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Osman Abdeen Osman Mohammed

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Integration of Decentralized Photovoltaic-based Productions into the Electricity Distribution Network. Impacts on Power Quality

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Thèse

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Présenté par
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Thème

Intégration des Productions Décentralisées à base Photovoltaïques dans le réseau électrique de distribution: impacts sur la qualité de l'énergie

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Dedication

I dedicate this project to:

The dearest people in my life, my mother for their love, care and encouragement.
My wife, you are the shining moon that lightens my life.
My sisters, constant source of inspiration and motivation for me.
My colleagues and my friends.
To soul of my supervisor, Professor Mourad Mordjaoui and his respected family.
All my family, near and far.

ABSTRACT:

Renewable energy sources are gaining more interest in recent years. The solar energy or solar photovoltaic (PV) technology is one of the most powerful and promising renewable energies for the future. It is very important to use a simulation tool for photovoltaic system to know the generating energy according to the geographical location and to choose the best operating for photovoltaic system. Three studies have been done to choose the best location from candidate geographical locations of photovoltaic, and then study the impact of integrated PV in best position to grid.

The first study showed the impacts of geographical location on the output of energy from photovoltaic system (5 MW) particularly apply in Skikda (Algeria) and Atbara (Sudan), by PVsyst program. The total quantity of electrical annual energy produced by photovoltaic system in Atbara is greater than that which produced with same system in Skikda, about 18.66%, 16.49%, 18.60%, and 8.93% of the energy injected into grid in Skikda by fixed tilt, seasonal tilt, tracking horizontal and tracking vertical respectively.

In most Sudanese cities, instability in electricity supply is a growing problem, and this problem can be solved by using renewable energies, especially solar photovoltaic energy because Sudan receives abundant amounts of solar radiation throughout the year.

The second study showed that the productive energy from PV (5MW) to connect with the grid in ten different areas (Portsudan, Alobied, Omdurman, Atbara, Dongola, Madani, Elginina, Alnhood, Kadogli, Nyala) in Sudan, these areas were proposed by the Sudanese Hydro Generation and Renewable Company, General Administration of Renewable Energies, Solar Power Management, the best position of PV (5WM) between the ten areas Portsudan city. The PV system which has been selected in this area produces an annual energy of 8566750 KWh by global incident in coll 2283 KWh/m^2, it is the highest annual energy generated by the photovoltaic system.

The third study shows analyzing the impacts on energy quality to integrate (20MW) decentralized Photovoltaic in Portsudan to grid. The integrated of PV 20MW in the grid of Portsudan decreases the losses. If the PV system is injected the mean value of PV (4.667MW) to grid, then the losses of system decreases 10.53% of total losses of system without PV. If the PV system is injected the max value of PV (16MW) to grid, then the losses of system decreases 30.05% of total losses of system without PV system. There is no overvoltage by integrated PV (20MW) to grid at customer sites.

Keywords: geographical location; effective energy; average temperature; fixed tilt; seasonal tilt; tracking horizontal; tracking vertical; annual energy; Algeria; Sudan.

Résumé:

Les sources d'énergie renouvelables attirent de plus en plus l'attention ces dernières années. La technologie de l'énergie solaire ou l'énergie photovoltaïque (PV) est l'une des énergies renouvelables les plus puissantes et prometteuses pour le future. Il est très important d'utiliser un simulateur de système PV pour connaître la puissance générée en fonction de la situation géographique et choisir le fonctionnement meilleur du système PV. Trois études ont été menées pour sélectionner le meilleur emplacement parmi les emplacements géographiques candidats pour les cellules photovoltaïques et, par la suite, étudier l'effet de l'énergie photovoltaïque lorsqu'elle est connectée au réseau au meilleur emplacement.

La première étude a montré l'effet de la situation géographique sur la production d'énergie du système photovoltaïque (5 mégawatts) dans la ville de Skikda (Algérie) et la ville d'Atbara (Soudan), à travers le programme PVsyst, cette étude a montré que l'énergie électrique annuelle totale produite par le système PV à Atbara est supérieure à celle produite par le même système à Skikda, environ 18,66 %, 16,49 %, 18,60 % et 8,93 % de l'énergie injectée dans le réseau de Skikda avec inclinaison fixe, Succession d'inclinaison saisonnière, de suivi horizontal et de suivi vertical.

Dans la plupart des villes soudanaises, l'instabilité de l'approvisionnement en électricité est un problème croissant, et ce problème peut être résolu en utilisant des énergies renouvelables, en particulier l'énergie solaire photovoltaïque, car le Soudan reçoit des quantités abondantes de rayonnement solaire tout au long de l'année.

La deuxième étude a montré que la capacité de production du système photovoltaïque (5 mégawatts) pour se connecter au réseau dans dix régions différentes (Portsudan, Alobied, Omdurman, Atbara, Dongola, Madani, Elginina, Alnhood, Kadogli, Nyala) au Soudan, où ces zones ont été proposées par la Société Soudanaise pour l'Eau et la Production Renouvelable, Administration générale des énergies renouvelables, le Département d'Energie Solaire, le meilleur site photovoltaïque (5 mégawatts) parmi les dix régions c'est la ville de Port Soudan. Le système photovoltaïque sélectionné dans cette région produit une énergie annuelle de 8566750 kWh grâce à un rayonnement solaire de 2283 kWh/m2, qui est l'énergie annuelle la plus élevée générée par le système photovoltaïque.

La troisième étude montre l'analyse des impacts sur la qualité de l'énergie pour intégrer (20MW) le photovoltaïque décentralisé à Portsudan au réseau. L'intégration de PV 20MW diminue les pertes dans le réseau de Portsudan. Si le système PV est injecté la valeur moyenne de PV (4.667MW) au réseau, alors les pertes du système diminuent de 10,53% des pertes totales du système sans PV. Si le système PV est injecté la valeur maximale de PV (16MW) sur le réseau, les pertes du système diminuent de 30,05 % des pertes totales du système sans système PV. Il n'y a pas de surtension par PV intégré (20 MW) au réseau sur les sites des clients.

Mots-clés : situation géographique ; énergie efficace; température moyenne; inclinaison fixe; inclinaison saisonnière; suivi horizontal; suivi vertical; énergie annuelle; Algérie; Soudan.

الملخص :

تكتسب مصادر الطاقة المتجددة اهتمامًا أكبر في السنوات الأخيرة .تعد تكنولوجيا الطاقة الشمسية أو الطاقة الكهروضوئية (PV)واحدة من أقوى الطاقات المتجددة الواعدة والمستقبلية .من المهم جدًا استخدام أداة محاكاة للنظام الكهروضوئي لمعرفة الطاقة المولدة وفقًا للموقع الجغرافي واختيار التشغيل الأمثل للنظام الكهروضوئي. تم إجراء ثلاث دراسات لاختيار أفضل موقع من المواقع الجغرافية المرشحة للخلايا الكهروضوئية ، ثم دراسة تأثير الطاقة الكهروضوئية عند ربطها مع الشبكة في أفضل موقع.

أظهرت الدراسة الأولى تأثير الموقع الجغرافي على إنتاج الطاقة من النظام الكهروضوئي (5 ميجاوات) في مدينة سكيكدة (الجزائر) ومدينة عطبرة (السودان) ، من خلال برنامج PVsyst .بان إجمالي كمية الطاقة الكهربائية السنوية التي ينتجها النظام الكهروضوئي في عطبرة أكبر من تلك المنتجة بنفس النظام في سكيكدة ، حوالي 18.66٪ ، 16.49٪ ، 18.60٪ ، و 8.93٪ من الطاقة المحقونة في الشبكة من سكيكدة بالإمالة الثابتة ، إمالة موسمية ، تتبع أفقي وتتبع عمودي على التوالي.

في معظم المدن السودانية ، يعد عدم الاستقرار في إمدادات الكهرباء مشكلة متنامية ، ويمكن حل هذه المشكلة باستخدام الطاقات المتجددة ، وخاصة الطاقة الشمسية الكهروضوئية لأن السودان يتلقى كميات وفيرة من الإشعاع الشمسي على مدار العام.

أظهرت الدراسة الثانية أن الطاقة الإنتاجية من النظام الكهروضوئي (5 ميجاوات) للربط مع الشبكة في عشر مناطق مختلفة (بورتسودان ، االابيض ، أم درمان ، عطبرة ، دنقلا ، مدني ، الجنينة ، النهود ، كادوقلي ، نيالا) في السودان ، حيث تم اقتراح هذه المناطق من قبل الشركة السودانية للتوليد المائي والمتجدد ، الإدارة العامة للطاقات المتجددة ، إدارة الطاقة الشمسية ، بان أفضل موقع للطاقة الكهروضوئية (5 ميجاوات) بين المناطق العشرة مدينة بورتسودان .ينتج النظام الكهروضوئي الذي تم اختياره في هذه المنطقة طاقة سنوية تبلغ 8566750 كيلوواط ساعة من خلال إشعاع شمسي 2283 كيلو واط في الساعة / م 2 ، وهي أعلى طاقة سنوية يولدها النظام الكهروضوئي.

أوضحت الدراسة الثالثة تحليل التأثيرات على جودة الطاقة لدمج (20 ميجاوات) من الخلايا الكهروضوئية اللامركزية في مدينة بورتسودان إلى الشبكة. حيث يعمل دمج الطاقة الكهروضوئية 20 ميجاوات في الشبكة من مدينة بورتسودان على تقليل الفقودات الكهربائية. فإذا تم حقن الشبكة بالقيمة المتوسطة للنظام الكهروضوئي (4.667 ميجاوات) ، فإن الفقودات للنظام تنخفض بنسبة 10.53 ٪ من إجمالي الفقودات للنظام بدون استخدام النظام الكهروضوئي. وإذا تم حقن الشبكة بالقيمة القصوى للنظام الكهروضوئي (16 ميجاوات) ، فإن الفقودات للنظام تنخفض بنسبة 30.05 ٪ من إجمالي الفقودات للنظام بدون استخدام النظام الكهروضوئي. لا يوجد ارتفاع في الجهد بواسطة حقن الطاقة الكهروضوئية (20 ميجاوات) للشبكة في مواقع العملاء.

الكلمات المفتاحية: الموقع الجغرافي؛ الطاقة الفعالة؛ معدل الحرارة؛ إمالة ثابتة؛ الميل الموسمي؛ تتبع أفقي؛ تتبع عمودي ؛الطاقة السنوية؛ الجزائر؛ السودان.

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List of Abbreviations

PV: Photovoltaic.
PVCs: Photovoltaic cells.
DGS: Distributed generation systems.
RDG: Renewable distributed generation.
DER: Distributed energy resources.
AC: Alternating current.
DC: Direct current.
Isc: Short-circuit current.
Voc: Open-circuit voltage.
SRCs: Standard rating conditions.
NOCT: Nominal operating cell temperature.
PCUs: Power conditioning units
BOS: Balance of system.
MPP: Maximum Power Point.
MPPT: Maximum Power Point Tracking
PFC: Power factor correction
VSDs: Variable speed drives
THD: Total harmonics distortion
EES: Electrical Energy Storage
LCI: Line-Commutated Inverter.
SCI: Self-Commutated Inverter.
VSI: Voltage Source Inverter.
CSI: Current Source Inverter.
SPTG-C PV: Single phase transformer less grid-connected PV.
MLI: Multilevel inverters.
TCT: Total cross tied.
SHS: Solar home systems.
BIPV: Building-integrated photovoltaic's.
PCS: Power conditioning systems.
PLL: Phase Locked Loop.
PCC: Point of Common Coupling.
PCSP: Power Control Shifting Phase.
ZCD: Zero crossing detector.
DSPWM: Digital Sinusoidal Pulse Width Modulation
DSM: Demand-side management.
LTC: Load tap changer
TOV: Temporary overvoltage.
PQ: Power quality.

Chapter 1
Introduction

1.1 General

The objective of this chapter is to explain the motivation for done this thesis. This chapter also provides the main objectives and methodology of research in addition organization of the thesis.

1.2 Motivation

Renewable energy has been given more consideration because it is environmentally friendly, reliable energy, has been increased as an alternative to replacing fossil fuels, related to shortage of energy, environmental pollution, and growth of global economic [1]. The utilization of renewable energy sources was encouraged fast to achieve rising of energy demand and deal with global climate change[2].Often outlook is generally of renewable energies, and photovoltaic's in specific, are often seen as sustainable alternative solutions to power and resource problems, at least in terms of electricity [3]. Earth gets an incredible amount of solar energy. The energy provided in minute by the sun is sufficient to cover the total energy requirements of the world for a year. In one day the sun provides more energy than current population consumption within 27 years. In actuality, the amount of solar radiation hitting the earth over a period of three days equals the energy stored in all fossil energy sources [4].To prevent global warming calamity, global warming must stay below $1.5C^0$above previous industrial temperatures. For this goal, the emissions from global greenhouse gas must be reduced. In 2050, emissions worldwide should be reduced by 80% from 1990 levels [5].There are many advantages to generating electricity from Photovoltaic, an example is free, noiseless, inexhaustible [6], not dangerous, has no fuel cost [7], does not produce CO2 [8], less maintenance requirement[9], design and install a new system takes a short period, fixed parts, similar output power to highest load demands, long period of work, each unit weighs a high capacity of energy, light weight can be easily moved[10].

PV systems are commonly used in three main fields, satellite applications, off grid or standalone applications and on grid or grid connected applications. Grid connected distributed resources are mostly used for peak shaving and local load demands. According to IEEE 1547 standards, they do not contribute voltage or frequency control regulation. Moreover, they need to operate at unity power factor or a range between 0.95 leading or lagging [11]. The advantages of grid connected systems than a standalone system, exploitation the total photovoltaic energy generated by the modules, economy about 40% on investment (no batteries needed) and improve life expectancy [1]. It seems that the Renewable distributed generation (RDG) is a promising option to improve the performance of the network power system. It has the ability to provide the energy required for increase the load and reduce the cost of electricity prices. With the low price of solar PV, the power of distributed PV systems is increasing accordingly [12].

The benefits of solar energy injection are evident where the output power of the generators is reduced, thus, there is no need to build an additional power plant and transmission losses are reduced. With high scale solar injection, some generators such as gas turbine generators can be turned off [13]. Most photovoltaic plants are connected to the low / medium voltage distribution level such as distributed generation (DG) [14]. PV array output depends heavily on environmental conditions such as lighting intensity and temperature [15].

The distributed generation also identified embedded generation, is known as a source of electrical power directly in the distribution network or on the client side [16].The traditional power systems of distribution networks are being designed that the centralized generated power flows from generation to load. From another side, the high penetration of the renewable generation on the load creates problems of stability of the energy system such as current faults, voltage fluctuations, and damages of equipment because the distribution networks are not designed for bidirectional energy flow. RDG systems can be classified by generation capacity and types of system generation technologies. The capacity generating from RDG systems can be from 1kW to several hundred kW. General, we classify RDG as micro (<5kW), small (5kW-5MW), medium (5MW-50MW), large (50MW-300MW). According to the Electric Power Research Institute (EPRI),the distribution generation is generate power from a few kilowatts up to 50 MW [13].furthermore, changes in radiation solar can cause fluctuations in power and voltage flicker, resulting in undesirable effects on high penetrating PV systems in the energy system. To improve the efficiency of photovoltaic systems, some control methods, such as Maximum Power Point Tracking MPPT, can be used. The main components of the grid connected PV system include a combination a series/parallel of photovoltaic arrays to convert direct sunlight to DC energy and conditioning unit of power to converts DC power to AC power; this module also keeps the PV system working in high efficiently [17].

The converters connected PV module with the grid include two main responsibilities. One is to make sure that the PV module is working at maximum power point. The second is the injection of a sinusoidal current to grid [18].

The best benefits of converters connected PV module and grid to enhance penetration levels more. The semiconductor switches control the Q amount of the inverter. When the active power injection is less than the estimated apparent power rated of inverter, the remaining capacity can be used to supplying reactive power. The new solar inverters are set at 0.9 power factor, which keeps them in the active energy injection estimated for auxiliary services for the grid [19].The total control mechanism enhances PV inverters to match the amount of power (real and reactive) required and thus reduce the effects on the electrical grid [20].In power systems, it is very important to find inverter parameters of the PV system in order to estimate efficiency and improve power quality [21].

Grid connected photovoltaic systems can be installed on the facades or/and roofs of buildings and on the shades of parking. It can also be installed as the power plants to inject all their productive power in the grid. Figure 1.1 Expected global cumulative PV capacity based on European Photovoltaic Industry Association (EPIA) data [3].

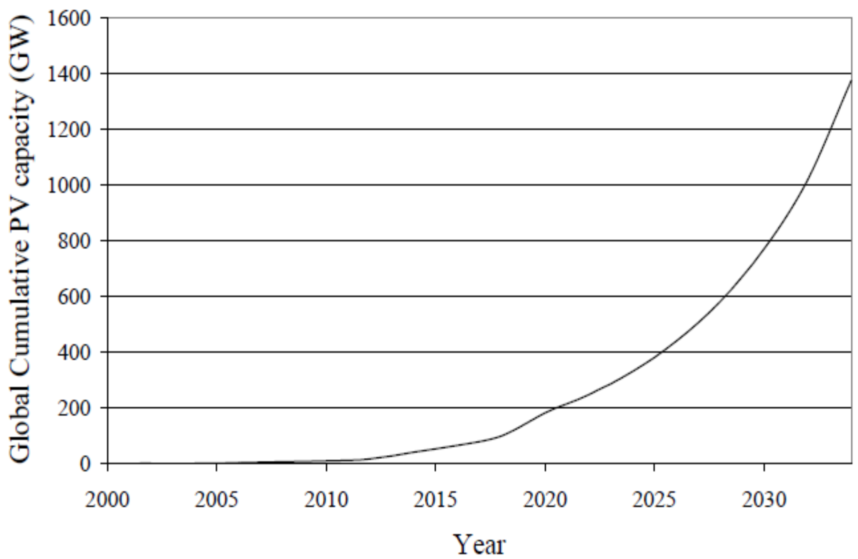

Figure 1. 1 Expected global cumulative PV capacity based on EPIA data

1.3 Thesis objectives

The aim of this thesis, study the impacts on power quality from integration decentralized Photovoltaic, based Productions in the electricity distribution network. This objective can be achieved through careful assessment the performance of the photovoltaic system without overestimating or underestimating its impacts on the electrical grid. The main objectives of the research can be summarized as follows:

- Study the impacts of the candidate geographical locations on the performance of PV system and choose the best location.
- Propose best algorithmic planning solutions for the placement of PV sources.
- Study the impact of the penetration of photovoltaic production into the distribution network.
- Search for the maximum permissible penetration level of PV sources in the distribution system.

1.4 Thesis Outline

To achieve the abovementioned objectives, this thesis was organized as follows:

- Chapter 2: PV System Components and Applications.
- Chapter 3: General overview of grid connected PV systems
- Chapter 4: Description of aspects related to the high integrations of renewable photovoltaic sources in the electricity distribution network in terms of energy quality
- Chapter 5: Study the impacts of the candidate geographical locations on the performance of PV system and choose the best location.
- Chapter 6: Study and analyzing of the impacts on energy quality to integrate decentralized Photovoltaic to grid. Sudan case study.
- Chapter 7: Conclusions and Recommendations

1.5 Conclusion

The goal of this chapter is to explain the motivation for this work done for this thesis. Explain, why renewable energy sources have more attention of researchers and investors. And explain, why the photovoltaic source (PV) is considered as the most promising technology especially in distributed generation systems (DGS).This chapter also provides the main objectives and methodology of research in addition organization of the thesis.

Chapter 2
PV System Components and Applications

2.1 Introduction

Recently, renewable energy sources have more attention of researchers and investors. Among the available renewable energy sources, the photovoltaic source (PV) is considered as the most promising technology especially in distributed generation systems (DGS) [22].There are many advantages of generation electricity from Photovoltaic system, mentioned in the previous chapter. The experience gained from the integration of PV into the distribution network provides useful guidance from the integration of other distributed energy resources (DER) techniques in the future [23].PV is an enabling technology that allows us to do things completely new, in addition to doing the old things better. It allows us to search for modern modes of supplying electricity to all markets surrounding the world. It also allows us to produce electricity, to be distributed to the transmission grid [24].

Solar cells are an electronic device that produces electricity directly from sunlight. Solar light on the solar cell produces both current and voltage to generate electricity. Photovoltaic systems are designed around the PV cell. Because the typical PV cell produces less than 3 watts at about 0.5 DC volt, PV cells must be connected in series-parallel configurations to generate sufficient energy for high energy applications [25].

The operation of a photovoltaic (PV) cell requires 3 basic attributes:

1. The absorption of light, generating either electron-hole pairs or exactions.

2. The separation of charge carriers of opposite types.

2.2 Types of Solar Cells

Solar cells are typically named after the semiconducting material they are made of these materials must have certain characteristics in order to absorb sunlight. Some cells are designed to handle sunlight that reaches the earth's surface, while others are optimized for use in space. Solar cells can be made of only one single layer of light-absorbing material (single-junction) or use multiple physical configurations (multi-junctions) to take advantage of various absorption and charge separation mechanisms [26].

The different Photovoltaic cells (PVCs) that have been developed up to date can be classified into 4 main categories called generations:

- **First-generation (1GEN):** It is based on crystalline silicon technologies, both monocrystalline (m-Si) and polycrystalline (p-Si), and on gallium arsenide (GaAs);
- **Second-generation (2GEN):** It includes amorphous silicon (a-Si) and microcrystalline silicon(µc-Si) thin films solar cells, cadmium telluride/cadmium sulfide (CdTe/CdS) and copper indium gallium selenide (CIGS) solar cells;
- **Third-generation (3GEN):** It involves technologies based on newer compounds including nanocrystalline films, active quantum dots, tandem or stacked multilayer's of inorganics based on3 to 5 materials, such as GaAs/GaInP (gallium indium phosphide), organic (polymer)-based solar cells, dyed-sensitized solar cells (DSSCs), etc.
- **Fourth-generation (4GEN):** Also known as "inorganics-in-organics", it combines the low cost/flexibility of polymer thin films with the stability of novel inorganic nanostructures such as metal nanoparticles and metal oxides or organic-based no material's like carbon nanotubes, graphene and its derivatives [6].

Figure 2.1 below show the market share of the different PV technologies [7].

