] PhD degree   [B]. M Sc. Degree   [C] B Sc. Degree

            [D] Diploma   [E] TVET graduates   [F] High school and below

2.4. Which of the following best describes your field of specialization?

            [A] Electrical Engineer [B] Other Engineering field [C] Natural Science

            [D] Social Science   [E] Other (please specify) _____

3. General Information of the company

3.1. Full Name of the company _____

3.2. Product type of your company_____

3.3. Production capacity of the company per day _____

4. Energy source and Power Problem of the company

4.1. What is the primary source of energy for your company

            [A] Coal   [B] Electric energy from Grid [C] Gasoline Generator

            [D] Renewable energy like wind and solar.

1

A Questionnaire for Need Assessment of Rooftop grid connected PV

4.2. If your company use electric energy form grid. Is it reliable?

[A] Not reliable   [B] Usually reliable [C] Somewhat reliable [D] completely reliable

4.3. Can you estimate how many interruptions could happen in a month frequently?

[A] Less than 5   [B] 5-10   [C] 10-20   [D] 20-30 [E] 30 – 40

[F] If other please write here_____

4.4. Is any product defect happen on your product due to power supply interruption?

[A] Not at all   [B] Little   [C] Medium   [D] Significantly

4.5. Can you describe the defect in the form of money loss (if any bankruptcy due to power interruption)? _____

4.6. What other problem did your company facing in electrical power?

[A] Power interruption   [B] Poor power factor [C] Voltage Dip   [D] Voltage Swell