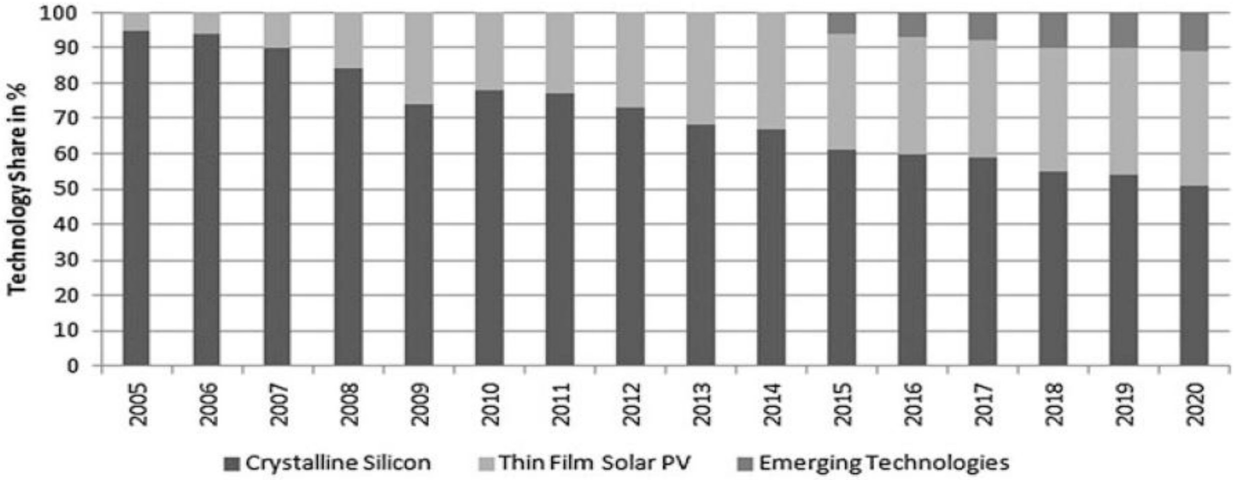

Figure 2. 1 Market share of the different PV technologies

Most 1GEN (m-Si, p-Si and GaAs) and 2GEN (a-Si, μc-Si, CdTe/CdS, and CIGS) technologies are highly standardized and have undergone few changes in recent years; they exhibit high efficiencies (20–25%) and are typically expensive, though there has been a reduction in the cost of silicon-based cells. On the other hand, the majority of 3GEN (quantum dots (QDs), perovskite cells, polymer solar cells (PSCs), DSSCs), as well as 4GEN (polymers combined with metal nanoparticles, carbon nanotubes (CNTs), grapheme (G) or its derivatives) technologies are in states very close to the so-called "basic research"; laboratory prototypes that lead to good results have been developed though they have not been implemented at an industrial scale yet (efficiencies 10–15%). However, the 3GEN multi-junction cells are already commercial, and have achieved very high energy conversion rates (>40%), thus becoming the best alternative if efficiency is sought. 4GEN cells based on CNTs, G or its derivatives are in a state of early-research, hence constitute a very promising field for investigation.

Figure 2.2 below shows a diagram of the first three generations of PVCs in terms of their costs and efficiencies.

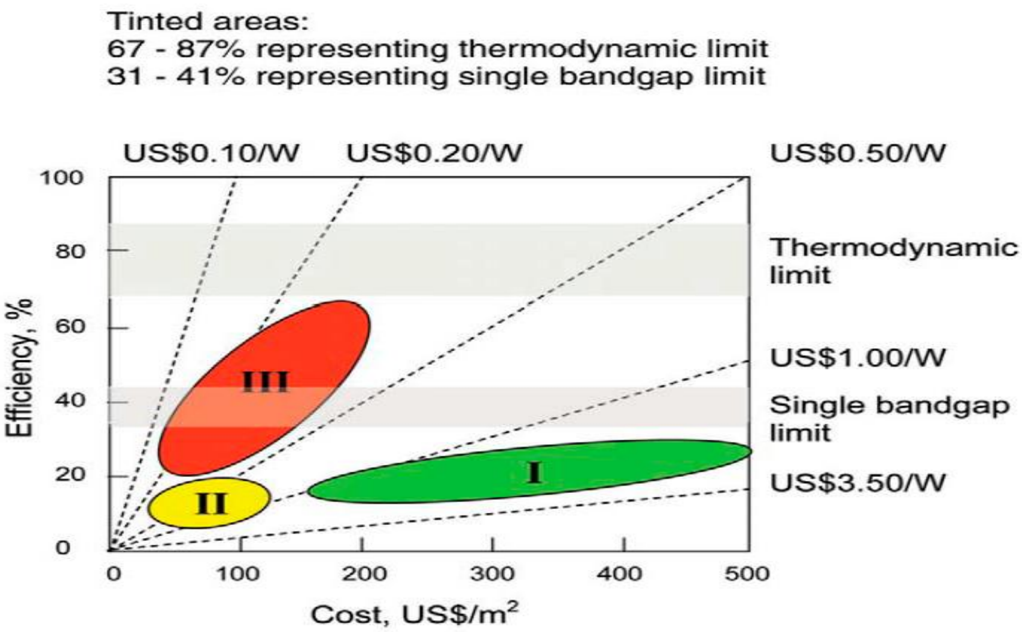

Figure 2. 2 Efficiency and cost projections for first, second and third generation PV technologies.

Figure 2.3 below show cumulative global PV installations in 2021.

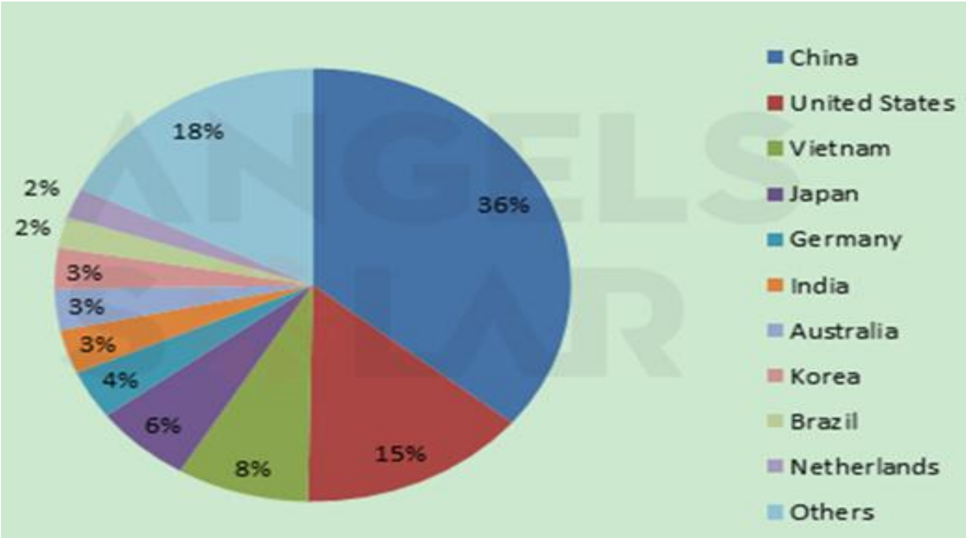

Figure 2. 3Cumulative global PV installations in 2021.

Figure 2.4 below show Cumulative global solar PV installed capacity by region [28].

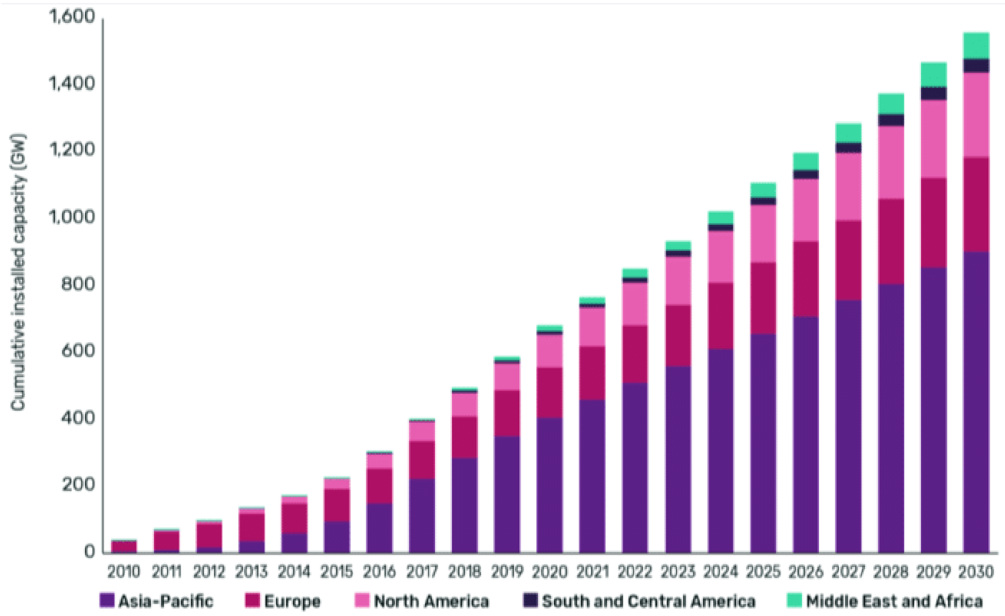

Figure 2. 4 Cumulative global solar PV installed capacity by region (2010-2030)

Photovoltaic system types can be broadly classified by answers to the following questions:

- Will it be connected to the utility's transmission grid?
- Will it produce alternating current (AC) or direct current (DC) electricity, or both?
- Will it have battery back-up?
- Will it have back-up by a diesel, gasoline or propane generator set ...etc?

Here we will focus on systems that are connected to the utility transmission grid, variously referred to as utility-connected, grid-connected, grid-interconnected, grid-tied or grid-intertied systems. These systems generate the same quality of alternating current (AC) electricity as is provided by your utility. The system to be studied is integration of decentralized photovoltaic-based productions in the electricity distribution network without battery back-up or generator back-up.

2.3 A Brief Glossary of Key PV Terms

- Solar radiation: Radiation originating from the Sun, in the 0.3 to 3 mm wavelength spectrum.

- Solar spectrum: Distribution of solar radiation intensity as a function of wavelength or frequency.

- Direct solar radiation: Solar radiation arriving at a plane directly from the solar disc.

- Diffuse solar radiation: Solar radiation arriving at a plane after scattering by atmospheric particles (e.g. water droplets, clouds) or ambient reflection.

- Global radiation: The sum of direct and diffuse solar radiation (i.e. aggregate radiation originating from the Sun) arriving at a level surface.

- Global irradiance G: Power density (power/area) of the global radiation arriving at a plane. Unit: W/m2.

- Irradiation H (radiation energy): Energy density (energy/area) of the global radiation arriving at a plane within a certain time interval, calculated by integration of irradiance G over this time interval. Common time intervals are one year (a), one month (mt), one day (d) or one hour (h). Units: kWh/m2 and MJ/m2 (kWh/m2 is more expedient for PV applications). Conversion: 1 kWh=3.6 MJ and 1MJ=0.278 kWh.

- Pyranometer: Instrument for measuring global radiation (global irradiance G) on a level surface over the whole wavelength range between approx. 0.3 and 3 µm. Based on the thermoelectric principle, pyranometers are highly accurate but expensive instruments that are mainly used by weather services.

- Reference cell: A calibrated solar cell for measuring global radiation G on a level surface. Reference cells are much cheaper than pyranometers. Like an actual solar cell, a reference cell only utilizes a portion of total incident insulation and is calibrated such that under standard conditions (standard spectrum AM1.5, where G =1 kW/m2) it exhibits the same insulation as a Pyranometer. In practice there are discrepancies ranging up to several per cent between the values indicated by pyranometers and reference cells, depending on the weather conditions.

- Solar altitude: Angle between the direction of the Sun (center of the solar disc) and the horizontal plane.

- Solar azimuthγ_s: For $\Phi > \delta$, the angle between south and the projection of the direction of the Sun on a horizontal plane. For $\Phi < \delta$, the angle between north and the projection of the direction of the Sun on a horizontal plane. In both cases, $\gamma_s<0$ for deviations to the east, $\gamma_s>0$ for deviations to the west. ((Φ = latitude, δ = solar declination).

- Solar generator tilt angle β: Angle between the solar cell plane and horizontal.

Solar generator orientation (solar generator azimuth) γ: In the northern hemisphere, the angle (clockwise) between south and the normal projection (vertical) of the solar cell and horizontal. In the southern hemisphere, the angle (anticlockwise) between north and the normal projection of the solar cell and horizontal. In both cases, $\gamma <0$ for deviations to the east, $\gamma >0$ to the west.

- Relative air mass number (AM): Ratio of (a) the actual atmospheric mass (optical thickness) through which solar radiation travels to (b) the minimum possible atmospheric mass at sea level (applicable when the Sun is at its zenith) [32].

2.4 PV System Components

Earlier before 1999, the market of PV was in off grid applications, for example pumping of water, rustic electricity and telecommunications. But in the present more than 78% of the global market is for grid connected applications where power is fed into the electrical grid.

Moreover, more capacity of a new PV installed in the distribution network as generation distributed [29]. The types of components in the PV system vary depending on the type of system and purpose. In this thesis we will discuss the basic components of grid connected PV systems. The system consists essentially of photovoltaic arrays, which converts the sunlight to DC power, and a power conditioning units that converts the DC power to AC power, and then injected into the grid and/or utilized by the local loads. To improve the availability of photovoltaic power, storage devices are used in some applications. Figure 2.5 below show the main components of grid-connected photovoltaic systems.

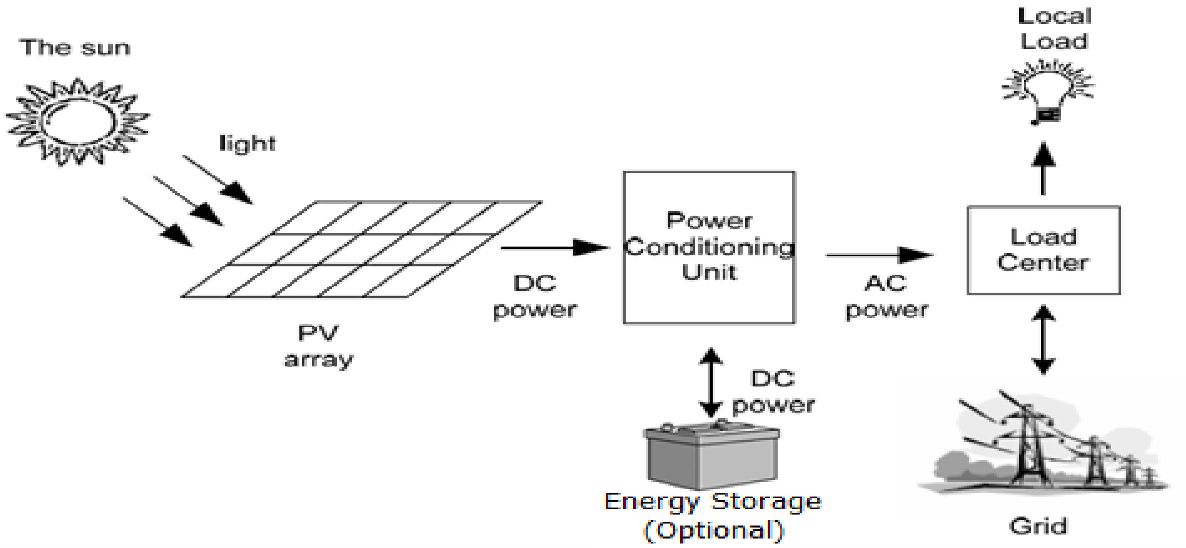

Figure 2. 5 Main components of grid-connected photovoltaic systems

2.4.1 The sun

The sun's energy, which emits at one hour, is sufficient for the earth's energy needs for almost a year. In other ways, this is 5,000 times the earth's energy budget input from all other sources.

The sun is composed of a mixture of gases with a predominance of hydrogen. As the sun converts hydrogen to helium in a massive thermonuclear fusion reaction, mass is converted to energy according to Einstein’s famous formula, E =mc2 (mass (m), speed of light (c2) is constant 300,000 km/s and kinetic energy (E).The amount of sunlight absorbed or dispersed depends on the length of the path across the atmosphere. The length of the path is generally compared with the vertical path directly to sea level, which is chosen as air mass = 1 (AM1). At AM1, after absorption has been accounted for, the intensity of the global radiation is generally reduced from 1367 W/m2 at the top of the atmosphere to just over 1000 W/m2 at sea level.

Radiation is a measure of the energy density of the sun and measured in W / m2.Thus, radiation is an instantaneous quantity. Thus, at a certain time, or on a particular day, these quantities depend on the location, weather conditions and time of year. It also depends on whether the surface of interest is shaded by trees or buildings and whether the surface is horizontal or tilted. The daily irradiation is numerically equal to the daily peak sun hours. The global irradiance, which reaches a horizontal surface on earth, is a sum of two components direct irradiance and diffuse irradiance. Different types of instruments are used to measure global, beam, diffuse or albedo components of irradiance. Figure 2.6 shows some devices are used to measure irradiance a. Black and white Pyranometer, b. Pyrheliometer with tracker, and c. Pyranometer mounted on a shadow band stand.

Figure 2. 6 a. Black and white Pyranometer b. Pyrheliometer with tracker c. Pyranometer on shadow band stand

The black and white Pyranometer is designed to measure global radiation, and operates on the principle of differential heating of a series of black and white wedges. It is normally mounted horizontally to collect general data for global radiation on a horizontal surface. The temperatures of each wedge are measured with thermocouples that yield voltage differences dependent on the temperature differences. The output voltage, approximately 10 μ V/W/m2, is then calibrated with respect to incident energy. The normal incidence Pyrheliometer uses a long, narrow tube to collect beam radiation over a narrow beam solid angle. The Pyranometer can be mounted on a shadow band stand to block out beam radiation so that it will respond only to the diffuse component [30].

There are three components of irradiance on inclined surfaces

- Direct (Beam) radiation, is the irradiance that reaches directly to the horizontal surface without being scattered in the atmosphere.
- Diffuse (Albedo) radiation, it reaches the horizontal surface after being scattered by clouds.
- Reflected radiation, it is the radiation that is reflected by the grounding of the surrounding area (likewise diffuse).

Figure 2.7 shows the three components of irradiance on inclined surfaces. Usually the Photovoltaic arrays are tilted to obtain the highest energy output of the system by maximizing the direct radiation that can be received.

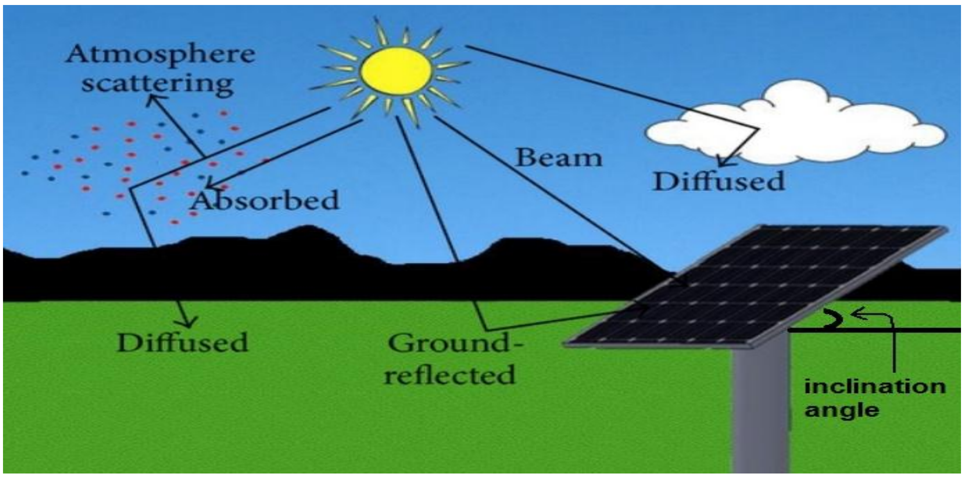

Figure 2. 7 Beam, Diffuse and Reflected radiation on inclined surface

The angle of inclination is the optimal angle at all times, giving the possibility of more solar energy on the inclined surface than the horizontal surface. Therefore, accurate knowledge of the global historical solar radiation is required at the study site to design and estimate the performance of any solar system. Knowing the incident of solar radiation on an inclined surface is essential for architects and engineers to design energy-efficient buildings and solar energy applications [33].

The direct radiation a surface receives depends on the angle of incidence of the solar rays. The diffuse radiation received by the inclined surface does not depend on the direction of the plane and does not come from the entire vault of the sky or the adjacent ground, it only comes from the part of the sky that the surface sees.

The solar radiation incident on a surface depends, among other things, on its slope and its orientation. For a surface in a particular location, increasing the slope leads to more radiation during winter than summer. Therefore, for solar applications that require energy from solar panels mainly during the winter, the slope must be large, whereas when the panels are used during summer, the slope should be small.

For maximum energy availability during winter, summer and the entire year, a base rule that applies to the collector slope is that this slope should respectively be approximately 10° to 15° greater than the latitude, approximately 10° to 15° smaller than the latitude, and equal to the latitude of the site. Hence, different sites/locations have different optimal slope angles for solar panels. The base rule mentioned above for the inclination of a fixed panel gives good results when applied in small solar installations. However, in the case of large solar installations, the slight change in slope corresponds to a large shift in incident radiation. In photovoltaic systems the cost of solar panels is high, it is necessary to study the optimum slope for each particular application.

For example, if photovoltaic panels are to be used for a grid connected system that remains effective throughout the year, the optimal slope must be calculated with the maximum solar irradiation on panels throughout the year. Usually, this optimum panel angle is close to the latitude angle. However, in the case of a stand-alone photovoltaic system with batteries as an energy store, the standard may not be the total solar irradiation, but the daily irradiation during the month with minimal amount of solar radiation, in order to reduce energy storage requirements. For example, in the northern hemisphere, December is the month with the lowest radiation rate, so the angle of the plate will be larger than the latitude angle. In general, the optimum panel slope is determined by the latitude of the site, the planned application and the time period intended to use the solar system [34].

The fluctuation of solar radiation has a very significant effect on the performance and reliability of the photovoltaic power system (PV).Currently, one of the major research activities in this area focuses on the analysis of short-term radiation fluctuations due to the passage of clouds. Some of these studies use frequency domain analysis to estimated frequency of occurrence of fluctuations along with their amplitude for each particular [35]. Other studies use frequency domain analysis to check the effect of radiation fluctuation on the performance of photovoltaic system in that area [36-37].

2.4.2 Solar Modules or PV arrays

The main part of a solar electric system, which converts the sunlight to DC power. Since 1839 until 1959 a laboratory curiosity started to study the photovoltaic effect. In 1954 by Japan et al, at Bell Laboratories was developed the first silicon solar cell with an efficiency of 6%[38].Nowadays, modern solar efficiency floats around 20% for residential applications and 40% for large scale power utility applications.

Photovoltaic systems are designed around the photovoltaic cell. Since a typical photovoltaic cell produces less than 3 watts at approximately 0.5 volt dc, cells must be connected in series-parallel configurations to produce enough power for high-power applications. Figure 2.8 shows how cells are configured into modules, and how modules are connected as arrays. Modules may have peak output powers ranging from a few watts, depending upon the intended application, to more than 300 watts. Typical array output power is in the 100-wattto- kilowatt range, although megawatt arrays do exist.

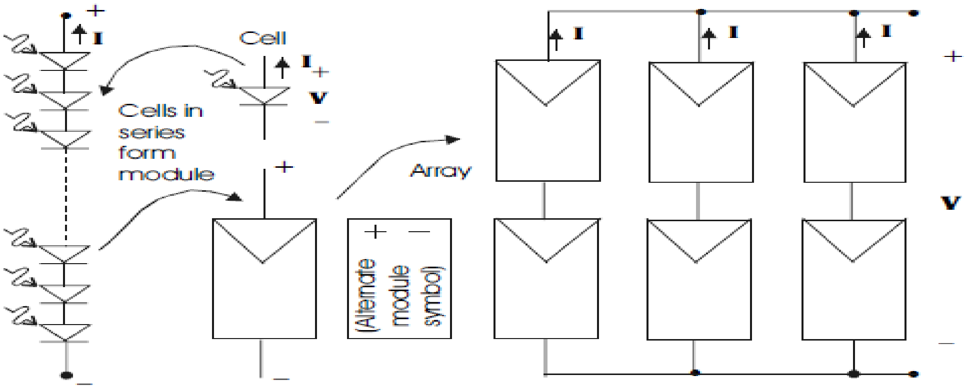

Figure 2. 8 Cells, modules and arrays

2.4.2.1 The PV Cell

The PV cell is a specially designed pn junction or Schottky barrier device. The well-known diode equation describes the operation of the shaded PV cell [30].A photovoltaic PV generator is mainly an assembly of solar cells, connections, protective parts, and supports. As was seen already, solar cells are made of semiconductor materials, usually silicon, and are specially treated to form an electric field with positive on one side (backside) and negative on the other side (front side facing the sun). When solar energy (photons) hits the solar cell, electrons are knocked loose from the atoms in the semiconductor material, creating electron–hole pairs. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons are captured in the form of electric current, called photocurrent, Iph. As can be understood from this description, during darkness the solar cell is not active and works as a diode, i.e., a p–n junction that does not produce any current or voltage. If, however, it is connected to an external, large voltage supply, it generates a current, called the diode or dark current, ID. A solar cell is usually represented by an electrical equivalent one-diode model, shown in Figure 2.9. This circuit can be used for an individual cell, a module consisting of a number of cells, or an array consisting of several modules.

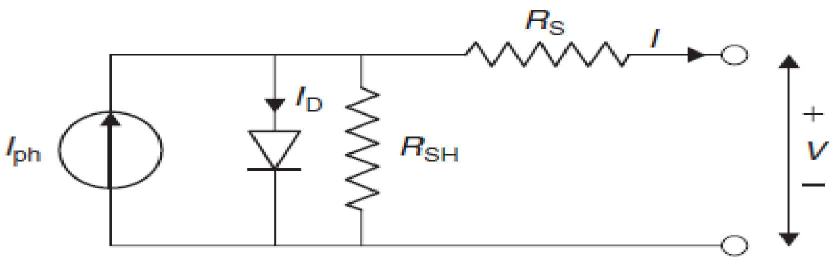

Figure 2. 9 Single solar cell module

As shown in Figure 2.9, the model contains a current source, Iph, one diode, and a series resistanceR_s, which represents the resistance inside each cell. The diode has also an internal shunt resistanceR_{sh}, The net current is the difference between the photocurrent, Iph, and the normal diode current, I_D, given by:

$$I=I_{ph}-I_D=I_{ph}-I_o\ [\exp\ (e\ (V+IR_s)/\ KT_C)\ -1]\ -\ ((V+IR_s)\ /R_{SH}) \qquad (2.1)$$

It should be noted that the shunt resistance is usually much bigger than a load resistance, whereas the series resistance is much smaller than a load resistance, so that less power is dissipated internally within the cell. Therefore, by ignoring these two resistances, the net current is the difference between the photocurrent, Iph, and the normal diode current, ID, given by:

$$I = I_{ph} - I_D = I_{ph} - I_o \left[\exp\left(eV / KT_C\right) - 1\right] \quad (2.2)$$

Where:

k: Boltzmann's gas constant = 1.3805 × 10^{-23} J/K;
T_c: absolute temperature of the cell (K);
e: electronic charge Electron charge = 1.602 × 10^{-19} J/V;
V: voltage imposed across the cell (V); and
Io: dark saturation current, which depends strongly on temperature (A).
Figure 2.10 below shows the I–V characteristic curve of a solar cell for certain irradiance (Gt) at a fixed cell temperature (T_c). The current from a PV cell depends on the external voltage applied and the amount of sunlight on the cell. When the cell is short-circuited, the current is at maximum (short-circuit current, Isc), and the voltage across the cell is 0. When the PV cell circuit is open, with the leads not making a circuit, the voltage is at its maximum (open-circuit voltage, Voc), and the current is 0. In either case, at open circuit or short circuit, the power (current times voltage) is 0. Between an open circuit and a short circuit, the power output is greater than 0. The typical current voltage curve shown in Figure 2.10 presents the range of combinations of current and voltage. In this representation, a sign convention is used, which takes as positive the current generated by the cell when the sun is shining and a positive voltage is applied on the cell's terminals.

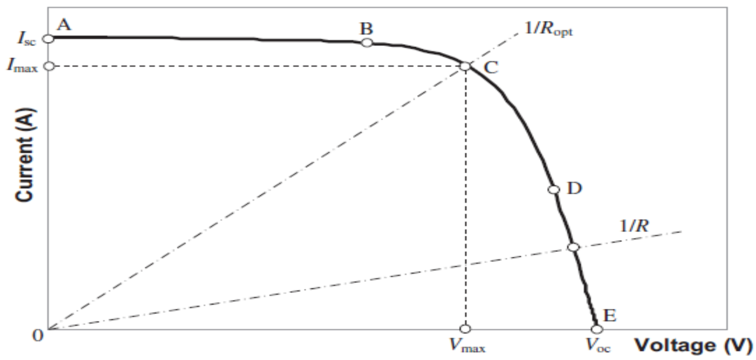

Figure 2. 10 I-V characteristics of a single PV cell

If the terminals of the cell are connected to a variable resistance, R, the operating point is determined by the intersection of the I–V characteristic of the solar cell with the load I–V characteristics. As shown in Figure 2.10 for a resistive load, the load characteristic is a straight line with a slope 1/V= 1/R. If the load resistance is small, the cell operates in the region AB of the curve, where the cell behaves as a constant current source, almost equal to the short-circuit current. On the other hand, if the load resistance is large, the cell operates on the region DE of the curve, where the cell behaves more as a constant voltage source, almost equal to the open-circuit voltage. The power can be calculated by the product of the current and voltage. If this exercise is performed and the results are plotted on a P–V graph, then Figure 2.11 can be obtained.

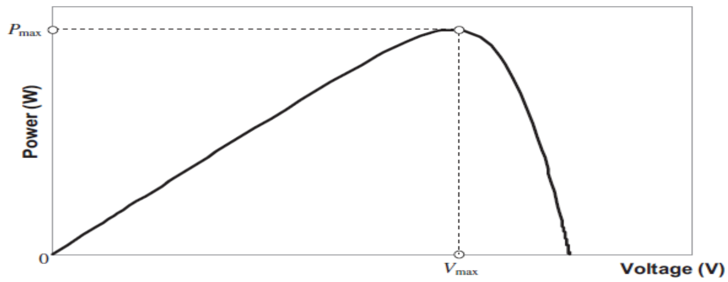

Figure 2. 11 P-V characteristics of a single PV cell

The maximum power passes from a maximum power point (point C on Figure 2.11 given by:

$$P_{max} = I_{max}V_{max} \tag{2.3}$$

The load current, I_{max}, which maximizes the output power, can be found by:

$$I_{max}=\frac{eV_{max}}{KT_C+eV_{max}}(I_{sc}+I_o) \tag{2.4}$$

Where:
I_{sc}: Short circuit current
By using Eq. (2.3),

$$P_{max}=\frac{eV_{max}^2}{KT_C+eV_{max}}(I_{sc}+I_o) \tag{2.5}$$

Efficiency is another measure of PV cells that is sometimes reported. Efficiency is defined as the maximum electrical power output divided by the incident light power. Efficiency is commonly reported (the PV performance in terms of Standard Reporting Conditions SRC)for a PV cell temperature of 25 C and incident light at an irradiance of 1000 W/m2 with a spectrum close to that of sunlight at solar noon.

The maximum efficiency, which is the ratio between the maximum power and the incident light power, given by:

$$\eta=\frac{Pmax}{GtA}=\frac{ImaxVmax}{GtA} \tag{2.6}$$

Where: A = cell area (m2).

The I–V characteristic of the solar cell, presented in Figure 2.10, is only for a certain irradiance, Gt, and cell temperature, TC. The influences of these two parameters on the cell characteristics are shown in Figure 2.12. As shown in Figure 2.12(a), the open-circuit voltage increases logarithmically by increasing the solar radiation, whereas the short circuit current increases linearly. The influence of the cell temperature on the cell characteristics is shown in Figure 2.12(b). The main effect of the increase in cell temperature is on open-circuit voltage, which decreases linearly with the cell temperature; thus the cell efficiency drops. As can be seen the short-circuit current increases slightly with the increase of the cell temperature.

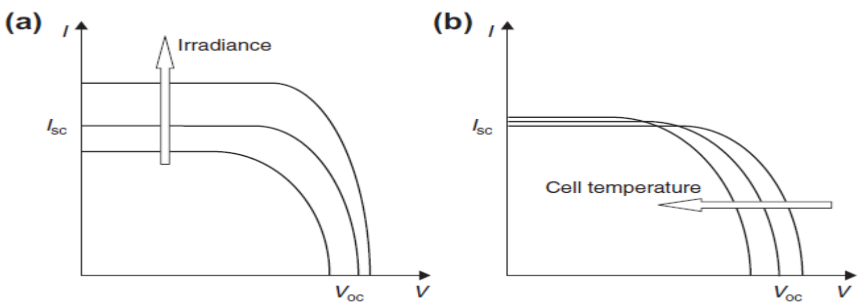

Figure 2. 12 2Influence of irradiation and cell temperature on PV cell characteristics.

(a) Effect of increased irradiation (b) Effect of increased cell temperature

In practice solar cells can be connected in series or parallel. Figure 2.13 shows how the I–V curve is modified in the case where two identical cells are connected in parallel and in series. As can be seen, when two identical cells are connected in parallel, the voltage remains the same but the current is doubled; when the cells are connected in series, the current remains the same but the voltage is doubled.

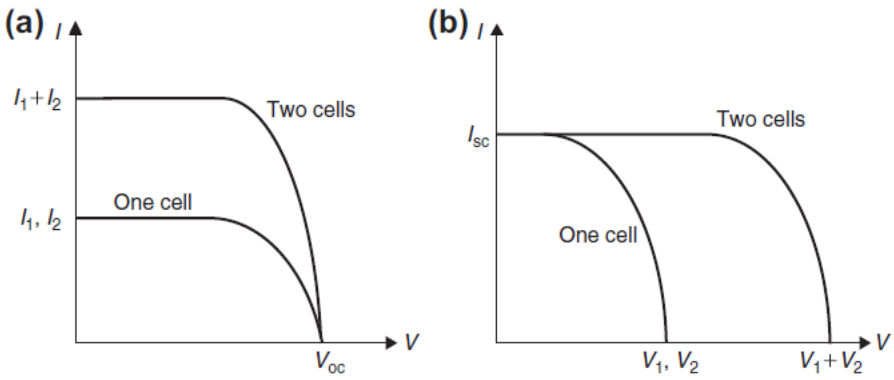

Figure 2. 13 Parallel and series connection of two identical solar cells. (a) Parallel connection. (b) Series connection [39].

2.4.2.2 The PV Module

In order to obtain adequate output voltage, PV cells are connected in series to form a PV module [30]. One single crystalline silicon solar cell with a surface area of approximately100 cm2 generates a current of 3A at a voltage of 0.5V [31]. The design goal is to connect a sufficient number of cells in series to keep Vm of the module within a comfortable range of the battery/system voltage under conditions of average irradiance. If this is done, the power output of the module can be maintained close to maximum. When connecting a module into a system, one consideration is what happens when the module is not illuminated. This can happen at night, but can also happen during the day if any cell or portion of a cell is shaded by any means. Under nighttime conditions, when none of the cells are generating appreciable photocurrent, it is necessary to consider the module as a series connection of diodes that may be forward biased by the system storage batteries, as shown in figure 2.14.If another diode is connected in series with the module to prevent current from flowing in the reverse direction, this blocking diode will then have a forward voltage drop and associated power loss of more than 1 watt when the module is providing photocurrent. If the module is only providing 50 watts, this loss represents 2–3% of the total module output power.

The exact number of cells will depend on the performance characteristics of the individual cell. Manufacturers of modules specify the open circuit voltage and short circuit current of the modules along with the module maximum power rating under full sun test conditions. To protect the system against such failure, modules are generally protected with bypass diodes, as shown in Figure 2.14 If PV current cannot flow through one or more the PV cells in the module, it will flow through the bypass diode instead [30]..

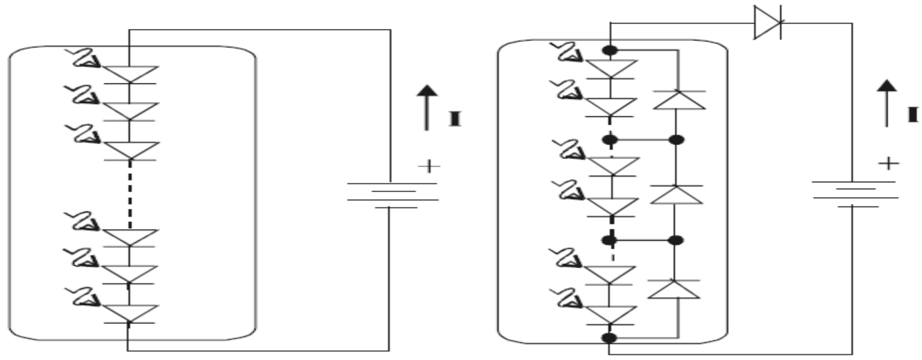

Figure 2. 14 Battery discharge path through PV module with and without blocking diode a. Module without blocking or bypass diodes b. Module with blocking and bypass diodes

PV modules are designed for outdoor use in such harsh conditions as marine, tropic, arctic, and desert environments. The choice of the photovoltaic ally active material can have important effects on system design and performance. Both the composition of the material and its atomic structure are influential. Photovoltaic materials include silicon, gallium arsenide, copper indium dieseline, cadmium telluride, indium phosphide, and many others. The atomic structure of a PV cell can be a single crystal, polycrystalline, or amorphous. The most commonly produced PV material is crystalline silicon, either single crystal or polycrystalline. As shown in Figure 2.15, PV cell modules consist of N_{PM}parallel branches and each branch has N_{SM} solar cells inseries. In the following analysis, superscript M refers to the PV module and superscript C refers to the solar cell. Therefore, as shown in Figure 2.16, the applied voltage at the module's terminals is denoted by V^{M}, whereas the total generated current is denoted by I^{M}.

A model of the PV module can be obtained by replacing each cell in figure 2.15 with the equivalent diagram from Figure 2.10. The model has the advantage that it can be used by applying only standard manufacturer-supplied data for the modules and the cells. The PV module current I^{M} under arbitrary operating conditions can be described by:

$$I^{M} = I_{sc}^{M}[1 - \exp((V^{M} - V_{oc}^{M} + R_{s}^{M} I^{M}) / N_{SM} V_{t}^{C})] \quad (2.7)$$

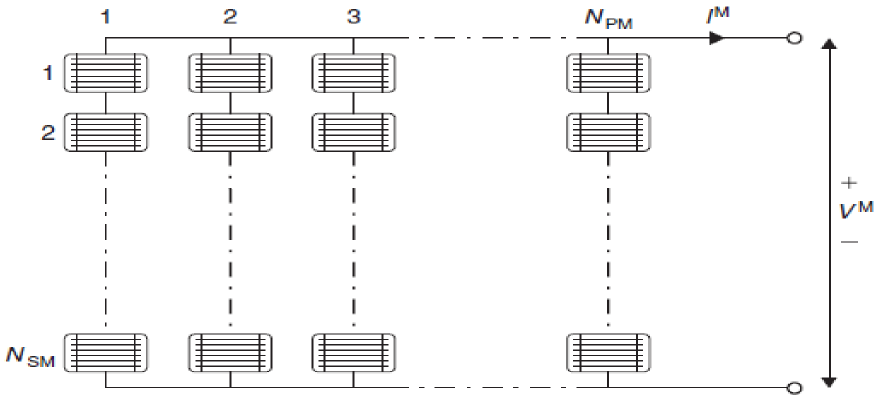

Figure 2. 15 Schematic diagram of a PV module consisting of N_{PM} parallel branches, each with N_{SM}cells

The current practice dictates that the performance of a PV module is determined by exposing it at known standard rating conditions (SRCs) of irradiance, $G_{t,o} = 1000\ W/m^{2}$, and cell temperature, $T_{0}^{C}=25^{0}C$. These conditions are different from the nominal operating cell temperature (NOCT), as indicated in Table2.1.

Table 2. 1 SRC and NOCT Conditions

SRC Conditions	**NOCT Conditions**
Irradiation:$G_{t,o}$ = 1000 W/m^2	Irradiation:$G_{t,NOCT}$ =800 W/m^2
Cell temperature:T_O^C =25^0C	Ambient temperature: $T_{a,NOCT}$ =20^0C
	Wind speed: W_{NOCT}= 1 m/s

2.4.2.3 PV arrays

The modules in a PV system are usually connected in arrays. An array with M_P parallel branches each with M_S modules in series (called string) is shown in figure 2.16. By using a superscript A to denote array characteristics, the applied voltage at the array's terminals is denoted V^A, whereas the total current of the array is denoted I^A, given by:

$$I^A = \sum_{i=1}^{M_P} I_i \qquad (2.8)$$

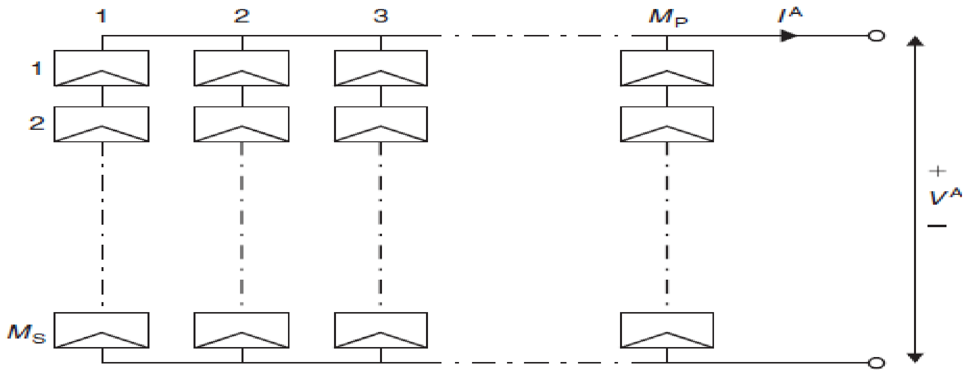

Figure 2. 16 Cell array consisting of MP parallel branches, each with MS modules in series.

Depending on the manufacturer and the type of PV material, modules have different appearances and performance characteristics. Also, modules may be designed for specific conditions, such as hot and humid, desert, or frozen climates. Usually, the cells are series connected to other cells to produce an operating voltage around 30–60 V. These strings of cells are then encapsulated with a polymer, a front glass cover, and a back material. Also, a junction box is attached at the back of the module for convenient wiring to other modules or other electrical equipment [39].

The following performance criteria determines the amount of PV output.

- **Power Output**

Power output is represented in watts and it is the power available at the charge controller/regulator specified either as peak power or average power produced during one day.

- **Energy Output**

Energy Output indicates the amount of energy produced during a certain period of time and it is represented in Wh/m2.

- **Conversion Efficiency**

It is defined as energy output from array to the energy input from sun. It is also referred as power efficiency and it is equal to power output from array to the power input from sun. Power is typically given in units of watts (W), and energy is typical in units of watt-hours (Wh).

2.4.3 Power Conditioning Units

In PV systems, power conditioning units (PCUs) are used to provide a match between the specific characteristics of the PV generator and the connected balance of system (BOS) components. In general, the characteristic curve of a PV generator varying with solar radiation and temperature does not match the characteristic curve of the load. In those cases, the power conditioning unit effects a transformation of the load's voltage and current in such a way, that the PV generator is operated at its optimum operation voltage V_{MPP} even under changing boundary conditions. The characteristics of the most common power conditioning units are charge controllers, DC/DC converters and inverters. In almost every stand-alone system, a charge controller is required to optimally operate the storage battery within safe limits as prescribed by the manufacturer [24].

Depending on the application, the converters used for grid connection are built using one or two conversion stages, show in figure 2.17.In single conversion stage, an inverter is used to perform all the required control tasks. But, in the second conversion stage, the power injected to the inverter from a DC-DC converter, and the control tasks are divided among the two converters. Two-stage configurations, allow an independent control of the voltage per string. It is suitable in order to perform distributed maximum power point tracking (MPPT) algorithms, with higher energy yields in the case of partial shading. Converter requirements for PV applications are related with the conversion efficiency, reliability, and the economic cost [40].Even though these two stage converters have been in existence for a while and work well, but due to a higher number of part count they have a drawback of lower efficiency along with higher costs, bigger size and low reliability [41].

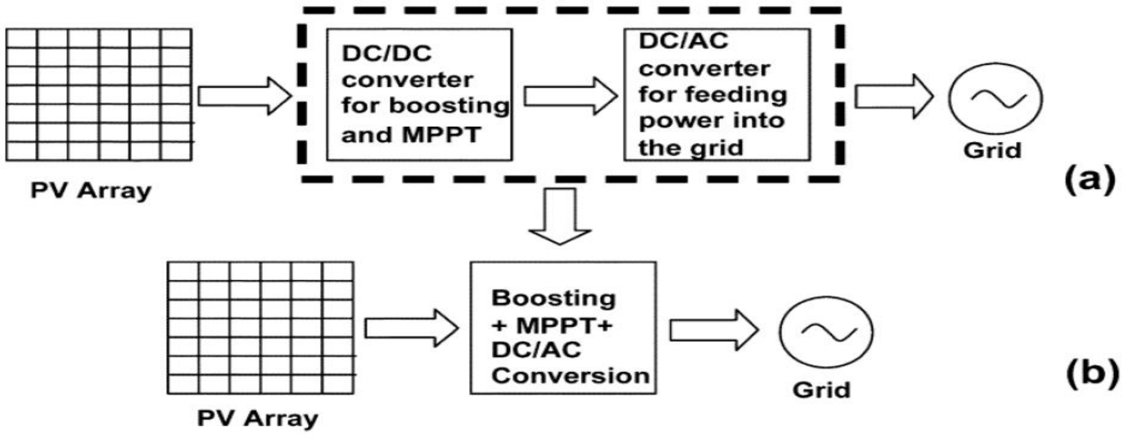

Figure 2. 17 Grid connected PV system topologies

(a) Conventional two-stage and (b) Single-stage configuration

The power range of the PV system could vary from hundreds of watts to thousands of megawatts, which need to comply with specific standards for different countries. The grid requirements are an important specification that has a big impact on the design and performance of the PV generation system. Grid requirements proposed by local grid companies in most countries are making efforts to come up with standard grid requirements that can be applied in most areas. Among these institutions, IEEE (Institute of Electrical and Electronic Engineers) in the US, IEC (International Electrotechnical Commission) in Switzerland and DKE (German Commission for Electrical, Electronic and Information Technologies of DIN and VDE) in Germany are the most popular ones that are developing worldwide standards for grid requirements in the PV market [42].