4.7. What is the Voltage Rating you use in your company?

[A] 380 V [B] 3.3 KV [C]   6.6 KV [D] 11 KV   [E] 15 KV

[F] If other please write here_____

4.8. What is the maximum power your factory Use

[A] Less than 50 KVA   [B] 50 KVA - 100 KVA   [C] 100 KVA-500 KVA

[D] 500 KVA-1MVA   [E] 1MVA and Above

5. Need Assessment of Solar Energy

5.1. How much did you know about solar energy

[A] I know well   [B] I know   [C] Somehow [D] A little [E] I don't know

5.2. Do you use solar power generator in your company currently?

[A] Yes   [B] No

5.3. If the answer for 5.2. yes, what is its capacity

[A] Less than 100W [B] 100W – 1KW   [C] 1KW -10 KW [D] Greater than 100KW

5.4. What problem did you facing in using solar energy? (Please Least them) you can use back of the paper.

_____

_____

2

A Questionnaire for Need Assessment of Rooftop grid connected PV

5.5. Did you know the advantage of solar power in improving the power problem in your industries?

    [A] Agree [B] Not that much [C] I don't Know [D] Disagree

5.6. Did your company interested to use solar power?

    [A] Agree [B] Not that much [C] I don't Know [D] Disagree

5.7. Did your company plan to install solar power in the future?

    [A] Yes [B] No

5.8. If yes for above Questions, then in how long

    [A] 1- 3 year [B] 4-7 year [C] 8-10 Year [D] 10-15 year [E] not at all

5.9. Do you have enough places on the ground to install solar power?

    [A] Yes enough [B] Yes but not enough [C] I don't know [D] We haven't at all

5.10. Did you believe solar power on the rooftop have benefit for your company?

    [A] Yes [B] No

5.11. How much tilt angle your factory roof have with respect to ground.

    [A] Less than 10^0 [B] $10^0 - 15^0$ [C] 15^0-20^0 [D] greater than 20^0

5.12. Please write down the area of rooftop of your company on the place below _____ m^2

5.13. What is your suggestion to be improved in solar energy technology?

_____

_____

_____

5.14. Any additional comment and suggestion

_____

_____

_____

3

Appendix B:- The response of the responder

TABLE 1: Monthly Peack load Dire Dawa industry zone Distribution feeder

Time	R1-04CB/P	R1-04CB/Q	R1-05CB/P	R1-05CB/Q
2019-01	2.27	1.36	0.00	0.00
2019-02	2.23	1.29	0.00	0.00
2019-03	2.46	1.44	0.00	0.00
2019-04	2.31	1.36	0.84	0.29
2019-05	2.41	1.42	0.87	0.36
2019-06	2.18	1.28	1.01	0.43
2019-07	2.26	1.33	0.83	0.32
2019-08	2.22	1.28	0.82	0.28
2019-09	2.17	1.23	0.83	0.27
2019-10	2.08	1.19	0.80	0.27
2019-11	2.32	1.26	2.92	1.51
2019-12	0.00	0.00	2.92	1.48
2020-01	0.00	0.00	2.62	1.37
2020-02	0.00	0.00	2.82	1.54
2020-03	0.00	0.00	2.78	1.48
2020-04	0.00	0.00	2.80	1.51
2020-05	0.00	0.00	2.55	1.32
2020-06	0.00	0.00	1.23	-0.67
2020-07	0.00	0.00	1.97	0.54
2020-08	0.00	0.00	2.01	0.49

TABLE 2: Defect due to Power problem

Defect due to P. problem	Quantity	Percent
Not at all	2	12.5
Little	4	25
Medium	3	18.75
Significant	7	43.75
Total	16	100

TABLE 3: Power problem of the grid in DDIZ

Other Power problem	Quantity	Percent
V. Swell	0	0
Poor Pf	2	12.5
Harmonics	0	0
V. Dip	16	100
Total	16	100

TABLE 4: Number of Interruption per month in DDIZ

No. Interruption/month	Quantity	Percent
less 5	1	6.25
6 to 10	2	12.5
11 to 20	1	6.25
21 to 30	0	0
30 to 40	5	31.25
41 to 100	3	18.75
101 to 200	4	25

TABLE 5: KVA load of the factories

Max. KVA	Quantity	Percent
less 50	1	6.25
51-100	5	31.25
101 -500	8	50
500-1MVA	1	6.25
1 MVA-24 MVA	1	6.25
Total	16	100

TABLE 6: Ground Area

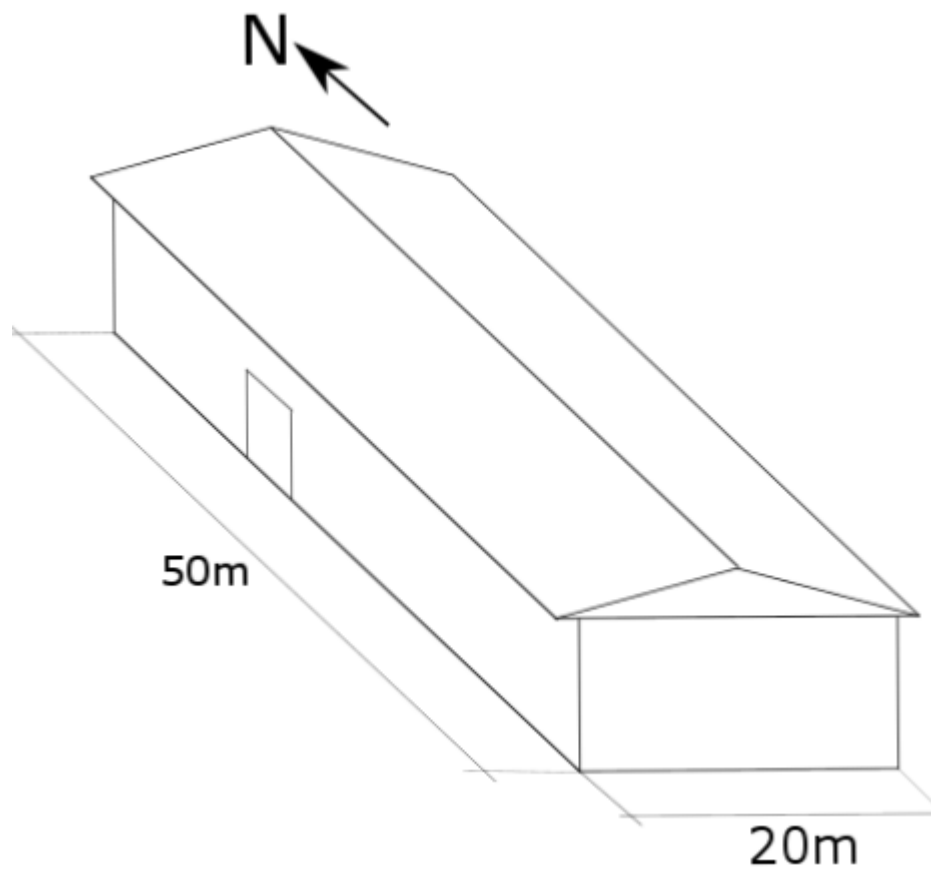| Have Ground Area	Quantity	Percent
yes enough	1	6.25
yes but not enough	5	31.25
I don't know 't know	0	0
we haven't't at all	10	62.5
Total	16	100