Inverters are used to convert the DC output of PV or a storage battery to AC electricity, either to be fed into the grid or to supply a stand-alone system. There are many different types of power electronic topologies used in the market. Early PV systems were equipped with thyristor inverters, which are commutated by the grid. Due to their poor voltage and current quality – such inverters have very large harmonics – they have been replaced in the market by self-commutating inverters (with insulated-gate bipolar transistor (IGBT) or metal oxide semiconductor field-effect transistor (MOSFET) as semiconductor switches).

The serial production of PV inverters was launched in the nineties. Before that time, only a small number of inverters were needed, mostly for stand-alone applications, for example, for residential PV systems. Because there was no connection to the public grid, the standard of power quality in the system was not as significant as it has to be if the generated power is fed into the grid. Inverter efficiency is generally more important in PV applications but of particular significance at partial load, as the bulk of the energy is yielded at partial load. Furthermore, with a large-area PV generator coupled to the DC side of the inverter and the public grid on the AC side, stricter standards have to be met with respect to harmonics and electromagnetic compatibility (EMC). EMC that mean the inverter is not allowed to send out electromagnetic waves or signals that can influence other electric devices, including the reception of television and radio. On the other side, incoming electromagnetic waves or signals should not affect the correct operation of the inverter.

Some design criteria and functionality of PV inverters are:

- Efficiency: well above 90% already at 5% of nominal load.
- Cost.
- Voltage and current quality: harmonics and EMC.
- Overload capability: some 20–30% for grid-connected inverters, up to 200% for short-time overload of island inverters.
- Precise and robust MPP tracking (reliably finding the overall MPP in partial shading situations).
- Supervision of the grid, safety/an islanding prevention.
- Data acquisition and monitoring [31].

Apart from the efficient conversion of direct to alternating current, the inverter electronics also include components that are responsible for the daily operation mode. They ensure that operation starts at the right time in the morning as soon as the solar cells deliver enough power. Unsuccessful start attempts require energy from the grid and should be avoided by good controls. During the day, the optimum working point on the I-V characteristic curve shifts according to the fluctuations in solar radiation and module temperature.

Intelligent inverter control includes maximum power point (MPP) tracking and continuous readjustment to the most favorable working point. Protective devices are also integrated into the inverter, which automatically disconnect the system if irregularities in the grid or the solar generator occur [24].Inverter interfacing PV module(s) with the grid involves two major tasks. One is to ensure that the PV module(s) is operated at the maximum power point (MPP). The other is to inject a sinusoidal current into the grid. These tasks are further reviewed in this section.

A. Demands Defined by the Grid

When connecting the inverter to the grid, the standards given by the utility companies must be taken. These standards deal with issues such as power quality, total harmonics distortion (THD), harmonics levels, detection of islanding operation, grounding, etc. It is important that any inverter system connected to the grid does not in any significant way degrade the quality of supply at the point of connection. It is also important to consider the effects of a poor quality of supply on an inverter added to the system. The harmonic content of most modern pulse with modulated sine wave inverters is typically less than 3% THD. This is better than the grid supply in many areas because of the many electronic loads connected to the grid which has simple rectifier front ends [43].To handle current harmonics, is easier to cope with the corresponding IEEE and IEC standards. This is also reflected in the chosen inverter topologies, which have changed from large thyristor-equipped grid-connected inverters to smaller insulated-gate-bipolar-transistor (IGBT)/MOSFET-equipped ones.

Islanding is the continued operation of the inverter when the grid has been removed on purpose, by accident, or by damage. In other words, the grid has been removed from the inverter, which then only supplies local loads. Therefore, the inverters must be able to detect an islanding situation, and take appropriate measures in order to protect persons and equipment. The available detection schemes are normally divided into two groups: active and passive. The passive methods do not have any influence on the power quality, since they just monitor grid parameters. The active schemes introduce a disturbance into the grid and monitor the effect. This may affect the power quality, and problems with multiple inverters in parallel with the grid are also known to exist. The IEEE and the IEC standards put limitations on the maximum allowable amount of injected dc current in to the grid. The purpose of limiting the injection is to avoid saturation of the distribution transformers.

The NEC 690 (National Electrical Code) standard demands that the PV modules shall be system grounded and monitored for ground faults, when the maximum output voltage of the PV modules reaches a certain level.

B. Demands Defined by the Photovoltaic Module(s)

The inverters must guarantee that the PV module(s) is operated at the MPP, which is the operating condition where the most energy is captured. This is accomplished with an MPP tracker (MPPT). It also involves the ripple at the terminals of the PV module(s) being sufficiently small, in order to operate around the MPP without too much fluctuation.

C. Demands Defined by the Operator

The operator (the owner) also has a few words to say. First of all, the inverter must be cost effective, which is easily achieved with similar circuits as these used in today’s single-phase power-factor-correction (PFC) circuits and variable-speed drives (VSDs). However, the user also demands a high efficiency over a wide range of input voltage and input power since these variables are defined in very wide ranges as functions of solar irradiation and ambient temperature. Further, the inverter must be highly reliable (long operational lifetime) since most PV module manufacturer offer a warranty of 25 years on 80% of initial efficiency, and a materials and workmanship warranty of five years [44].

Generally, commercial grid connected inverters comply with harmonic levels, total harmonics distortion (THD), power factor, dc current level, frequency variation, islanding detection, leakage current and grounding issues. In Table 2.2, a summary of the grid requirement in three typical standards considering the harmonic levels, injected dc current, voltage variation and frequency variation is presented. IEEE 1547 is most influential standard for interconnection of all forms to develop a single interconnection standard that applies to all technologies. IEC 61727 has done a great job in harmonizing the grid requirements. VDE 0126-1-1 has extended the thresholds for disconnection in the case of abrupt grid impedance changes and even allows an alternative method of an anti-islanding requirement similar to IEEE 1547 [43].

Table 2. 2 Summary of the grid requirements in different standards.

	IEEE 1547		IEC 61727		VDE0126-1-1	
Nominal power	30 kW		10 kW		-	
Harmonic level	Order	%	Order	%	Order	A
	3–9	4.0	3–9	4.0	3	3
	11–15	2.0	11–15	2.0	5	1.5
	17–21	1.5	17–21	1.5	7	1
	23–33	0.6	23–33	0.6	9	0.7
	>35	0.3	>35	0.3	11	0.33
					13	0.4
	even harmonics < 25% of odd harmonics				even	1.5/h
	total harmonics distortion (THD) < 5%				>40	4.5/h
DC current	<1% of rated current		<0.5% of rated current		<0.22 A	
Votlage variation	V < 50%	0.1 s	V < 50%	0.16 s	V < 85%	0.2 s
	50% < V < 88%	2 s	50% < V < 88%	2 s	V > 110%	0.2 s
	110% < V < 120%	2 s	110% <V < 120%	1 s		
	V > 120%	0.05 s	V > 120%	0.16 s		
Frequency variation	49 Hz < f < 49 Hz	0.2 s	59.3 Hz < f < 60.5 Hz	0.16 s	47.5 Hz < f < 50.2 Hz	0.2 s

Today most inverter models are additionally equipped with data loggers and measurement computers, which allow the power, voltage, current and other operating parameters to be recorded continuously. These data can be read out at intervals via a serial interface with a laptop computer and analyzed [24].

2.4.4 Energy storage

Electrical Energy Storage (EES) refers to a process of converting electrical energy from a power network into a form that can be stored for converting back to electrical energy when needed. There are variety types of EES such as Pumped Hydroelectric Storage (PHS), Compressed Air Energy Storage system (CAES), Battery, Flow Battery's, Fuel Cell, Solar Fuel, Superconducting Magnetic Energy Storage system (SMES), Flywheel, Capacitor, Super capacitor and Thermal Energy Storage system (TES).Such a process enables electricity to be produced at times of either low demand, low generation cost or from intermittent energy sources and to be used at times of high demand, high generation cost or when no other generation means is available [45].

Batteries are required in many PV systems to supply power at night or when the PV system cannot meet the demand. The selection of battery type and size depends mainly on the load and availability requirements. The main types of batteries available today include lead-acid, nickel cadmium, nickel hydride, and lithium. The principal requirement of batteries for a PV system is that they must be able to accept repeated deep charging and discharging without damage. The efficiency of a battery is the ratio of the charge extracted (Ah) during discharge divided by the amount of charge (Ah) needed to restore the initial state of charge (SOC) [39].The energy is stored in the batteries from the solar panels during excessive power generated from the source, and it can back through the bi-directional converter during the load demand. The dynamic variation of solar power is utilized efficiently using battery storage system. The effect of the inherent nature of solar photovoltaic source (SPV) is avoided using battery storage system. The effective utilization made with battery storage system [46]. The SPV with battery is considered for micro grid and isolated mode for single phase distribution system [39] [46].

The grid connected solar-PV system is ideally located close to the grid, which is directly fed by its output power. In the case of the power balance, the constraint for supplying the local load is secured by the grid, there is no need for storage devices with grid connected solar PV systems. This is due to the sufficient reliability of the grid for supplying these local loads. Therefore, the grid-connected solar PV systems are classified into either grids with insufficiently low reliability or grids with sufficiently high reliability, based on the grid reliability level [47].

2.5 Classification of the power electronic based converters

For a grid connected PV system, appropriate phase, frequency, and voltage magnitude of the three phase AC output signal of the PV system is required for the fast and accurate synchronization with the grid. The DC to AC conversion is performed by an important component of the grid-connected PV system. The inverter in most of the cases is a power electronics based grid side converter and can be categorized in to two main types based on their turn-on and turn-off behaviors (commutation), that are the line commutated inverters and the self-commutated inverters. The line commutated converters depend on the circuit parameters and the switches operate based on the polarity or direction of the current flow. On the other hand, the self-commutated converters are operated with a full control over the turn–on and –off process of switching devices. The two main categories can further be divided in to various subtypes as illustrated in figure 2.18and discussed as follows:

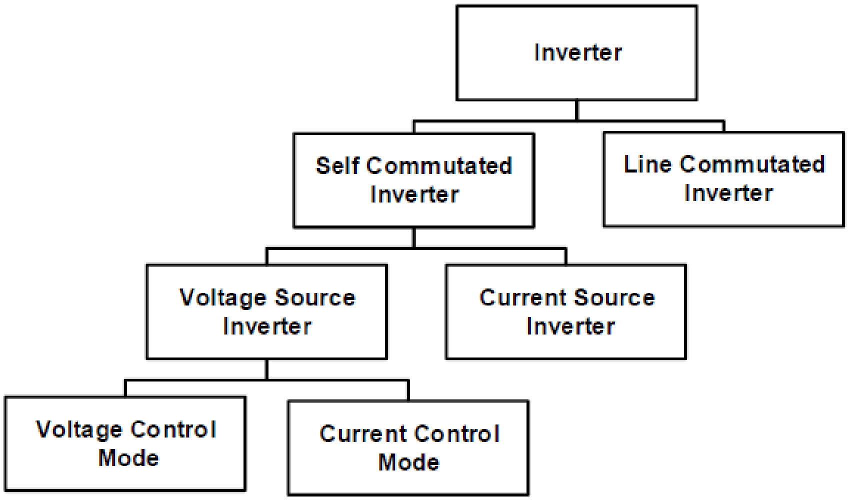

Figure 2. 18 Classifications of power electronic based converters

2.5.1 Line-Commutated Inverters

In Line-Commutated Inverter (LCI) the commutation process is carried out by the parameters of the utility grid, that is, the reversal of AC voltage polarity and the flow of negative current (or zero current) initiates the commutation process. The LCI in general uses the commutating thyristor as power switching devices, which are semi-controller devices. The gate terminal of the device control the turn-on operation, whereas the turn off cannot be controlled by the same mechanism as it depends on the line current or grid voltage for its turnoff. Thus, if a forced commutation is necessary, an external circuitry is added to the semi-controlled devices to control the turn-off process as well. For example, an anti-parallel diode is added in the case of half bridge LCI converter for enabling the process of forced commutation. The basic schematic diagram for a line commutated current source inverter is shown in figure 2.19 [57]. The line commutated converters (LCC) are used mainly where high capacity and efficiency are needed. Major disadvantage is that it produces a square wave current output rich with harmonics which further can be reduced by the use of filters [58].

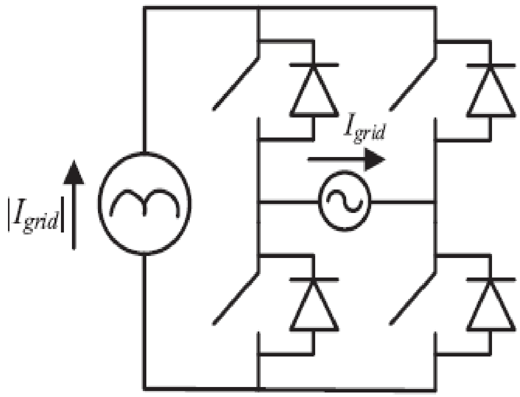

Figure 2. 19 Grid-connected Line-commutated CSI

2.5.2 Self-Commutated Inverter

The Self-Commutated Inverter (SCI) is the fully controlled power electronic converter. The potential at the gate terminal controls both the turn-off and the turn-on process of the power switching devices. The transfer of current from one switching device to the other is enabled in a controlled manner. The devices used in the SCI include MOSFET and IGBT. For medium to high power application exceeding 100 kW and low-frequency range of 20 kHz, IGBTs are used. On the other hand, for a high frequency typically in the range of 20–800 kHz and a low power less than 20 kW, MOSFETs are employed. For generating the output voltage waveform and for controlling the SCI, the Pulse Width Modulation (PWM) switching technique is used. For grid-connected inverter applications, high switching frequency is required to allow the reduction in weight of the inverter, reduce the output current and voltage harmonics, and also to decrease the size of the output filter.

The SCI is a fully controller power electronic converter, thus it controls both inverter output current and voltage waveform. Furthermore, it is highly robust to the utility grid disturbances, suppresses the current harmonics and improves the grid power factor. Nowadays, SCI is preferred over LCI for grid-connected PV systems due to the advancement made to the control system for SCI and in addition, due to the evolution of advance switching devices similar to that of the power IGBTs and MOSFETs. The SCI can further be divided in to voltage source converters and current source converters.

2.5.2.1 Voltage Source Inverter

In Voltage Source Inverter (VSI), the DC voltage source is at the input side of converter, thus the polarity of the input voltage remains the same. However, the polarity of the input DC current determines the direction of average power flow through the inverter. At the output side, an AC voltage waveform of a variable width and a constant amplitude can be obtained. A tie-line inductor is used along with the VSI to limit the current flow from the inverter to the utility grid. Furthermore, a relatively large capacitor, similar to a voltage source is connected in parallel with the input DC side of VSI. The self-commutated VSI configuration is shown in figure 2.20.

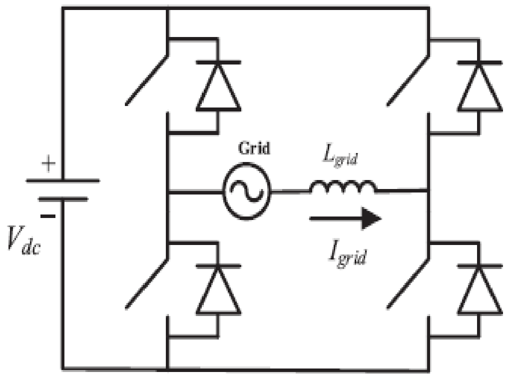

Figure 2. 20 Grid-connected Self-commutated VSI

The VSI can be operated in two modes that are the Voltage Control mode (VCM) and the Current Control Mode (CCM). In case of VCM, the main controller variable is the point of common coupling (PCC) voltage, thus there is no control on the line currents. On the other hand, in CCM the line currents are delivered in a control manner. The differences between the VCM and the CCM are presented in Table 2.6 The VCM is recommended for the standalone or off-grid PV systems, as maintaining the PCC voltage magnitude, frequency and phase is of major importance in case of the standalone power networks. Nevertheless, both VCM and CCM can be implemented for the grid-connected PV system, but CCM is most commonly used method.

The reason for using CCM is that the stiff electrical grid dictates the PCC voltage, thus controlling the currents for delivering the produced PV power is more reliable and safer than the VCM method with no control on currents. In case of grid disturbances, the transient current suppression is possible with CCM and a high-power factor can be acquired by simple control structure that is why inverters with the CCM are extensively utilized in grid-connected PV systems. Thus, the preferred inverter for a grid connected PV system is the VSI operated in current control mode.

Table 2. 3 Difference between the VCM and CCM of VSI

Parameter	**VCM**	**CCM**
Inverter type	Self-commutated VSI	Self-commutated VSI
Fault short circuit current	High	Low (Limited to rated current)
Control parameter	AC voltage	AC current

2.5.2.2 Current Source Inverter

In Current Source Inverter (CSI), the input side of the inverter is connected to a DC current source and hence, the polarity of the input current remains the same. The polarity of the input DC voltage, however, determines the direction of average power flow through the inverter. An AC current waveform of a variable width and a constant amplitude can be obtained at the output side. As opposed to VSI, a large inductor that upholds the stability of the current is attached in series to the input side of the CSI. A comparison summary between the VSI and the CSI is presented in tabular form in Table 2.4

Table 2. 4 Dissimilarity between the VSI and CSI [57].

Parameters	VSI	CSI
Dependency on load	The output voltage amplitude is independent of load. On the other hand, the output current magnitude and waveform are dependent on the nature of load	The output current amplitude is independent of load. On the other hand, the output voltage magnitude and waveform are dependent on the nature of load
Power Source	A DC voltage source with lesser or insignificant impedance is the input of VSI.	Changeable current from a DC voltage source having high impedance is the input of a CSI
Related loss	The total power loss is low because of low conduction loss and high switching loss.	The total power loss is high because of high conduction loss and Low loss switching loss.
Input parameter	A constant input voltage is maintained. In parallel to the input DC side of a VSI, a capacitor is connected. Whereas DC capacitor is efficient, cheap, and small energy storage.	The input current is continuous however changeable. In series to the input DC side of a CSI, an inductor is connected. Whereas, DC inductor contributes more losses, expensive, and bulky.

2.6 Various Inverter Topologies

Based on the configuration and types of components used, inverters can be classified into different categories. These division of categories is based on various factors, such as, number of power processing stages i.e. single stage and multi-stage, transformer and transformerless configurations, number of levels involved in the design and the type of switching used. Each category is briefly discussed and described as follows:

2.6.1 Inverters based on number of power processing stages

The inverters based on the power processing stages are classified into two main types, which are the single stage inverters and the multiple stage inverters.

2.6.1.1 Single stage inverter

The single stage inverter performs various functions, such as the control of injected grid currents, the function of voltage amplifications and the process of maximum power point tracking show in fig.2.17 (a). The single stage inverters are classified as buck, boost and buck-boost. Further they are classified as four switch and six switch inverters depending upon the number of switches the inverter uses. The choice of the type depends upon the requirement of particular application [64].

The best option is to have only a single power electronic stage between the PV array and the grid to achieve all the functions—namely the electrical MPPT, boosting and inversion leading to a compact system. Such compact systems are also in line with the modern day need to have highly integrated systems built into modules having high reliability, high performance (e.g., intelligence, protection, low electromagnetic interference (EMI), etc.), reduced weight and low cost . Lesser is the number of (power) stages, easier is the module integration. Also, the number of devices in a power stage should also be minimized. In other words, a complete circuit optimization is required [65].

In single stage inverter, the use of line frequency transformer (operating at low frequency) adds a large amount of weight to the inverter as well as contribute to the peak efficiency losses of 2 %. The use of high-frequency transformer or transformer-less converter design on the other hand are the most efficient, cost effective and lighter in weight. They are increasingly replacing the line frequency transformers. The DC to AC conversion and MPPT voltage amplification take place in a single stage. In these topologies, either an inductor is used as the energy storage element or a high-frequency transformer performing the functions of isolation and energy storage. The key characteristics of the buck-boost single stage inverter are the elimination of line frequency transformer. However, single stage inverters frequently suffer from a low range of input DC voltage, low power quality, and reduced power capacity. Furthermore, the current stresses on the power switching devices increase with the increase of power capacity. Consequently, the single stage inverters are avoided in certain application where wide input voltage range, high power quality, and high distribution capacity is required. Consequently, for such applications, multiple stage inverters are preferred.

2.6.1.2 Multiple stage inverter

An inverter with more than one power processing stage is referred to as the multiple stage inverter as presented in Fig. 2.17 (b). In this type of inverter, the last stage performs the function of DC to AC conversion while the starting one (and the intermediate) stages achieve the voltage amplification and in some cases the function of galvanic isolation [57].

In a multi-stage power inverter, for example the two-stage inverter the two-stage inverter, the gain of continuous voltage and the electrical isolation insurance is realized in the first stage (dc-dc converter) and the dc-ac conversion is realized on the second stage (inverter). Each stage can be controlled separately or integral synchrony for both stages [66].

The multi-stage inverters are classified as dc-dc-ac, dc-ac-dc-ac and dc-ac-ac topologies. In the dc-dc-ac topology, the first stage gives elevated dc with tolerable ripples as input to the second stage which is a simple buck inverter. The inverter output is controlled by controlling firing pulses given to the gate of IGBTs of inverter. The dc-acdc- ac topology consists of a first stage which converts dc from PV panels to ac by the use of inverter whose ac output is fed to a rectifier through a high frequency transformer. The full wave rectified output from this stage is fed to an inverter converts the half rectified sine waves into full sine waves which can be interfaced with grid. The dc-ac-ac topology is basically useful for standalone systems and usually not adopted for grid connected inverter applications. In this topology both stages of inverter give an AC output with the difference that the second stage is bidirectional. This is to make the provision for power flow from output side to input side. This is useful for grid connected inverters when they are a part of hybrid systems, where sometimes the power flow direction may have to be reversed for battery charging purpose [64].Two-stage inverters have the advantage of fewer series-connected PV modules and better MPPT performances in comparison with single-stage inverters.

In the grid-connected mode, the inverters are controlled as current sources. In the island mode, there is no grid connection to regulate voltage and frequency profiles, and the inverter is required to determine the voltage and frequency of system, so the inverter generally adopts voltage-type control. Transitions between operation modes can cause deviations in voltage and current, because of the mismatch in frequency, phase of the inverter output voltage and those of the grid voltage. If a voltage-type control structure can still be used in the grid-connected mode, the mode switching process can be avoided and the above problem will be effectively mitigated and eliminated [67].

For passing the DC component of the input PV source and filtering out the voltage spikes the process of power de-coupling is required in single and multiple stage inverters. A bulky electrolytic capacitor having high capacitance is utilized to accomplish this decoupling. The capacitor can be placed in two different ways, that are, in between the two converter stages as a DC link or in parallel with the PV modules, as illustrated in figure 2.21. In general, the main objective of the inverter is to convert the DC power into the AC power at the high switching frequency. However, operating at such high switching frequency results in undesired switching transients. Thus, the input side of the PV system is protected with a DC-link capacitor, which blocks the flow of these transients from moving in a backward direction. These capacitors, however, have several disadvantages, for example, at high operating temperatures their lifetime is lower in comparison to the other devices utilized in the inverter circuits. In addition, they are costly, and bulky in size. Furthermore, in practical cases, these capacitors produce various significant problems. Their reliability and power conversion efficiency are low. Because of these concerns, a prominent research is progressing day by day to reduce or eliminate the capacitance of electric capacitor and to utilize the small film capacitors as an alternative.

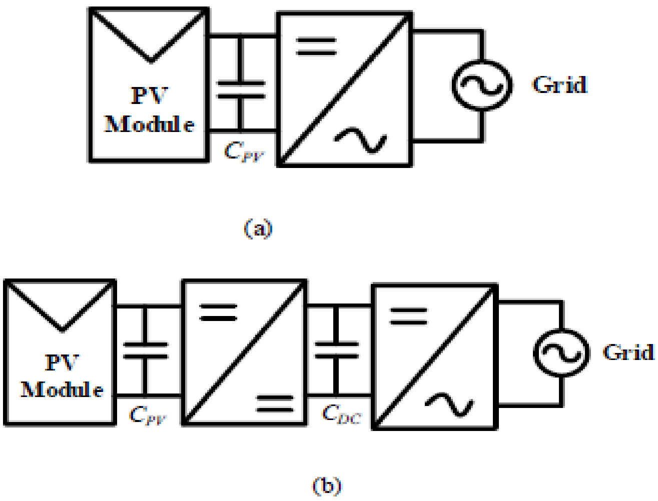

Figure 2. 21 Power de-coupling capacitor different positions for single stage and multiple stage Inverter

2.6.2 Transformer and transformer less inverters

Another classification of the inverters, as per the existing literature, is made based on the existence or absence of the transformer. In other words, this classification can also have the single or multiple power stages but the main categorization in this case is based on the transformer. In general, on the basis of transformer, the grid connected PV inverter topologies are categorized into two groups, i.e., those with transformer and the ones which are transformer less. Line-frequency transformers are used in the inverters for galvanic isolation between the PV panel and the utility grid. The isolation transformer helps in eliminating the problem of DC current injection from the PV system into the utility grid. Since, line frequency transformers are heavy in weight and bulky in size increasing in this way the overall cost of PV system, so therefore the line-frequency transformer are considered as the problematic component of the inverter. An alternative solution to this is to utilize the high-frequency transformer embedded in the inverter or DC/DC converter, which reduces the size and weight of the system, and thus decreases the overall cost. Considering this, some inverter topologies are presented in figure 2.22.

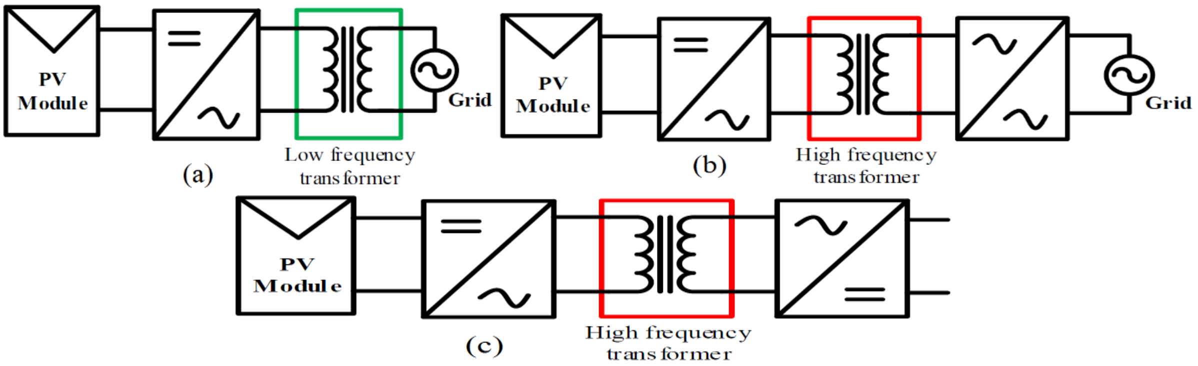

Figure 2. 22 (a) Placement of the Line-frequency transformer between the inverter and the grid. (b) HF-link grid-connected ac/ac inverter. (c) High-frequency transformer is embedded in a dc-link PV-module-connected dc-dc converter

The transformer-less inverter in comparison with the transformer topologies are cost-effective solutions and present higher efficiency. However, for addressing the problem of DC current injection, they require extra circuitry to be installed. Another problem related to transformer-less topologies is that there is no galvanic isolation between the utility grid and the PV array. Furthermore, it may cause voltage fluctuations between the PV array and the ground, depending upon the inverter circuit. A virtual capacitor formed between the surface of PV array and the installed ground, this fluctuating voltage contributes to energizing the capacitor. Depending on the structure of PV panel and the weather parameters, the capacitor may have values up to 1 μF/KW_p for thin-film cells and typically lies in the range of 50 and 150μF/KW_p . An electrical hazard may cause if a person standing on the ground touches the PV array due to the capacitive current flow in his body [57].The fluctuation of the potential between solar array and the ground which is also known stray capacitance or parasitic capacitance. The value of the stray capacitance depends on the surface of the PV array and grounded frame, distance of PV cell to the module, atmospheric conditions, dust and humidity [68].

Another problem related to the leakage current may appear, flowing from the grid to the PV panels through the existing parasitic capacitance between them, since there is no galvanic isolation. As a result, electromagnetic interferences and security issues arise [69].However, there are many studies [69-70] on topologies of transformer less PV converters, applied to reduce a leakage current. However, to prevent unsafe current levels (above 10 A) in the design of transformer-less grid-connected inverter, certain recommendation should be followed. The figure2.23 showed the general layout of a single-phase transformer less inverter using an L-filter.

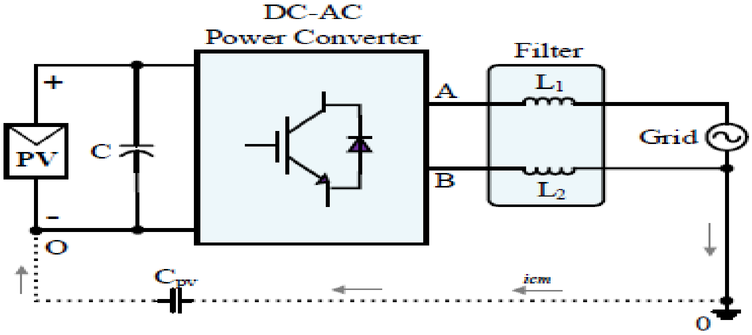

Figure 2. 23 The general layout of a single-phase transformer less inverter using an L-filter.

The differences between transformer-less and transformers-based inverter are presented in Table2.5. The line frequency transformers are bulky in size, expensive and reduce the system efficiency because of power losses in the transformer windings. Transformer-less inverter topologies are introduced for PV application to overcome these issues. It can improve the system efficiency by 1–2%. Furthermore, they are lighter, smaller and lower in cost. Transformer-less inverters can be single stage or multiple stages. A major drawback of the single-stage PV topologies is that the output voltage range of the PV panels/ strings is limited especially in the low power applications (e.g., AC-module inverters), which thus will affect the overall efficiency. The double-stage PV technology can solve this issue since it consists of a DC–DC converter that is responsible for amplifying the voltage of the PV module to a desirable level for the inverter stage.

Table 2. 5 Differences between transformer based and transformer-less inverters

Inverter	**Line-frequency transformer based inverter**	**High-frequency transformer based Inverter**	**Transformer-less inverter**
Advantages	Safer due to galvanic isolation High reliability Simpler design	Safer due to galvanic isolation High efficiency Lightweight, compact and simpler design	High efficiency Light weight and compact Complex design
Disadvantages	High volume and weight Low efficiency	Costly technology, and complex	Additional safety measures essential

The most commonly used transformer-based topologies of single-phase grid-connected inverters are full H-bridge, half H-bridge, HERIC (High Efficient and Reliable Inverter Concept*)*, H5, H6, NPC (Neutral point clamped), active NPC, flying capacitor (FC), and Coenergy NPC. Recently, in the market there are many manufacturers for transformer-less PV inverters e.g.: REFU, Danfos solar, Ingeteam, Conergy, Sunways, and SMA, offering the maximum efficiency of up to 98% and high European efficiency (>97%) [57].Table 2.6 depicted a comparison of various single phase transformer less grid-connected PV (SPTG-C PV) inverter topologies, most commonly used. And Table 2.7 shows the Switches, advantageous and disadvantageous of various transformer less inverter topologies [70].

Table 2. 6 Comparison of various SPTG-C PV inverter topologies

TI/PI	**Full Bridge**	**Half Bridge**	**HERIC**	**H5**	**H6**	**Neutral Point Clamped**	**Active NPC**	**Flying Capacitor**	**Conergy NPC**
Cost	M	L	H	H	H	M	H	M	M
Input Capacitance	L	H	L	L	H	H	H	H	H
Maximum Efficiency	-	-	-	98.5	97.4	98.16	97.34	-	97.67
Transistor Voltage	400	800	400	400	600	400	400	400	400
Leakage Current	H	VL	VL	VL	VL	VL	VL	VL	VL

Number of MPPT	1	1	1	1	1	1	1	1	1
Output Voltage Level	3	2	3	3	3	3	3	3	3
Diode	0	0	2	0	2	2	0	0	0
Switches	4	2	6	5	6	4	6	4	4
Note: TI/PI: Types of Inverter /Performance Indices, M: Medium, L: Low, H: High, VL: Very Low									

Table 2. 7 Switches, advantageous and disadvantageous of various transformer less inverter topologies

Topologies	**Switches**	**Disadvantageous**	**Advantageous**
Half Bridge	2 T	high DC-link voltage stress	low cost
Conergy NPC	3 T+ 4 D	device stress is high	low conduction losses
Full Bridge	4 T	High Leakage Current (HLC)	Very Low Leakage Current (VLLC)
Dual-Buck	4 T+ 2 D	Extra Devices Essential (EDE)	better proficiency
Neutral Point Clamp	4 T + 2 D	high device stress	VLLC
Three-Level NPC	4 T + 2 D	highly Complex	VLLC
H5	5 T	unbalance switching	low component count
Single-Buck	5 T + 1 D	HLC	only one filter inductor
HB-ZVR	5 T + 5 D	low efficiency and high complexity	VLLC
Virtual DC Bus	5 T	On 5 Switch current stress	only one filter inductor
HERIC	6 T + 2 D	EDE and leakage current at line frequency	VLLC
H6	6 T + 2 D	EDE and leakage current at line frequency	VLLC
HRE	6 T + 6 D	highly Complex	very better Proficiency
H5	6 T	EDE	VLLC
Cascaded	8 T	EDE and complex control	Lower commutation & THD

2.6.3 Multilevel Inverters

The multilevel inverters (MLI) have been inspired in 1975, then followed by contentious work to develop various topologies based on altering the infrastructure regarding semiconductor switches arrangements and dc sources as well. The other research direction was towards achieving higher power by using power semiconductor switches in series arrangement with multiple low voltage dc sources to perform the power conversion and voltage synthesizing in a staircase manner [72].

Recently, a demand for a high voltage, higher power converters which are capable of producing the high quality waveforms, whilst utilizing low voltage devices and reduced switching frequencies has led to the multilevel inverter development. As a result of high efficiency, they have been benefitting the applications which require medium voltage levels with high power in comparison to the traditional inverters with two levels. It must be noted that high power ranges from 1 - 50 MW, while medium ranged voltage from 2.3 - 6.6 kV. Over the past decades, there are various multilevel inverter topologies which have been successfully developed as a substitute for high power and medium voltage applications, and they offer better approaches than series connection and single switch. Following are the advantages of utilizing multilevel inverters:

1. The efficiency is very high due to the minimum switching frequency.
2. They can improve power quality and dynamic stability of the utility systems.
3. The switching stress and electromagnetic interference (EMI) are low.
4. Due to their modular and simple structure, they can be stacked up to an almost unlimited number of levels.
5. They are an ideal interface between the utility and renewable energy sources (i.e. PV or fuel cells).

The origin of multilevel inverter idea is from the power semiconductors array with several sources of DC voltage producing waveforms of multiple step voltage with controllable and variable amplitude, frequency and phase when it is controlled properly. The major difference between two level voltage source inverter (VSI) and the multilevel inverter is the quantity of voltage levels which have been illustrated in figure 2.24. With two-level VSI producing only two levels of voltage, multilevel inverters are capable of producing an unlimited quantity of voltage levels, theoretically. The multilevel inverters have a minimum of three voltage levels.

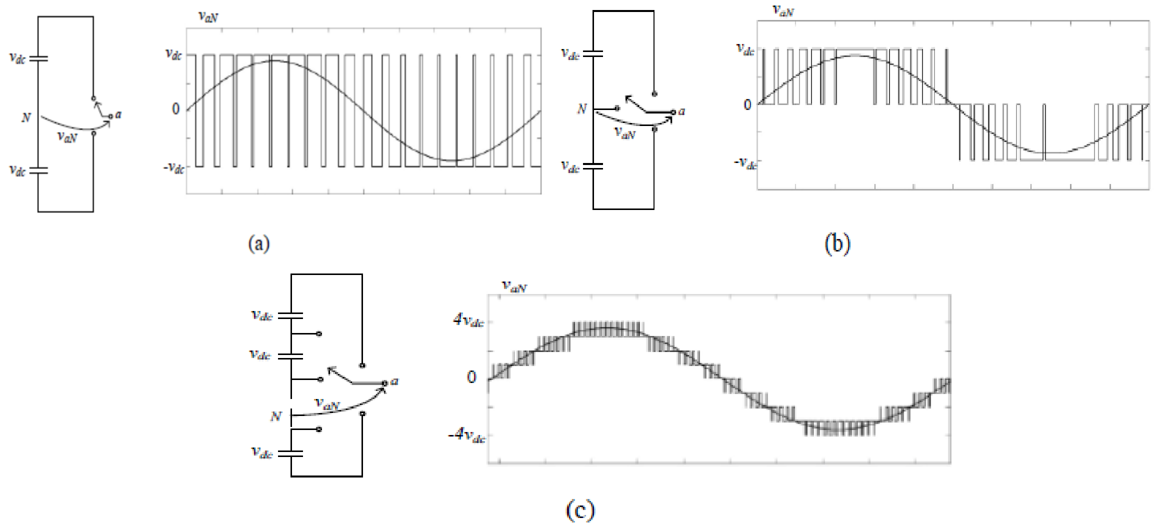

Figure 2. 24 Basic concepts of inverters (a) two-level (b) Three-level (c) Nine-level

The quality of a power converter is judged by the quality of its voltage and current waveforms. The measurement of harmonic spectra can be expressed in terms of total harmonic distortion (THD). In the case of multilevel inverter system, the most significant criterion is the minimization of harmonic components in the inverter output voltage/current. The THD could be decreased by increasing the number of levels in the voltage output by either using certain control schemes or filter designs. The lower the THD value, the better its power quality [73]. Study in [74], It is shown that THD is 28.88% in three level FC-MLI while THD is 18.56% in five level topology. Therefore, we can decrease the total harmonic distortion adopting the higher-level topology.

Generally, there are three well established and classical topologies of multilevel inverter. These are as follows:

1. Neutral point clamped (NPC) or diode clamped
2. Flying capacitor (FC) or capacitor clamped
3. Cascaded H-bridge (CHB) [73-75]

The MLIs are mainly classified into two broad categories according to the implemented dc source structure whether is single dc source or multiple ones. The first category uses a single dc source then the multiple voltage levels can be obtained through multiple capacitors arrangement. The topology is widely adopted in the industrial field due to its simplicity, efficiency, and high-power delivery capabilities. The most applicable topology in this category is the Neutral Point Clamped (NPC) MLI which introduced by Nabae, et al., in 1981. NPC inverters have been widely implemented due to its high capability in medium voltage applications with the relatively high efficiency. In addition to, the neutral point provides the zero-voltage level which results in obtaining three different voltage levels. The NPC topology utilizes multiple capacitors in series to provide multiple dc voltage levels by dividing the total dc voltage into a set of equally voltages as shown in figure 2.25. The NPC inverters are efficient in fundamental frequency switching range hence they are used efficiently in high power medium voltage grid connected converters. Fundamental frequency switching produces elevated levels of voltage, and current THD hence additional reactors are required to mitigate that issue which can increase the implementation cost. On the other hands, increasing the voltage levels requires increasing the number of clamping diodes and capacitors which could decrease the overall structure reliability. However, the benefit of this topology is its ability to reduce the harmonic contents in the produced voltage by adding the zero-voltage level. Higher levels can be obtained by increasing the switching devices, clamping diodes and capacitors. However, because of the unbalance capacitor voltages issue, practically, the NPC inverters are limited to three levels only.

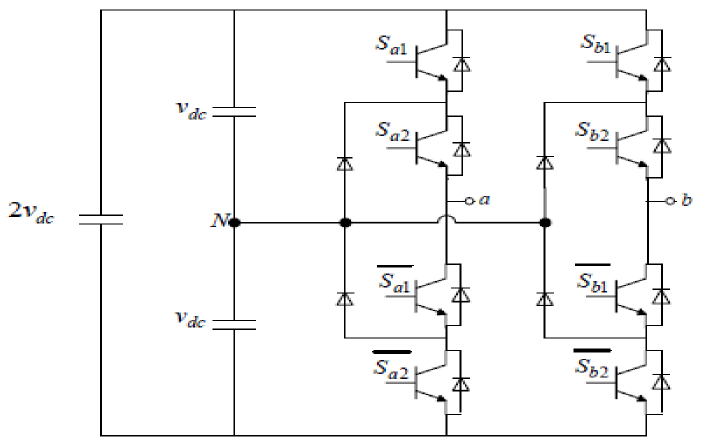

Figure 2. 25 NPC-MLI Topology

Another single dc-source inverter topology is called Flying Capacitor (FC-MLI) which has been introduced in 1992 by Meynard et al., [33]. The structure of FC-MLI is similar to NPC inverter except the FC-MLI uses multiple capacitors instead replacing the clamping diodes as illustrated in figure 2.26. Still, the bidirectional control of active and reactive power can be achievable. However, the increment of voltage levels will restrain the proper charging and discharging control of capacitors. The cost of the inverter will increase, and the device will be bulkier and the lifetime will be reduced due to the growing number of capacitors. This topology requires dedicated control algorithms to balance the capacitors voltage. As the number of levels increases, the capacitors also increase which limits its use to three or five levels.

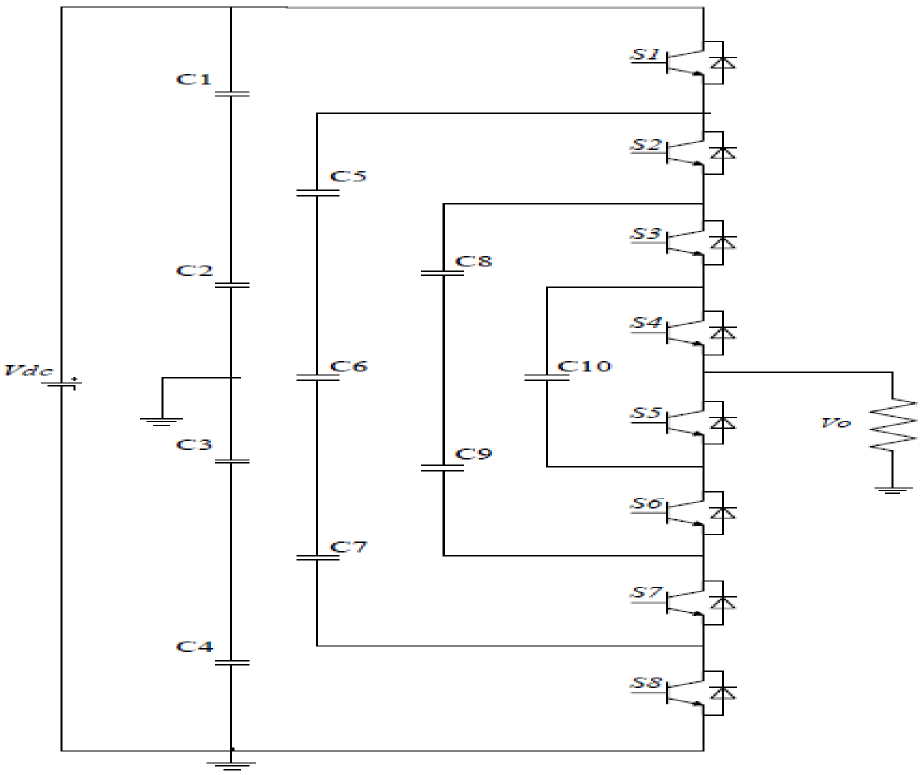

Figure 2. 26 FC-MLI Topology

The disadvantage of single dc source is the limitation when higher voltage levels are required. Hence, multiple dc sources structure has been introduced. The most adopted structure is what so-called Cascaded H-Bridge (CHB) as shown in figure 2.27. CHB consists of multiple dc sources. The advantage of this topology is a modular configuration which eases the control and maintenance in case of failure. Unlike the NPC configuration, FC topology has isolated dc sources per cell per phase voltage and power levels are easily scaled in this topology, but this requires a significant number of several separate dc sources which is considered one of major disadvantage of this configuration. The CHB-MLI has less discrete components for a given number of levels according to topologies discussed before. The CHB-MLI topology mainly consists of a series of H-bridge cells to synthesize the desired voltage. All these properties of cascaded inverters allow the use of various modulation techniques such as pulse width modulation (PWM) to control the inverter accurately [74].