FIGURE 1: Hire Flour Factory

Appendix C:- SVPWM

```
function [Valpha,Vbeta,Theta] = Angle(Va,Vb,Vc)
Valpha=2/3*(Va-Vb/2-Vc/2);
Vbeta=2/3*(sqrt(3)/2*Vb-sqrt(3)/2*Vc);
Theta=atan2(Vbeta,Valpha);
end


function S = Sector(Theta)
S=0;
if (Theta>=0)&&(Theta<pi/3) S=1;
end if (Theta>=pi/3)&&(Theta<2*pi/3) S=2;
end if (Theta>=2*pi/3)&&(Theta<pi) S=3;
end if (Theta>=pi)&&(Theta<4*pi/3) S=4;
end if (Theta>=4*pi/3)&&(Theta<5*pi/3) S=5;
end if (Theta>=5*pi/3)&&(Theta<2*pi) S=6;
end
end


function phi = Theta(n,Theta) phi=0;
if(n==1) phi=Theta;
end if(n==2) phi=Theta-pi/3;
end if(n==3) phi=Theta-(2*pi/3);
end if(n==4) phi=Theta-(3*pi/3);
end if(n==5) phi=Theta-(4*pi/3);
end if(n==6) phi=Theta-(5*pi/3);
end
end


function Vref = Vref(Valpha,Vbeta)
```

```
Vref=sqrt(Valpha^2+Vbeta^2);
end


function R = Region(Vref,phi,Vdc)
R=0;
m=Vref/(2/3*Vdc); m1=m*2/sqrt(3)*sin(pi/3-phi);
m2=m*2/sqrt(3)*sin(phi);
mr=m1+m2; if(m1<0.5)&&(m2<0.5)&&(mr<0.5) R=1;
end if(m1<0.5)&&(m2<0.5)&&(mr>0.5) R=2;
end if(m1>0.5) R=4; end if(m2>0.5) R=3;
end
end


function [Ta,Tb,Tc ] = Time(Vref,R,phi,Vdc,Ts)
Ta=0;Tb=0;Tc=0;
m=Vref/(2/3*Vdc);
k=2/sqrt(3)*m*Ts;
if(R==1)
Ta=2*k*sin(pi/3-phi);
Tb=Ts-2*k*sin(pi/3+phi);
Tc=2*k*sin(phi);


end if(R==2)
Ta=Ts-2*k*sin(phi);
Tb=2*k*sin(pi/3+phi)-Ts;
Tc=Ts-2*k*sin(pi/3-phi);


end if(R==3)
Ta=2*k*sin(phi)-Ts;
Tb=2*k*sin(pi/3-phi);