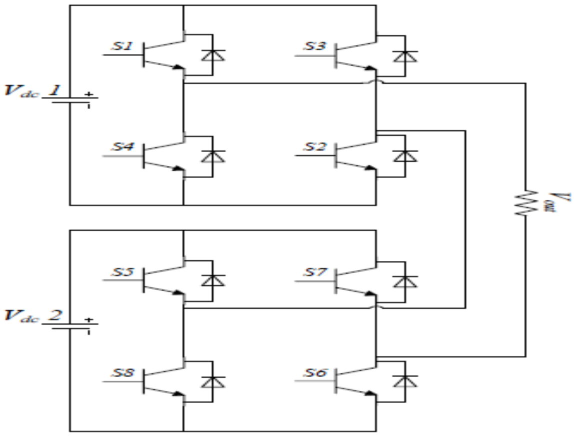

Figure 2. 27 Cascaded H-Bridge MLI Topology

The overall advantages and disadvantages of three topologies of multilevel inverter mentioned above showed in Table 2.8 below [75].

Table 2. 8 Advantages and disadvantages of three topologies of multilevel inverter

Topologies	Advantages	Disadvantages
Diode clamp	1. With the increase in the level of the voltage, the harmonic content decreases which can signifies minimum requirement of filters. 2. This provides high efficiency with controlled reactive power flow. 3. This type of inverter uses very simple method of control due to back to back intertie system	1. Increased number of clamping diodes with the increased number of levels. 2. Real power flow of individual converter is difficult.
Flying capacitor	1. Large number of storage capacitor implies extra ride through capabilities during power outages. 2. Provides switch combination redundancy for balancing different voltage levels. 3. Harmonic content reduces with the increased number of voltage levels. 4. Both real and reactive power flow can be controlled.	1. An excessive number of storage capacitors are required when the number of converter level is high which can be more costly. 2. Inverter control will be more complicated
Cascaded H-bridge	1. Requires least number of components in comparison with any other type of converters. 2. Modularized circuit layout and packaging is possible because each level has some configuration and there are no extra clamping diodes and flying capacitors. 3. Soft switching can be possible to avoid bulky and lossy resistor capacitor combination	1. It needs separate dc source for real power conversion hence limited in use

In recent times, researchers have overcome the multilevel inverter circuit's complexity by switches arrangement which helped in production of a completely new variety of topologies such as active NPC (ANPC) multilevel inverter, hybridized cascaded H-bridge (HCHB) multilevel inverter, modular multilevel converter (MMC), switched series/parallel sources (SSPS)-based multilevel inverter and H-bridge and two-level power modules (HBTPM)-based multilevel inverter [73].

2.6.4 Soft/Hard Switching Inverters

The inverters can also be categorized based on the type of switching employed. In this case, the inverters are categorized based on the type of switching employed and not on the number of power stages. In general, there exist two types, the hard and soft switching inverters. Thus, both hard and soft switching transformers can consist of one or more power stages. Nowadays, the grid-connected PV inverters are designed using the soft switching technique in order to achieve high power density, high efficiency, and better performance. Serious EMI problems and switching losses are caused by abrupt variation in switch currents and voltages, especially in the high-frequency switching inverter. This abrupt switching of the devices at a random instance is referred to as the hard switching and thus, causes various problems in the switching process. Due to the stray inductances and parasitic capacitances of the power electronic devices, the high current or voltage spikes occurs during the abrupt switching transients. Passive components based high-frequency resonant networks such as the capacitor-inductor tank, the power-switching devices and the auxiliary diodes are combined with the traditional hard-switching PWM circuits to form the soft-switching topology [57].Soft switching inverter alleviate and treat the negative impacts resulted from hard switching inverter. It provides many advantages such as low power losses, high efficiency, stress reduction during switching instants, and high reliability and lowering EMI generation. Therefore, soft switching can be implemented in the dc-dc conversion stage and/or in the dc-ac conversion stage. These converters have the ability to remove the switching power losses under high switching frequencies. On the other hand, it demonstrates some benefits compared to conventional hard switching VSI such as high power densities, high efficiencies, and 100% power device utilization [76].There are two types of soft-switching: zero-voltage switching (ZVS) for reducing dv/dt and zero-current switching (ZCS) for reducing di/dt.

The traditional PWM based buck-boost inverter topologies have several disadvantages such as:

(a) High-frequency harmonic components causing EMI.

(b) Large leakage current due to the intrinsic high-frequency common mode voltage at the output terminals.

(c) Low efficiency at high switching frequency.

(d) Increases the size and weight of the converter if designed to operate at low switching frequency and high efficiency.

These limitations are overcome by the resonant soft switching techniques, the voltage across or the current through the switching device is ensured to be zero at the instance of switching. This minimizes the switching losses of the power switching devices. Various soft-switching inverter topologies are discussed in the literature [57].The study in [76], showed the total hard switching power losses are higher compared to the total losses associated with soft switching. And soft switching can improve the efficiency and reliability of the PV energy conversion system. The study in [77], a soft switched triangular current mode TCM T-Type inverter was compared to a hard switched T-Type and a hard switched full bridge inverter for a 22kW, 3 phase photovoltaic grid interface with the constraint, that all systems have the same power density of 5 kW/liter. The comparison is based on model based optimizations of each system and measured switching losses for all three topologies. The hard switched T-Type reaches a European efficiency of 99.0%. The soft switched TCM T-Type can improve the efficiency to

99.1%.A detailed comparison and benchmarking evaluation of the aforementioned inverter topologies is presented in Table 2.9 [57].

Table 2. 9 Evaluation of different inverter topologies

Category of inverter	Power rating	Switch	Diode	PD	ToTI	ELT	EC	Topology type
Single-stage inverter	500 - 3 kW	Four	Two	LIEC	T-L	M	M	Four switching devices based Single stage buck-boost inverter topology
	>3 kW	Four	-	LIEC	T-L	M	M	Single stage boost inverter
	500 - 3 kW	Four	-	LIEC	T-L	M	M	Zeta-Cuk configuration derived Single-stage inverter
	500 W	Three	Two	LIEC	H-FT	M	M	Single-stage isolated fly back inverter
	>3 kW	Four	Two	LIEC	T-L	M	M	Single-stage inverter based on buck-boost configuration
Multiple-stage inverter	2 kW	Six	Two	LIEC & IDI	H-FT	M	H	Two-stage non-isolated buck-boost inverter
	2 kW	Five	One	LIEC & IDI	H-FT	M	H	Two-stage isolated buck-boost inverter
	4 kW	Eight	Four	LIEC	H-FT	M	H	Multiple stage boost inverter by General Electric Company (GEC)
Inverter using electrolytic capacitor of low capacitance or using film capacitor in place of a large electrolytic capacitor	5 kW	Five	Two	SFC	T-L	L	H	Novel selective dual-mode timesharing sine wave controlled soft-switching inverter
High-frequency transformer inverter	160 W	Six	Four	LIEC	H-FT	M	H	Two-switch flyback inverter
Multilevel inverter	>3 kW	Four	Two	LIEC	T-L	M	M	Half-bridge diode clamped three-level inverter
Multilevel inverter	>1.5 kW	Six	Two	LIEC	T-L	M	H	Full bridge single leg switch clamped inverter

	High power application	Eight	-	LIEC	T-L	M	H	Cascaded inverter
Soft-switching inverter	250 W	Six	Six	LIEC	H-FT	M	H	Series resonant dc-dc converter with bang-bang dc-ac converter
Note: PD: Power De-coupling, LIEC: Large Input Electrolytic Capacitor, IDI: Intermediate DC-link Inductor, SFC: Small Film Capacitor, ToTI: Type of Transformer Interconnection, T-L: Transformer-Less, H-FT: High Frequency Transformer, ELT: Expected Life Time, L: Low, M: Moderate, H: High, EC: Expected Cost.								

2.7 Types of PV applications

These are some of the most common PV applications:

2.7.1 Remote-site electrification.

Photovoltaic systems can provide long-term power at sites far from utility grids. The loads include lighting, small appliances, water pumps (including small circulators of solar water heating systems), and communications equipment. In these applications, the load demand can vary from a few watts to tens of kilowatts. Usually, PV systems are preferred to fuel generators, since they do not depend on a fuel supply, which can be problematic, and they do avoid maintenance and environmental pollution problems.

2.7.2 Communications.

Photovoltaic's can provide reliable power for communication systems, especially in remote locations, away from the utility grid. Examples include communication relay towers, travelers' information transmitters, cellular telephone transmitters, radio relay stations, emergency call units, and military communication facilities. Such systems range in size from a few watts for callbox systems to several kilowatts for relay stations. Obviously, these systems are stand-alone units in which PV-charged batteries provide a stable DC voltage that meets the varying current demand. Practice has shown that such PV power systems can operate reliably for a long time with little maintenance.

2.7.3 Remote monitoring.

Because of their simplicity, reliability, and capacity for unattended operation, photovoltaic modules are preferred in providing power at remote sites to sensors, data loggers, and associated meteorological monitoring transmitters, irrigation control, and monitoring high way traffic. Most of these applications require less than 150W and can be powered by a single photovoltaic module. The batteries required are often located in the same weather-resistant enclosure as the data acquisition or monitoring equipment. Vandalism may be a problem in some cases; however, mounting the modules on a tall pole may solve the problem and avoid damage from other causes.

2.7.4 Water pumping.

Stand-alone photovoltaic systems can meet the need for small to intermediate-size water-pumping applications. These include irrigation, domestic use, village water supply, and livestock watering. Advantages of using water pumps powered by photovoltaic systems include low maintenance, ease of installation, and reliability. Most pumping systems do not use batteries but store the pumped water in holding tanks. Charging vehicle batteries. When not in use, vehicle batteries self-discharge over time. This is a problem for organizations that maintain a fleet of vehicles, such as the fire-fighting services. Photovoltaic's battery chargers can help solve this problem by keeping the battery at a high state of charge by providing a trickle charging current. In this application, the modules can be installed on the roof of a building or car park (also providing shading) or on the vehicle itself. Another important application in this area is the use of PV modules to charge the batteries of electric vehicles.

2.7.4 Building-integrated photovoltaic's.

BIPVs is a special application in which PVs are installed either in the facade or roof of a building and are an integral part of the building structure, replacing in each case the particular building component. To avoid an increase in the thermal load of the building, usually a gap is created between the PV and the building element (brick, slab, etc.), which is behind the PV, and in this gap, ambient air is circulated so as to remove the produced heat. During wintertime, this air is directed into the building to cover part of the building load; during summer, it is just rejected back to ambient at a higher temperature. A common example where these systems are installed is what is called zero-energy houses, where the building is an energy-producing unit that satisfies all its own energy needs. In another application related to buildings, PVs can be used as effective shading devices [39].

2.8 Conclusion

In this chapter, we've highlighted at the types, costs, and efficiencies of solar cells. And overview of key PV terms, PV system components, classification and comparison summary of the power electronic based converters , inverter topologies and types of PV applications.

Chapter 3
General overview of grid connected PV systems

3.1 Introduction

Power systems are designed to deliver electricity to end-users in a reliable, continuous, clean and cost-effective way. Grid-connected PV systems offer a unique set of benefits to both consumers and grid operators. Such benefits relate to cleaner and sustainable energy production, reduced transmission, and distribution network losses, lowered generation cost, improved resilience and protection, and boosted energy independence [59].

3.2 Connection topologies of PV systems

Based on the power level, the power configurations for a PV system can be classified as a centralized topology, string topology, multi-string topology, ac module topology and team concept topology. And a comparison between these topologies is given in Table 3.1.

3.2.1 Centralized topology

This topology means that PV panels are connected in one common array both series and parallel that is connected to one large inverter (implemented by MPPT system) connected to the grid or to MPPT converter that transfers the energy to AC-grid inverter. This topology has the economic benefits as the number of the inverters is small, but the partial shadowing of the one panel will affect the whole array power output. The reduction of the generated power is caused by the characteristics of the PV panels. The current of the series string in this case is limited by the most shadowed panel. This topology has two types of connection: series-parallel (SP) and total cross tied (TCT) connection illustrated in Figure 3.1. TCT connection allows reducing the system element mismatch problem. To escape the problems of the partial shadowing of array each of the PV-modules gets equipped by parallel diode, that bypasses the module in case if module is shadowed or damaged [49].

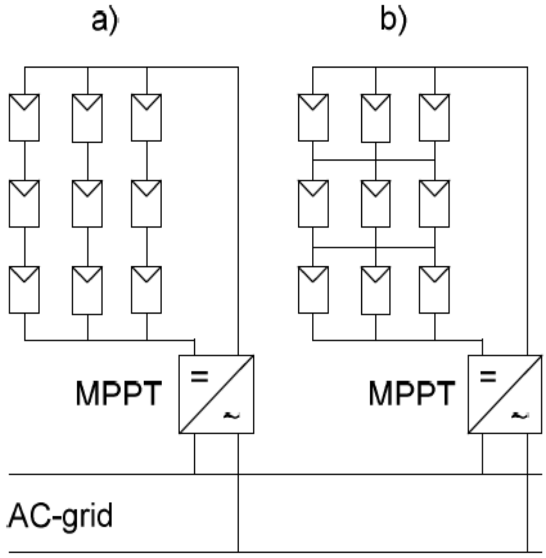

Figure 3. 1 (a) 3x3 SP and (b) 3x3 TCT centralized MPPT inverter topology.

The power rating of these inverters is of the order of several kilowatts. This inverter concept has some further disadvantages, such as poor power factor (power factor lied in the range of 0.6 and 0.7), high content of harmonics in the output current [41].Low system efficiency and redundancy [42]. High voltage dc cables between the PV modules and the inverter, power losses due to a centralized MPPT, mismatch losses between the PV modules, losses in the string diodes, and a nonflexible design where the benefits of mass production could not be reached [44].

3.2.2 String topology

This topology means that the array of the panels is split to the several PV module strings connected in series, called series-connected string converter topology. This topology has following benefits: high voltage and low current, that means costs reduction on wires, reduced voltage drops and power losses in wire copper. Each of the strings is connected to the MPPT-AC converter and the outputs of MPPT-AC converters are connected to the grid show in Figure 3.2.

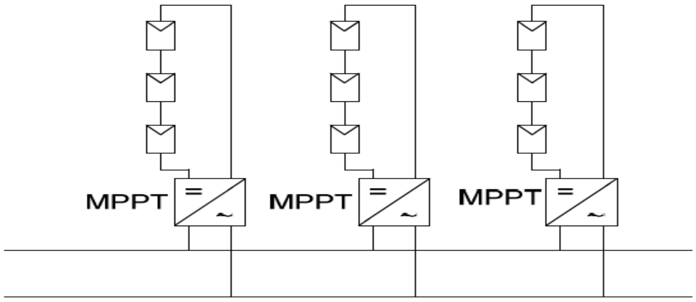

Figure 3. 2Series-connected string converter topology

This type of converter connection topology is able to produce the voltage in cases when one (or number) of the panels is shadowed in one string, but other string is not affected and irradiance level remains the same for other string [49].Compared with the centralized topology, increased the number of the inverters increases the “per W” cost [42]. The advantages of string configuration include minimum losses, higher power output and increased reliability; the efficiency of string inverters is 1–3% higher than the central inverters lying in a range of 94 to beyond 97% [41] and reduces the price, due to mass production [44].

3.2.3 Multi-string topology

Multi-String Grid-Connected topology is the implementation of the Series-connected String topology with separate AC-grid inverter and MPPT DC-DC converter. The structure of DC-DC converter is simpler and requires fewer semiconductors, therefore it cost-effective and more efficient. The string of the photovoltaic panels is connected to the MPPT converter and several MPPT converters` outputs are in parallel or series connection to the DC-bus (Figure 3.3). One common AC inverter is used for DC-AC conversion.

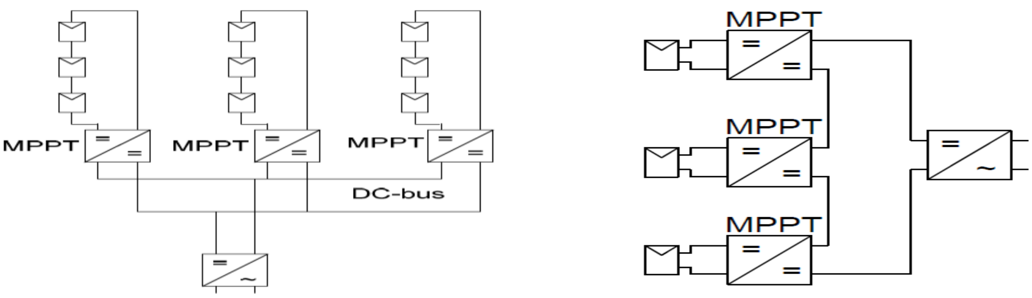

Figure 3. 3 a. Multi-string parallel-connected b. Cascaded DC-DC converter topology

Separate MPPT and inverter control is reducing the total costs of the PV-system as well, because combination of the control techniques and DC-AC conversion techniques makes system complex and expensive both on the stage of production and design as in the case of the series-connected string topology. The other benefit of this topology is that inverter has high power rate and system expected efficiency is higher. And the converter is able to keep high efficiency in case of mismatched irradiance operation conditions [49].The multistring topology is combines the advantages of the centralized and string topology [42].This system is unreliable due to a common inverter. If a fault occurs in the inverter then the entire system goes down [41].

3.2.4 AC module topology

The ac module is the combination of one PV module with a grid-connected inverter, show in figure 3.4.These inverters use self-commutation to turn-off the switches. Structure wise, this is the smallest possible configuration. Module inverters are also called module oriented inverters, rating of up to 500W. Some of the advantages of this configuration are: use of similar components results in reduced costs and improved reliability easier fault detection [41].Use of only one PV module results in the elimination of mismatching losses [41][50].Moreover, the hot-spot risk is removed. It also includes the possibility of an easy enlarging of the system [50].

This configuration can be used as a plug and play device very easily [41] [42]. However as the power output of module inverters is very low they suffer from the disadvantage of poor efficiency [41].

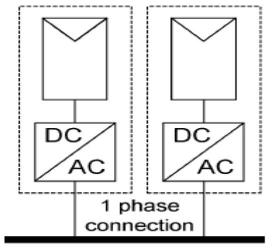

Figure 3. 4 AC module topology

3.2.5 Team Concept topology

This topology is used for large PV systems. However, these concepts are less widely utilized than the ones already presented. One of the alternative concepts is so called team concept, which combines the string technology with the master-slave concept. A combination of several string inverters working with the team concept is shown in figure 3.5. At very low irradiation the complete PV array is connected to a single inverter. This reduces the overall losses as any power electronic converter is designed such that it has maximum efficiency near full load. With increasing solar radiation more inverters are being connected dividing the PV array into smaller units until every string inverter operates close to its rated power. In this mode every string operates independently with its own MPP tracker. At low solar radiation the inverters are controlled in a master-slave fashion [51].

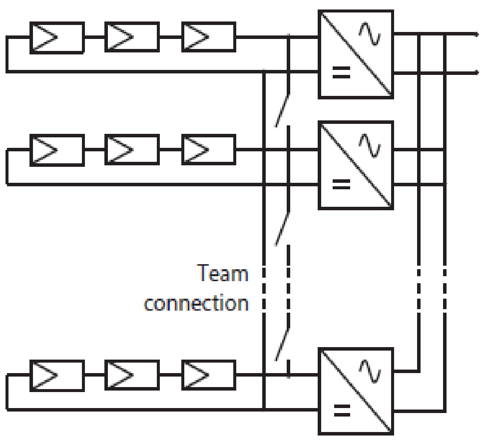

Figure 3. 5 Team concept topology

Table 3. 1 Comparison between different connection topologies of PV systems

Topology	Advantages	Disadvantages	Power Rating
Centralized topology	Low cost High power rating	Poor power factor Inverter is subjected to high voltage DC cables High harmonic contents in the output current Poor efficiency due to a common MPPT Mismatch losses	Several kilowatts to megawatts
String topology	Reduced cost per watt Higher system efficiency Requirement of voltage amplification may be avoided No losses due to string diodes	Low power output as compared to central inverters If voltage amplification becomes necessary, the efficiency of the system comes down	Few kilowatts per string
Multi-string topology	Local MPPT for each string Flexible system	Highly unreliable due to a common inverter	Few kilowatts
AC module topology	Reduced costs and improved reliability Maximum power is extracted from the PV module Least power loss No mismatch losses Easier fault detection Flexible system	Low power output High cost per watt Reduced efficiency Higher amplification factor Replacement is costly in case of inverter failure	Up to 500W
Team concept topology	Higher reliability as compared to centralized topology Improved efficiency for the operating inverters Extended lifetime of inverters	DC losses in high voltage DC cables Power loss due to centralized MPPT, string diodes and mismatch in PV modules High cost due to use of multiple inverters Not flexible in design	Up to several Megawatts [41]

3.3 Kinds of grid-connected PV systems

PV generation connected to the utility grid has gained growing attention, given the rapid increase in the world's demand for clean energy. Micro generation technologies, particularly PV installations, have a huge potential to be used in urban and rural environments, not only to satisfy demand and provide decentralized production, but also to help reduce fossil fuel dependency and reduce emissions [52].

Normally there are almost no effects of the PV systems on the grid affecting power quality, load-on lines, and transformers, etc. However, for a larger share of PV in low-voltage grids, as in solar settlements, these aspects need to be taken into account [31].Grid-connected PV systems can be subdivided into two kinds:

1. Decentralized grid-connected PV systems.
2. Central grid-connected PV systems.

3.3.1 Decentralized grid-connected PV systems

Decentralized solar power system is the opposite of centralized system. Decentralized solar plant, refers to solar energy solution that produce energy on-site, or near-site. For some cases, in this system there are less or no voltage losses as no transmission line is required to reach electricity to the consumers. Sometimes the end user owns the solar power system and directly receives the benefits of the system. By this system, energy needs of the owner can be taken care by themselves.

A decentralized energy system is a relatively new approach in the power industry in most countries. Traditionally, the power industry has focused on developing large, central power stations and transmitting generation loads across long transmission and distribution lines to consumers in the region. Decentralized renewable power generation gains much attention as an environmentally friendly power source and a promoter of local economies. One additional advantage often advocated is that decentralized renewable electricity generation helps avoiding infrastructure cost, because the transmission system is used less, as generation is geographically close to the consumption. However, in many cases, variable renewable energy hardly reduces the annual net peak load [53].Decentralized grid-connected PV systems have mostly a small power range and are installed on the roof of buildings (rooftop or flat-roof installation) or integrated into building facades, called solar home systems (SHS). Energy storage is not necessary in this case. On sunny days, the solar generator provides power, e.g., for the electrical appliances in the house. Excess energy is supplied to the public grid. During the night and overcast days, the house draws power from grid show in figure 3.6 [31].