Tc=2*Ts-2*k*sin(pi/3+phi);
```

```
end if(R==4)
Ta=2*Ts-2*k*sin(pi/3+phi);
Tb=2*k*sin(phi);
Tc=2*k*sin(pi/3-phi)-Ts;
end
end


function[S1A,S2A,S1B,S2B,S1C,S2C]=Switch1(R,Ta,Tb,Tc,Ts)
S1A=0;S2A=0;S1B=0;S2B=0;S1C=0;S2C=0;
if(R==1)
S1A=Tc/4+Ta/4;
S2A=Ts/2;
S1B=Tc/4;
S2B=Ts/2-Ta/4;
S1C=0;
S2C=Ts/2-Ta/4-Tc/4;


end if(R==2)
S1A=Tc/4+Ta/4+Tb/2;
S2A=Ts/2;
S1B=Tc/4;
S2B=Ts/2-Ta/4;
S1C=0;
S2C=Ta/4+Tc/4;


end if(R==3)
S1A=Ts/2-Tc/4;
S2A=Ts/2;
S1B=Tc/4+Ta/2;
S2B=Ts/2;
```

```
S1C=0;
S2C=Tc/4;


end if(R==4)
S1A=Ts/2-Ta/4;
S2A=Ts/2;
S1B=0;
S2B=Ta/4+Tb/2;
S1C=0;
S2C=Ta/4;
end
end
function [PS1A,PS2A,PS1B,PS2B,PS1C,PS2C] = SVM(S,S1A,S2A,S1B,S2B,S1C,S2C,Ts)
PS1A=0;PS2A=0;PS1B=0;PS2B=0;PS1C=0;PS2C=0;
if(S==1) PS1A=S1A; PS2A=S2A;PS1B=S1B;
PS2B=S2B; PS1C=S1C; PS2C=S2C;
end if(S==2) PS1A=Ts/2-S2B;PS2A=Ts/2-S1B;
PS1B=Ts/2-S2C; PS2B=Ts/2-S1C;
PS1C=Ts/2-S2A; PS2C=Ts/2-S1A;
end if(S==3) PS1A=S1C; PS2A=S2C;
PS1B=S1A; PS2B=S2A;
PS1C=S1B; PS2C=S2B;
end if(S==4) PS1A=Ts/2-S2A;
PS2A=Ts/2-S1A; PS1B=Ts/2-S2B;
PS2B=Ts/2-S1B;PS1C=Ts/2-S2C;
PS2C=Ts/2-S1C;
end if(S==5) PS1A=S1B; PS2A=S2B;
PS1B=S1C;PS2B=S2C; PS1C=S1A; PS2C=S2A;
end if(S==6)PS1A=Ts/2-S2C; PS2A=Ts/2-S1C;
PS1B=Ts/2-S2A; PS2B=Ts/2-S1A;
PS1C=Ts/2-S2B; PS2C=Ts/2-S1B;
end
```
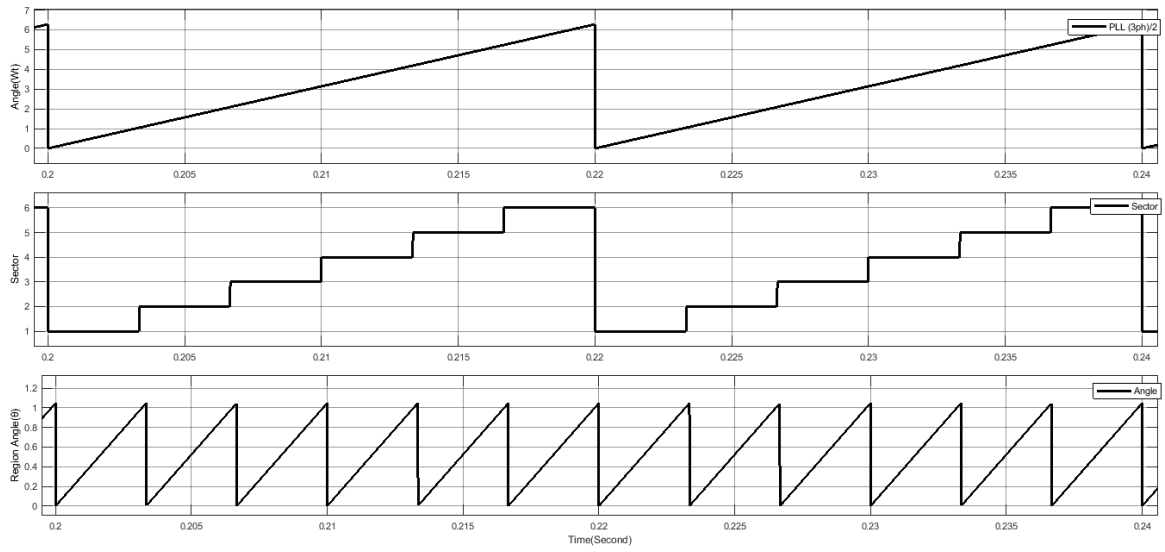
FIGURE 2: The angle Sector and region angle of space vector
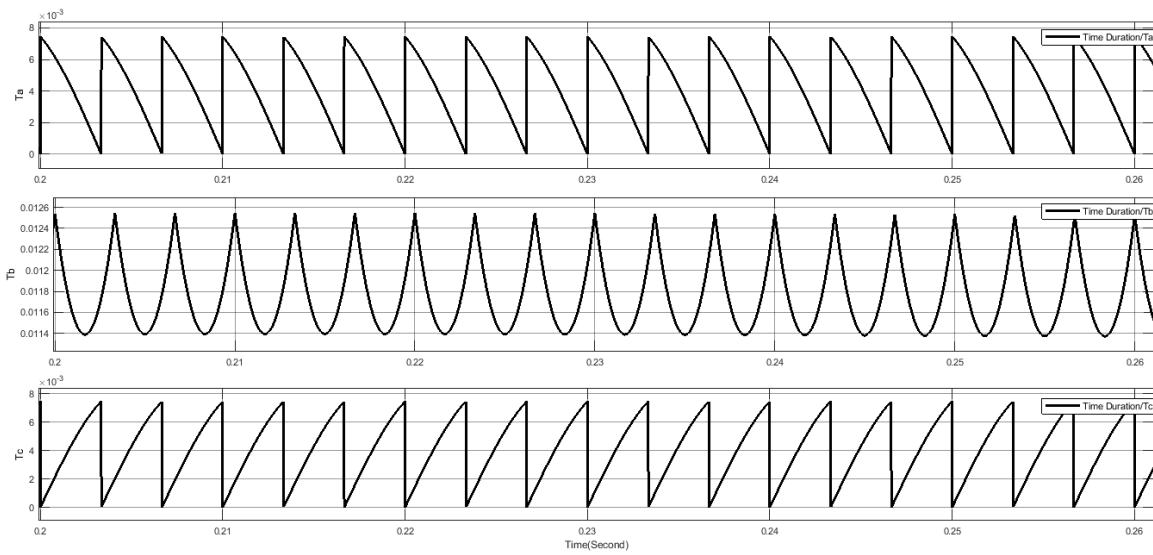

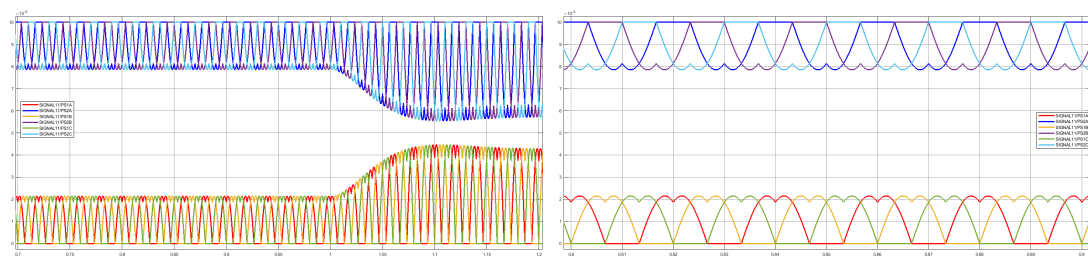FIGURE 3: Time duration of space vector

FIGURE 4: Controlled space vector modulation carrier signal

Appendix D:- PVSyst Result

PV Array Characteristics

PV module		Inverter	
Manufacturer	Generic	Manufacturer	Generic
Model	SPR-X22-360	Model	Soleaf DSP-33100K
(Original PVsyst database)		(Original PVsyst database)	
Unit Nom. Power	360 Wp	Unit Nom. Power	100 kWac
Number of PV modules	23735 units	Number of inverters	81 units
Nominal (STC)	8545 kWp	Total power	8100 kWac
Modules	4747 Strings x 5 In series	Operating voltage	200-820 V
At operating cond. (42°C)		Pnom ratio (DC:AC)	1.05
Pmpp	8119 kWp		
U mpp	279 V		
I mpp	29107 A		
Total PV power		**Total inverter power**	
Nominal (STC)	8545 kWp	Total power	8100 kWac
Total	23735 modules	Nb. of inverters	81 units
Module area	38705 m²	Pnom ratio	1.05
Cell area	34930 m²		

FIGURE 5: PVsyst result for PV characteristics

Main results

System Production

Produced Energy	16325 MWh/year	Specific production	1911 kWh/kWp/year
		Performance Ratio PR	84.20 %

Economic evaluation

Investment		Yearly cost		LCOE	
Global	320'304'297.40 ETB	Annuities	0.00 ETB/yr	Energy cost	0.99 ETB/kWh
Specific	37.5 ETB/Wp	Running Costs	67'904.24 ETB/yr		
		Payback period	5.6 years		

Normalized productions (per installed kWp)