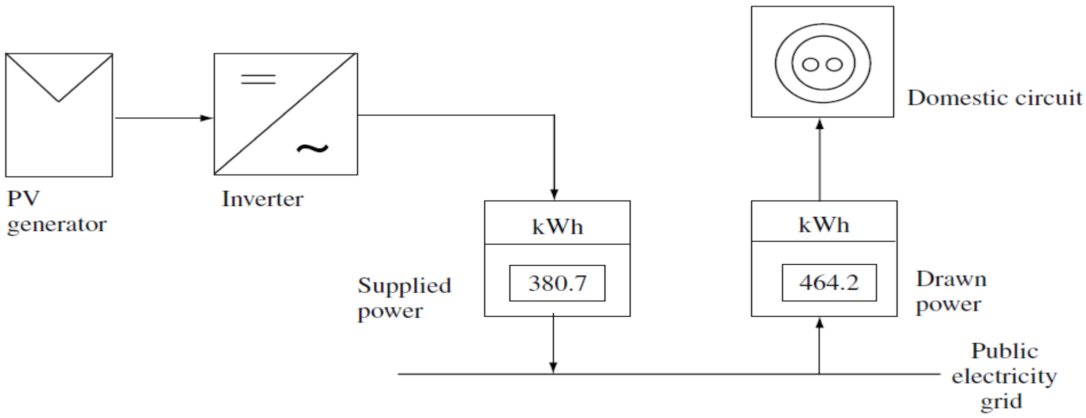

Figure 3. 6 Block diagram of the power supply for a house with a decentralized PV system and grid connection

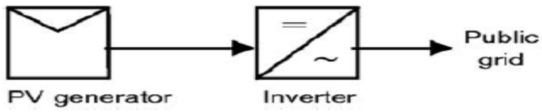

Figure 3. 7 Schematic principle of a grid-connected PV system

The performance of building-integrated photovoltaic's (BIPV) grid-connected system depends on PV efficiency, local climate, the orientation and inclination of the PV array, load characteristics and the inverter performance. From architectural, technical and financial perspectives, building-integrated photovoltaic's:

- Reduce the initial investment costs by displacing facade/roof/shading elements.
- Are aesthetically appealing.
- Electricity is generated at the point of use, reducing the costs and losses associated with transmission and distribution.
- Are suitable for installation on roofs and facades in densely populated areas.
- Require no additional land area for the installation.
- Can satisfy all, or a considerable part, of the electricity consumption of the building.
- Can act as a shading device.
- Can act as a source of day lighting if semi-transparent PVs are used for fenestration.

Can provide part of the hot water or space-heating loads of the building [39].
Governments are fostering the use of these technologies by using a feed-in electrical tariff, but its implementation is strongly dependent on economical/financial aspects. The main objective and challenge of RE integration in decentralized locations are the incorporation of technically and economically viable systems in collecting and processing RE sources. Decentralized energy production, that is, distributed generation (DG), has high economic potential.

The technology that uses the sun as an energy source presents direct and indirect benefits. The direct benefits include sustainable electrical power generation and financial savings on the part of the producer and consumer. Indirect benefits include self-sustaining buildings, increased awareness about global warming, and about technical issues, such as the advantage of generating energy near the place of consumption and subsequent strengthening of the grid, and the capability of reinforcing the grid during periods of high-energy demand. The other type of decentralized energy system, grid-tied commercial and industrial (C&I) solar systems.

Micro grids comprise low voltage (LV) distribution systems together with distributed energy sources and storage devices as energy capacitors and batteries, which have nonlinear electronic devices. These cause considerable harmonic pollution in power supply systems, having severe undesirable influences on system components by changing parameters of grid impedance, distorting the fundamental voltage and current waveforms, influencing the availability of short circuit power, overheating the transformers and cables, and causing resonance and false operation of protection devices. Once it becomes prominent, it will decrease power quality and increase unexpected maintenance processes and expenses [52].

Some of published literature reports that PV micro-grids improves the network reliability, however, such micro grids are not always economically viable. Some of the other reported literature looked at economical deployment of micro-grids with improved reliability [54].

Customers in the low voltage (LV) distribution networks are increasingly installing Solar PV resources in the form of rooftop PV units in residential households. With an increasing level of solar PV penetration, there is a possibility that the total power generation from the PV resources connected to the low voltage distribution feeder may exceed the total load demand.

This situation could typically arise in distribution feeders with high PV penetration during midday, when generation from PV resources is typically highest and may be greater than the load level. The surplus power resulting from the mismatch of load and generation would flow to the upstream networks, and this will produce reverse power flow and voltage rise in the feeders. Changes in voltage and power flow created by PV resources will impact the normal behavior of distribution networks. Rooftop PV units typically operate at unity power factor. That is, only real power is produced by the PV units. If the PV resources were allowed to inject reactive power as well, different situations may arise depending on the control strategies adopted for reactive power injection. Control strategies such as IEEE 1547 control, voltage control, maximum reactive power control, and power factor control could be adopted [55].

3.3.2 Central Grid-Connected PV Systems

Centralized solar power system refers to a large-scale solar plant installation to produce large amount of electricity. Like the conventional national grid system, Centralized solar farms need the same infrastructure which includes electrical substations and transmission lines to be run over long distances. The main disadvantage of this system is sometimes low efficiency and voltages loss, when electricity has to travel long distances.

Central grid-connected PV systems have an installed power up to the MW range. With such central photovoltaic power stations it is possible to feed directly into the medium or high voltage grid. Mostly central photovoltaic power stations are set up on otherwise unused land, but in some cases an installation on buildings, mostly on the flat roof of greater buildings, is also possible. As can be seen in Figure 3.6 both decentralized and central grid connected PV systems consist of the following two main components PV module and inverter. In addition to some other components such as support structure, cabling, and other conventional components [31].The PV module was previously described, so we will describe the second most important part of the system which is the inverter.

3.4 Basic MPPT techniques

Many different algorithms are used for MPP tracking, trying to cope with three major tasks:

1. Precision: high precision of MPP tracking needs high-precision measurement components.
2. Finding the global maximum power output in the case of partial shading, when a local maximum can occur.
3. Fast enough adaptation of the MPP to changing insolation, e.g., if clouds pass by [31].

For each PV system, there is a singular operating point labeled as MPP in I-V and V-P curves for each temperature and irradiation condition. The maximum power point (MPP) changes its position with any change in atmospheric conditions. Because of that, the tracing system was designed to keep tracking MPP, and because of that they are a necessary part of the PV system. The controller changes the resistance seen by the panel, and hence forces the panel to operate closer to MPP. The most popular and basic MPPT techniques such as perturbation and observation (P&O), incremental conductance (IC), constant voltage (CV) and fractional open-circuit voltage (FOCV).

3.4.1 Perturbation and Observation (P&O) Method

The P&O algorithm based on increasing or decreasing the array terminal voltage, or current, at regular period and then comparing the output power of the PV with those of the previous sample point show in figure 3.8. Based on the simple mathematical condition ($dP/dV = 0$), figure 3.9 viewed the process of MPPT system. When the PV array operates to the left area of the MPP curve, the output power will be increased due to the increase in voltage and output power decreases on increasing voltage when the same operates to the right area of the MPP

Curve. Hence if dP/dV > 0, the system keeps the disturbance, and if dP/dV < 0, the disturbance should be reversed. The process repeats until the operating point is across to the maximum power point. Where P and V are power and voltage at output of PV module respectively.

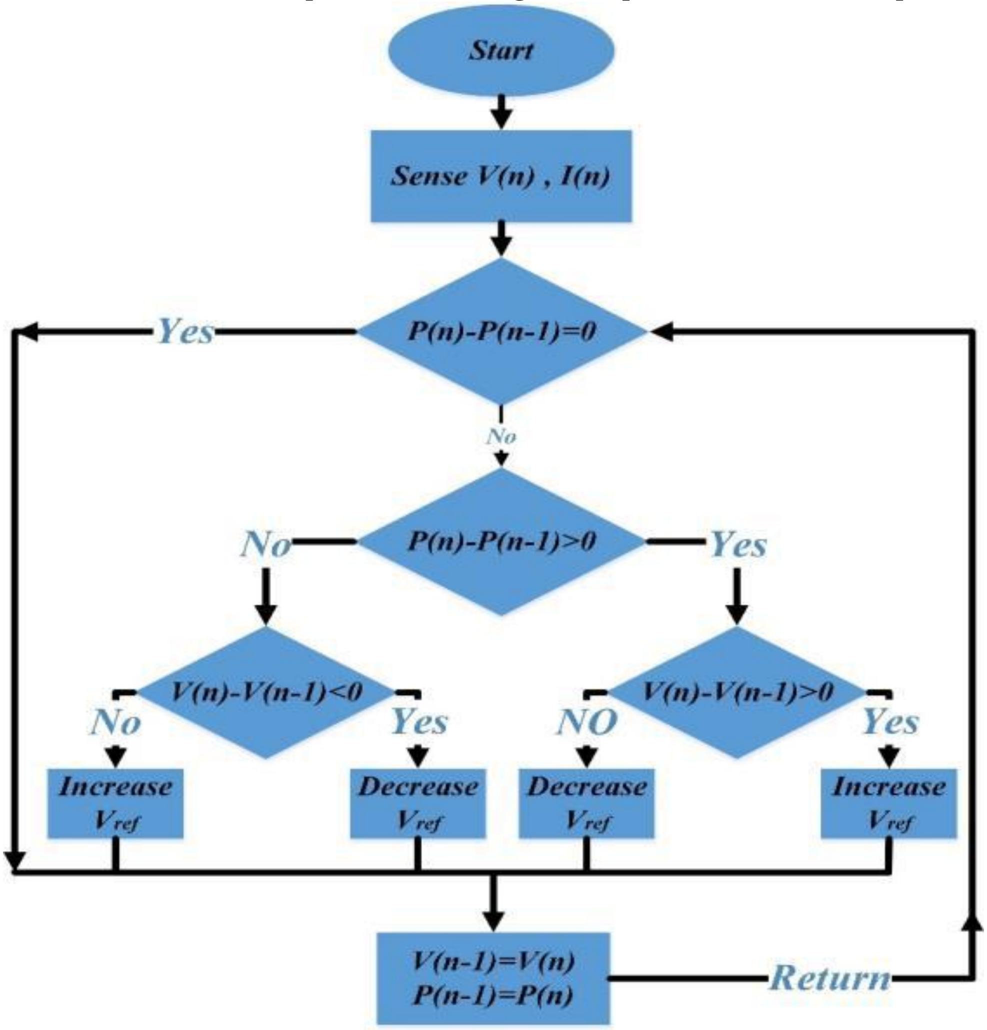

Figure 3. 8 Perturbation and observation method flowchart

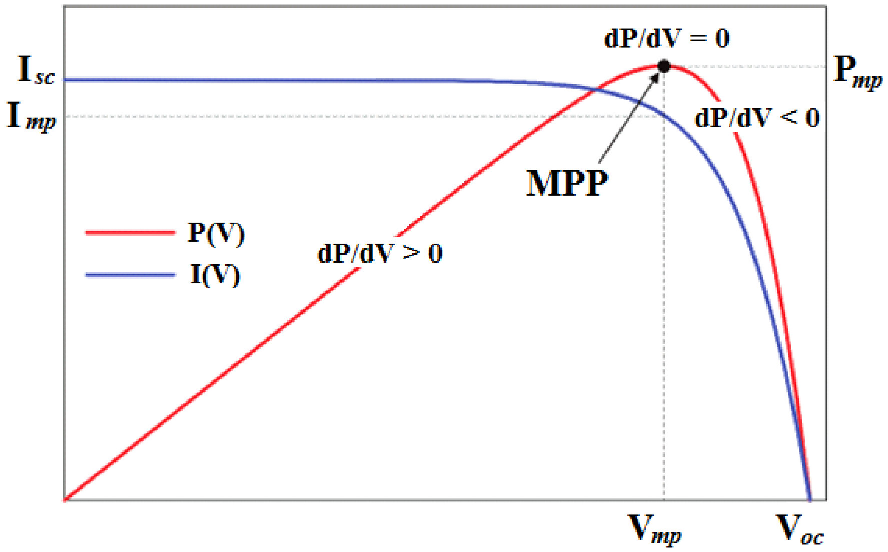

Figure 3. 9 Example of a Perturbation and Observation method technique Block diagram of PV system

The main advantage of the P&O algorithm is its simplicity. In general, this method shows a good operation provided the solar radiation does not deviate too quickly. The classic perturb and observe (P&O) method has the disadvantage of poor efficiency at steady state and low irradiation, the operating point oscillates around the MPP voltage (usually fluctuates lightly) but never reaches exactly the MPP.

3.4.2 Incremental Conductance (IC) Method

The method of Incremental Conductance works when the dP/dV = 0, because the derivative of the power of the PV module is equal to zero at the MPP, the positive results off the left area of the MPP curve and negative results on the right of the MPP curve. Table 3.2 show the mathematical relations for Incremental Conductance technique.

Table 3. 2 Mathematical properties of Incremental Conductance

$\frac{dp}{dV} = 0$	At MPP
$\frac{dp}{dV} > 0$	Left Area of MPP
$\frac{dp}{dV} < 0$	Right Area of MPP

Since:

$$\frac{dp}{dV} = \frac{dIV}{dV} = I + V\frac{\Delta I}{\Delta V} \quad (3.1)$$

For MPP, Putting $\frac{dp}{dV} = 0$, it gives

$$I + V\frac{\Delta I}{\Delta V} = 0 \quad (3.2)$$

So we have

$\frac{\Delta I}{\Delta V} = \frac{1}{V}$ At maximum point

$\frac{\Delta I}{\Delta V} > -\frac{1}{V}$ Left of maximum point

$\frac{\Delta I}{\Delta V} < -\frac{1}{V}$ Right of maximum point

According to equation 2.24 and 2.25, the flowchart of IC method is shown in figure 3.10. The maximum power point of PV system can be tracked by comparing the I/V to ΔI/ΔV.

Where

I/V: Instantaneous conductance

ΔI/ΔV: Incremental conductance.

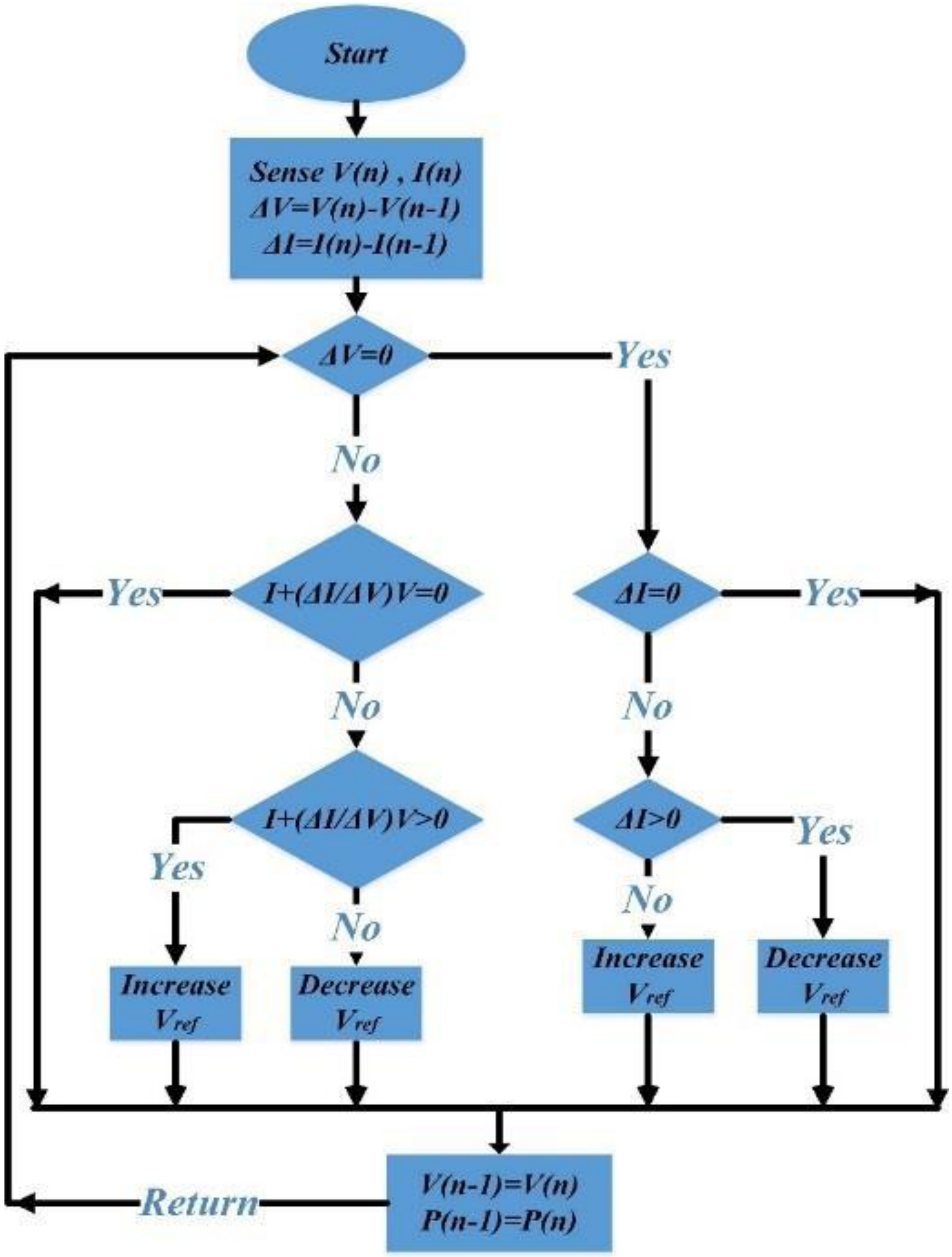

Figure 3. 10 Incremental Conductance method flowcharts

V_{ref} is the reference voltage of the PV array operation. When the MPP is achieved at that moment, V_{ref} must be equal to Vmpp. When it happens, the system keeps the output voltage at MPP, until a change or change in atmospheric conditions occurs. The IC algorithm decided to decrease or increasing the V_{ref} to always reach the new MPP.

The advantage of this technique is its ability to track more accurately in extremely variable weather conditions and shows less oscillating behavior around MPP compared to Perturbation and Observation technique. The disadvantage of this algorithm is the complexity of the hardware to implement it.

3.4.3 Constant Voltage (CV) Method

Considered the constant voltage (CV) algorithm is one of the simplest algorithm of MPPT algorithms. The operating point of the PV system is fixed close to the maximum power point (MPP) by setting the output voltage of solar to conform to the continuous reference voltage (Vref). The Vref is regulated to the same value of the voltage at the maximum power point

(Vmpp) of the characteristic PV array. For this technique, the panel variations in irradiation and temperature are not substantial, and the constant reference voltage (Vref) is antecedent regulated to achieve performance closely to the MPP. Because of that, in practice, this method may never exactly find the MPP. The CV method requires data collection before to demonstrate a constant voltage reference, and this may vary from place to place.

3.4.4 Fractional Open-Circuit Voltage (FOCV) Method

In the FOCVM, the MPP voltage can be calculated from the mathematical relationship shown in Equation (3.3).

$$Vmpp \approx Voc \tag{3.3}$$

The constant value Koc usually changes between 0.78 and 0.92, and can be calculated by analyzing the PV system at a broad range of solar temperatures and radiations. In this method, the PV system is open-circuited at load end for a fraction of a second and is measured, then the voltage calculated using the equation (3.3). The sample is taken repeatedly every few seconds and the output value is updated. The advantage of this method is its simplicity to implement. On the other hand, the drawback is that the true MPP may be never reached [56].

3.4.5 Fuzzy Logic Control

Microcontrollers have made using fuzzy logic control popular for MPPT over last decade. Fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity. Fuzzy logic control generally consists of three stages: fuzzification, rule base table lookup, and defuzzification. During fuzzification, numerical input variables are converted into linguistic variables based on a membership function similar to figure 3.11. In this case, five fuzzy levels are used: NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), and PB (Positive Big).

In some cases seven fuzzy levels are also used probably for more accuracy. In figure 3.11 a and b are based on the range of values of the numerical variable. The membership function is sometimes made less symmetric to give more importance to specific fuzzy levels. The inputs to a MPPT fuzzy logic controller are usually an error E and a change in error ΔE. The user has the flexibility of choosing how to compute E and ΔE. Since dP/dV vanishes at the MPP, approximation can be applied as follows:

$$E(N) = \frac{P(N) - P(N-1)}{V(N) - V(N-1)} \tag{3.4}$$

And

$$\Delta E(N) = E(N) - E(N-1) \tag{3.5}$$

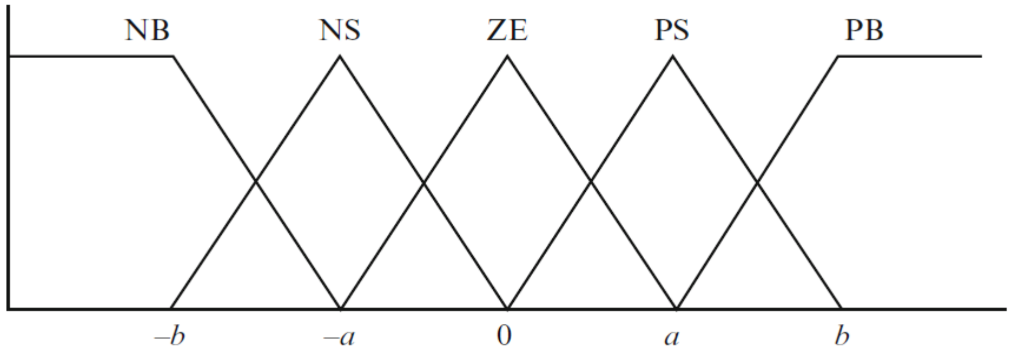

Figure 3. 11Membership function for inputs and output of fuzzy logic controller

Once E and ΔE are calculated and converted to the linguistic variables, the fuzzy logic controller output, which is typically a change in duty ratio ΔD of the power converter, can be looked up in a rule base table such as Table 3.3.

Table 3. 3 Fuzzy rule base

	ΔE				
E	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

The linguistic variables assigned to ΔD for the different combinations of E and ΔE are based on the power converter being used and also on the knowledge of the user. The rule base shown in Table 3.3 is based on a boost converter. If for example, the operating point is far to the left of the MPP, that is E is PB, and ΔE is ZE, then we want to increase the duty ratio largely, that is ΔD should be PB to reach the MPP. In the defuzzification stage, the fuzzy logic controller output is converted from a linguistic variable to a numerical variable still using a membership function as shown in figure 3.11. This provides an analog signal that will control the power converter to the MPP. MPPT fuzzy logic controllers have been shown to perform well under varying atmospheric conditions. However, their effectiveness depends a lot on the knowledge of the user or control engineer in choosing the right error computation and coming up with the rule base table.

3.4.6 Neural Network

Along with fuzzy logic controllers another technique of implementing MPPT are the neural networks, which are also well adapted for microcontrollers. Neural networks commonly have three layers: input, hidden, and output layers. The number nodes in each layer vary and are user-dependent. The input variables can be PV array parameters like $V_{OC}$and I_{SC}, atmospheric data like irradiance and temperature, or any combination of these.