Lc: Collection Loss (PV-array losses)   0.77 kWh/kWp/day
Ls: System Loss (inverter, ...)   0.22 kWh/kWp/day
Yf: Produced useful energy (inverter output)   5.23 kWh/kWp/day

Performance Ratio PR

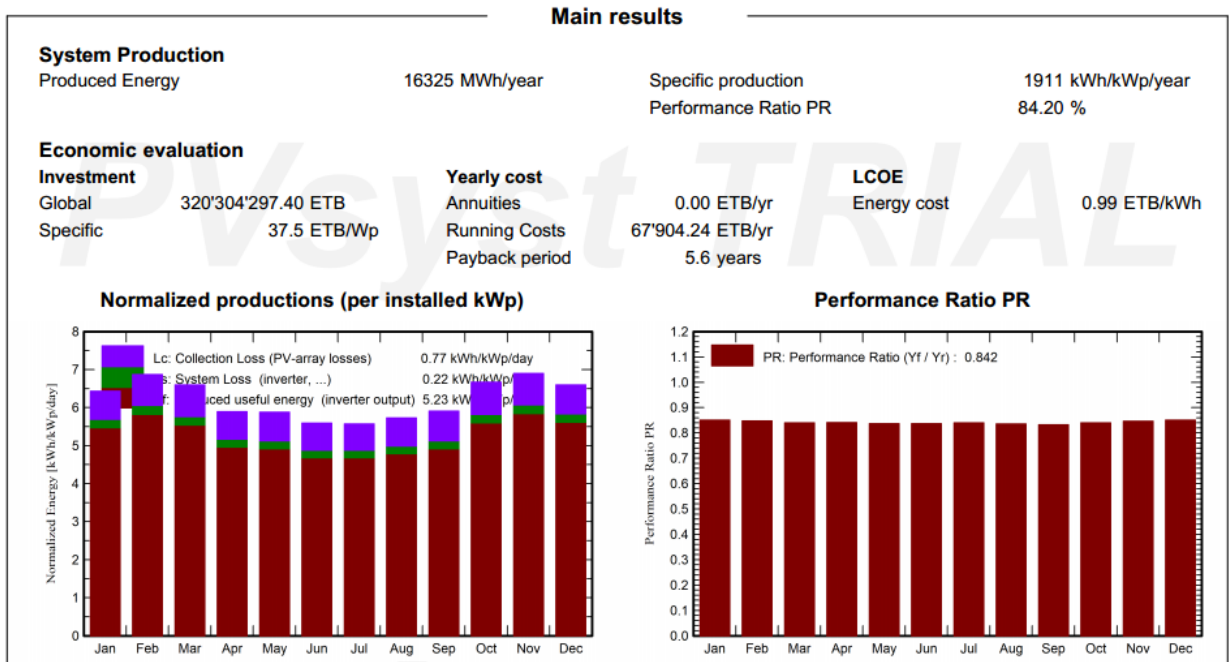PR: Performance Ratio (Yf / Yr) : 0.842

FIGURE 6: PVsyst result for performance ratio and investment cost for rooftop PV
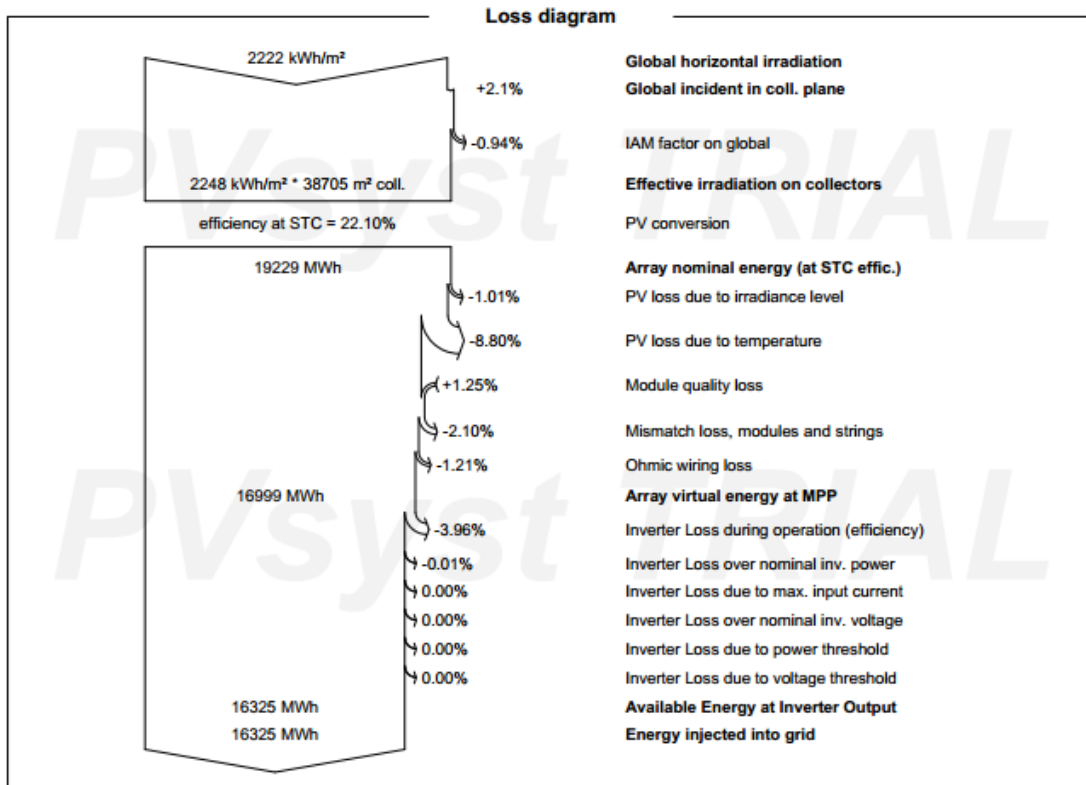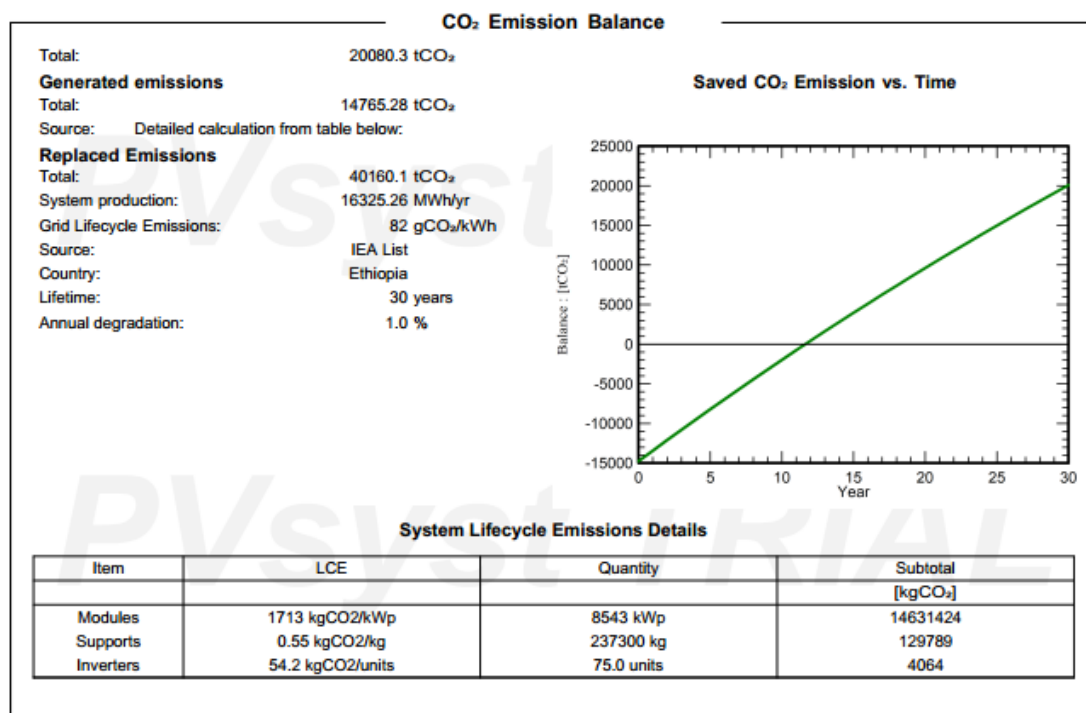
FIGURE 7: PVsyst result for general loss diagram

FIGURE 8: PVsyst result for Carbon emission