The output is usually one or several reference signal(s) like a duty cycle signal used to drive the power converter to operate at or close to the MPP. How close the operating point gets to the MPP depends on the algorithms used by the hidden layer and how well the neural network has been trained. The links between the nodes are all weighted.

The link between nodes i and j is labeled as having a weight of wij. To accurately identify the MPP, the wij must be carefully determined through a training process, whereby the PV array is tested over months or years and the patterns between the input(s) and output(s) of the neural network are recorded. Since most PV arrays have different characteristics, a neural network has to be specifically trained for the PV array with which it will be used. The characteristics of a PV array also change with time, implying that the neural network has to be periodically trained to guarantee accurate MPPT [84].

Table 3.4 summarizes the various features of some techniques and the main characteristics of MPPT methods.

Table 3. 4 The main characteristics of the different MPPT techniques

MPPT Algorithm	PV Array Dependent	Digital or Analog	Convergence Speed	Implementation Complexity	Sensors
Perturbation and Observation	N	B	V	L	Voltage and Current
Incremental Conductance	N	D	V	M	Voltage and Current
Fractional Open Voltage	Y	B	M	L	Voltage
Fuzzy Logic Control	Y	D	F	H	V
Neural Network	Y	D	F	H	V

Where- Y: Yes, N: NO, B: Both, D: Digital, A: Analog, V: Varies, L: Low, H: High, M:Medium, F: Fast[56]

3.5 Inverter control strategy

The inverter control strategy consists of two main cascaded loops. Typically, a loop which controls the grid current is a fast-internal current loop, and loop which regulates the DC-link voltage is a slow external voltage loop. The current protection and power quality issues are associated with the current control loop. The significant features required from the current controller are faster dynamic response and harmonic compensation under distorted grid conditions. For balancing the power flow in the system, the DC-link outer voltage controller is employed. Generally, the purpose of the external controller is the stability of slow dynamic system and optimal regulation. For stability purpose, the current control loop is designed with dynamic speed lower than the speed of voltage control loop (approximately 5–20 times greater). The designing of voltage controller does not require the transfer function of internal current control loop, since the external and internal loops can be designed in a decoupled way. In some cases, the cascade of voltage control loop and power loop can be used as an alternative of the current loop and the injected currents are indirectly controlled.

The overall operation of the grid-connected PV system depends on the fast and accurate control of the grid side inverter. The problems associated with the grid-connected PV system are the grid disturbances if suitable and robust controllers are not designed and thus, it results in grid instability. According to the specific operating condition and behavior of the electrical grid, the controllers of PV system are divided into 6 categories, which are the linear controllers, the non-linear controllers, the robust controllers, the adaptive controllers, the predictive controllers, and the intelligent controllers

3.5.1 Linear controllers

These controllers are designed based on the features and dynamics of the linear system. The typical feedback control theory is used for analyzing and designing these controllers.

3.5.1.1 Classical controllers

This family consists of the Proportional-Integral-Derivative (PID), the Proportional-Integral (PI), the Proportional-Derivative (PD), and Proportional (P) controllers. These controllers are the base of classical linear systems and control science.

3.5.1.2 Proportional Resonant (PR) controllers

PI and PR controllers work in a similar manner but in two different operating frames. The PI controller allows efficient tracking of DC signals, whereas the PR controller tracks a sinusoidal signal with the frequency of sinusoid as its central frequency. The way the integration takes place in PI controller is different form the one that takes place in PR controller. As opposed to PI controller, the integrator in case of PR controller integrates the frequencies, which are close to the resonant frequency. Consequently, phase shifts or stationary errors are not involved.

3.5.1.3 Linear Quadratic Gaussian (LQG) controllers

The combination of the linear-quadratic regulator and the Kalman filter forms an LQG controller. According to separation principle, these two controllers can be designed and computed independently. LQG controller is suitable for both time-varying and time-in varying systems. The design of linear feedback controllers for the control of nonlinear and uncertain systems is provided by the application of LQG control to linear time-invariant (LTV) systems

3.5.2 Non-linear controllers

These controllers have an extraordinary operation compared to the basic controllers. However, in terms of design and implementation, these controllers are complicated.

3.5.2.1 Sliding mode controllers

For the regulation of the output voltage of the PWM inverters, Sliding Mode Controller (SMC) technique has been used extensively due to its robust and improved performance. The main advantages of this technique are insensitivity to parameter variation and load disturbances. Hence, in the ideal case, an invariant steady-state response can be accomplished by the application of SMC to the PV system. On the other hand, it is difficult to locate a legitimate sliding surface, to which the performance of SMC is heavily dependent. The performance of the SMC is also dependent on the sampling time and suffers from distortion if an inadequate sampling time is selected. In addition, when SMC tracks a variable reference, the phenomena of chattering is observed, which is a major disadvantage of (SMC), degrading in this way the overall efficiency of the PV system.

3.5.2.2 Partial Feedback Linearization (PFL) controllers

Feedback linearization is the direct way for designing the non-linear controllers, as a non-linear system is converted to fully or partially linear system. By cancelling the non-linearities within the system makes this possible. So, the linear controller design approaches can be utilized to design the controller for these systems. When the non-linear system is converted into a halfway linear system, is known as Partial Feedback Linearization (PFL) and if converted into a completely linear system is known as Exact Feedback Linearization (EFL).

3.5.2.3 Hysteresis controllers

One of the non-linear controllers is hysteresis controller. An adaptive band of the controller must be created in order to attain a stable switching frequency, which is an important step for implementing hysteresis controller. Hence the output of this controller is the state of the switches, therefore consideration regarding the isolated neutral is important again.

3.5.3 Robust controllers

A robust control theory approach is utilized in order to design a controller with concern to uncertainties. The goal of these methods is to acquire stability in the occurrence of partial modelling errors as well as robust performance. In the robust control, bounds, clear description, and good criteria must be defined. This controller can promise robust performance and stability of the closed-loop systems, even in the multivariable systems [83].

3.5.3.1 H-infinity controllers

To use H-infinity methods, the control problem is represented as an optimization problem by the control designer and then solves it. Multivariable system problems are solved by H-infinity techniques. But, it needs a good model of the system to be controlled and has high computational complexity. Additionally, non-linear constraints are not well handled.

3.5.3.2 Mu-synthesis controllers

The effect of unstructured and structured uncertainties on the performance of the system is considered by the mu-synthesis approach. On the notion of an organized singular value, the design of the controller is based, in this method.

3.5.4 Adaptive controllers

In adaptive control methods, depending on the operating conditions of the system the control action is automatically adjusted. With high performance, the accurate system parameters are not required. This control scheme has high computational complexity.

3.5.5 Predictive controllers

The future behavior of controlled parameters is predicted by using system model in predictive controllers. Based on predefined optimization criteria, to obtain the optimal actuation the controller utilizes this information. It can be applied to different systems while a multivariable case can be considered, because of its non- linearities, constraints that can be simply incorporated, and very fast dynamic response. It has also easy implementation. The comparison of classic controller and this controller comparison shows, that an excessive number of calculations is required in the predictive controller.

3.5.5.1 Deadbeat controllers

The dynamic response of the controlled system which is controlled by the differential equation is discretized and derived, in the deadbeat control theory. Centered on these equations, at the end of the sampling period for the state variables to reach the reference values the control signal is calculated, at the start of the individually sampling period.

3.5.5.2 Model Predictive Controller (MPC)

In the MPC, a cost function is defined from a flexible criteria, to select optimal actions that should be minimized. In this strategy, a model of the system is utilized for predicting the response of the variables till a precise time. In design stage of the controller, the MPC simply includes system constraints and non-linearities.

3.5.6 Intelligent controllers

Intelligent controllers obtain automation through the imitation of biological intelligence. Furthermore, the way biological systems troubleshoot problems are borrowed for the idea. Then, that is utilized to solve the control problem.

3.5.6.1 NN controllers

Neural Network (NN) is inspired from the human nervous system. It is a connection of a biological brain system that is stimulated by a number of artificial neurons. It has the ability to obtain a higher fault tolerance and estimate an optional function mapping. When NN is used in control system, it can train either off-line or online.

3.5.6.2 Repetitive controllers

The basic idea of the Repetitive Controllers (RC) is derived from the principle of the internal model. Good tracking/rejection can be achieved, in the closed-loop path if the model of any disturbance/reference is injected. During a period the error signal should be stored, in order to determine the reduction or elimination of the error in other periods. Hence, for periodic non-linear loads, RC has been used. The dynamic response of this controller is not desirable although its performance is appropriate for periodic nonlinear loads. In order to tackle this issue, RC by parallel or cascaded structure can be joined with extremely dynamic response controllers.

3.5.6.3 Fuzzy Logic Controllers

In Fuzzy Logic Controllers (FLC), the knowledge of smart human being is defined and implemented to control the dynamics of a system. The architecture of FLC method consists of (a) Fuzzification, (b) Rule base, (c) Inference mechanism, and (d) De-Fuzzification. In fuzzification, a set of crisp data is converted into fuzzified data, in rule bases certain rules are defined according to the requirement of application to be controlled, in inference mechanism the rules are evaluated and the decision is made according to the defined rules, in de-fuzzification the fuzzified data is converted back to crisp data and thus, a proper control action is achieved.

3.5.6.4 Autonomous controllers

To perform the complex control tasks independently, autonomous controllers are used. By adding intelligence to the procedure of refining autonomy, to acquire an advance level of automation, engineers directly try to automate the human’s technology and knowledge.

3.6 Control structures for grid-connected photovoltaic systems

The DC to AC inverter helps in controlling the power factor by injecting the sinusoidal current into the grid. The DC energy generated from the solar PV is converted into the AC power and is efficiently transferred to the electrical grid by the application of grid side inverter (GSI). The proper operation of the grid side inverter is ensured by designing fast and accurate control system. Thus, the control of GSI is one of the most significant parts of the grid-connected PV system connected.

The two main sub-classifications of the PV control system are:

(1) MPP control module: The maximum power extraction from the PV module or input renewable energy (RE) source is performed by the MPP control.

(2) Inverter control module: ensures (a) a proper grid synchronization and high quality of the injected power, (b) control of the active and reactive power delivered to the grid and (c) the control of DC-link voltage [57].

The control strategy applied to the inverter mainly of two cascaded loops. Usually, there is a fast internal current loop, which regulates the grid current, and an external voltage loop, which controls the DC-link voltage. The current loop is responsible for power quality issues and current protection; thus, harmonic compensation and dynamics are the important properties of the current controller. The DC-link voltage controller is designed for balancing the power flow in the system. Usually, the design of this external controller aims the optimal regulation and stability of systems having slow dynamics. This voltage loop is designed for a stability time higher than the internal current loop by 5 to 20 times. The internal and external loops can be considered decoupling; therefore the transfer function of the current control loop is not considered when the voltage controller is designed. In some works, the control of the inverter connected to the grid is based on a DC-link voltage loop cascaded with an inner power loop instead of a current one. In this way, the current injected into the grid is indirectly controlled.

3.6.1 Control structure for single phase with DC–DC converter

The most common control structure for the DC–AC grid converter is a current-controlled H-bridge PWM inverter having low-pass output filters. Typically L filters are used but the new trend is to use LCL filters that have a higher order, which leads to more compact designs:

- Control of instantaneous values current
- Current is injected in phase with the grid voltage (PF=1)
- Use Phase Locked Loop(PLL) for synchronization of the currentI_{grid} and V_{grid}

3.6.1.1 MPPT control

In order to capture the maximum power, a maximum power point tracker (MPPT) is required. The maximum power point of PV panels is a function of solar irradiance and temperature as depicted in Figure 3.12 This function can be implemented either in the DC–DC converter or in the DC–AC converter. Several algorithms mentioned above can be used in order to implement the MPPT. The IC and P&O are the most frequently used. The incremental conductance 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. Also, incremental conductance can rapidly track the increase and decrease of irradiance conditions with higher accuracy than perturb and observe.

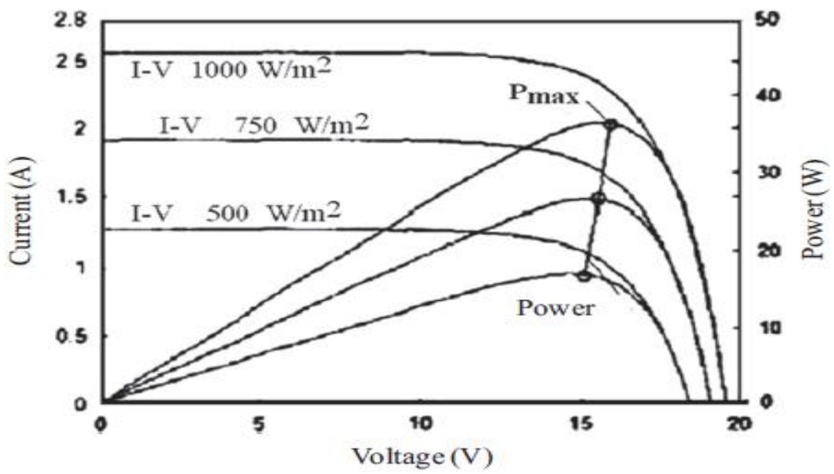

Figure 3. 12 V and PV characteristic

3.6.1.2 DC–DC boost converter control

In order to control the output DC-voltage to a desired value, a control system which can automatically adjust the duty cycle is needed.

Inverter control in Fig. 3.13, the variable control of a control structure for a PV system connected to the grid is shown. This control is divided into 2 control loops, the internal current control loop and the external DC-bus voltage control loop. The internal control loop is used to control the instantaneous values of AC current in order to generate a sinusoidal current in phase with the grid voltage. The reference currentI_{ref} is generated from a PLL sinusoidal signal reference which synchronizes the output inverter current with grid voltage as shown in figure 3.13. The amplitude current is regulated from the external voltage loop. The external loop ensures the regulation of DC-bus voltageV_{DC}. It's necessary to limit the V_{DC} voltage, however, the control of V_{DC} guarantees the regulation of power injected into the grid.

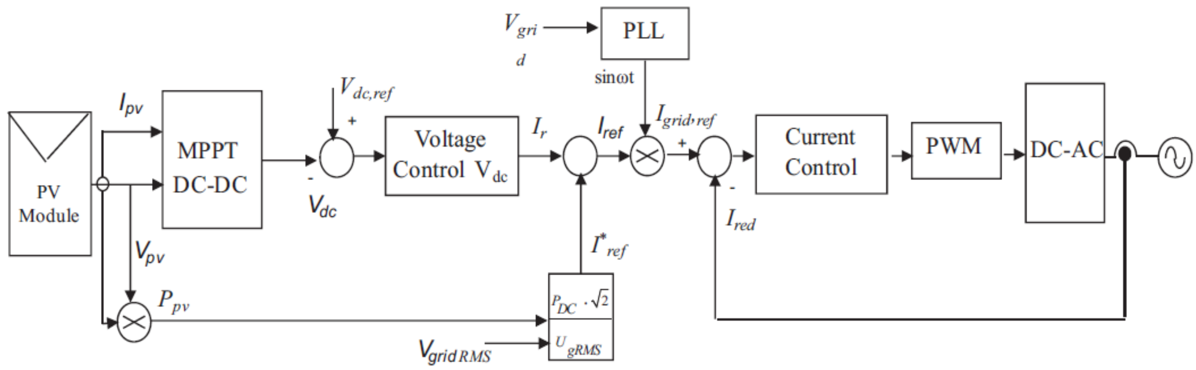

Figure 3. 13 Control structure topology for single phase with DC–DC converter

A control structure for topology with DC/DC converter and L filter is presented in figure 3.14. In this case, the reference current I_{ref} is generated from the sinusoidal signal reference, determinate from a grid voltage sample.

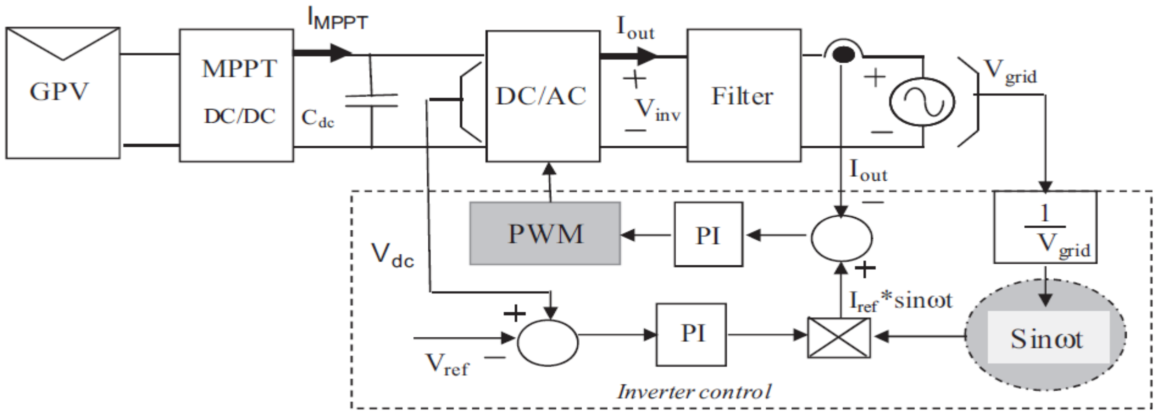

Figure 3. 14 Control structure with DC–DC converter and L Filter.

This structure is associated with proportional integral controllers (PI). To improve the performance of the PI controller, in current control structure and to cancel the voltage ripples of the photovoltaic generator, due to variations in the instantaneous power flow through the photovoltaic system, will depend on the change of atmospheric conditions (mainly the irradiance and temperature), the faster response of the boost control loop, the inverter and the value of the DC bus capacitor. On the other hand, the output voltage (the mains voltage) represents an external disturbance of considerable magnitude at 50 Hz for the system. There exists a compensation of these effects at the output of the PI controller so as to calculate directly the reference voltage for the inductance. Figure 3.15proposes a control structure for topologies with DC–DC converter and LCL filter. This structure has the following characteristics:

1. Typical structure for powers 5 kW max.
2. PI controller (Proportional Integral) or PR (Proportional Resonant) for current control.
3. PWM control, hysteresis or predictive.
4. PI controller for voltage control.
5. Optional transformer.

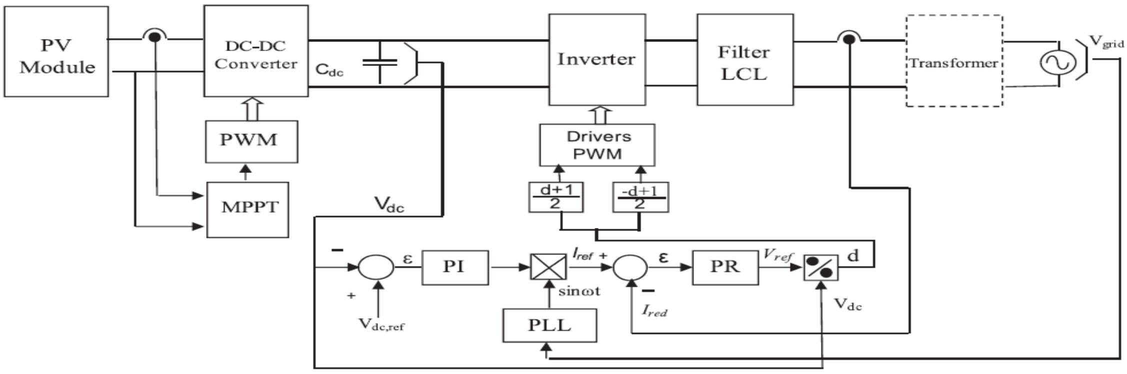

Figure 3. 15 Control structure with DC–DC converter and LCL filter.

The advantage of this control structure is the control of the instantaneous power injected into the grid from the solar module and the synchronization of the current signal with the grid voltage (voltage and current in phase) which guarantee a higher power factor and improve the MPPT dynamic. The disadvantage is the noise in the inverter output current signal due to the use of the grid signal sample for generating and synchronizing the reference current with the grid signal [78].A simple control method for two stage utility grid connected photovoltaic power conditioning systems (PCS) is proposed in [79]. This approach enables maximum power point (MPP) tracking control with post stage inverter current information instead of calculating solar array power is shown in Figure 3.16 and Figure 3.17, which significantly simplifies the controller and the sensor. Furthermore, there is no feedback loop in the pre-stage converter to control the solar array voltage or current because the MPP tracker drives the converter switch duty cycle. This simple PCS control strategy can reduce the cost and size, and can be utilized with a low cost digital processor.

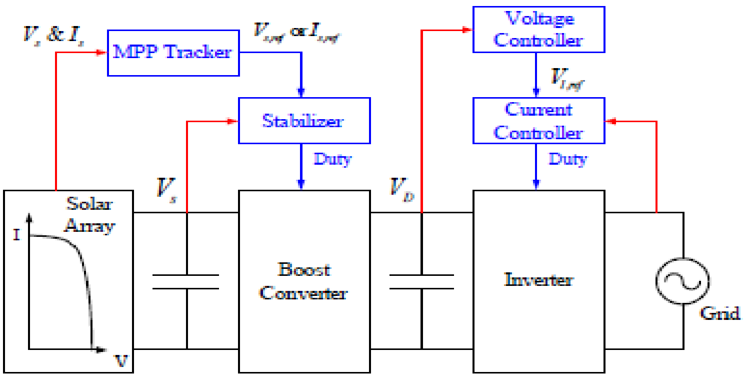

Figure 3. 16 The conventional PCS control scheme

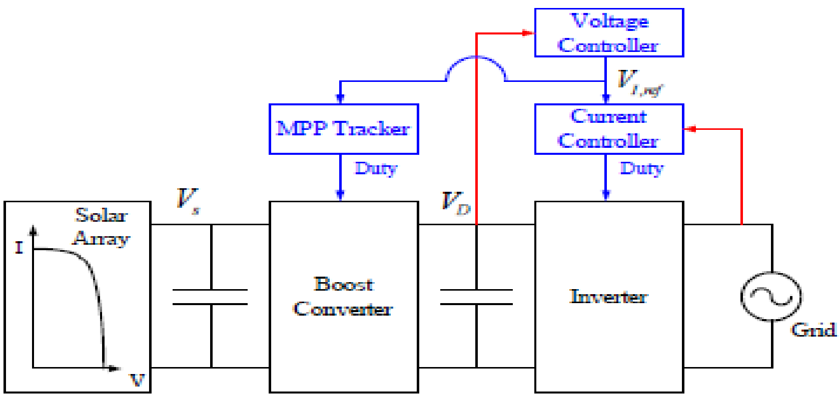

Figure 3. 17 Simple PCS control scheme

3.6.2 Control structure for single phase without DC–DC converter

The difference with respect to the control structure for topologies with DC–DC converter, the DC–AC inverter determines the maximum power point. The control structure for single phase without DC–DC converter show in Figure 3.18. This control structure has the same control loop, the internal current one and the external voltage loop.

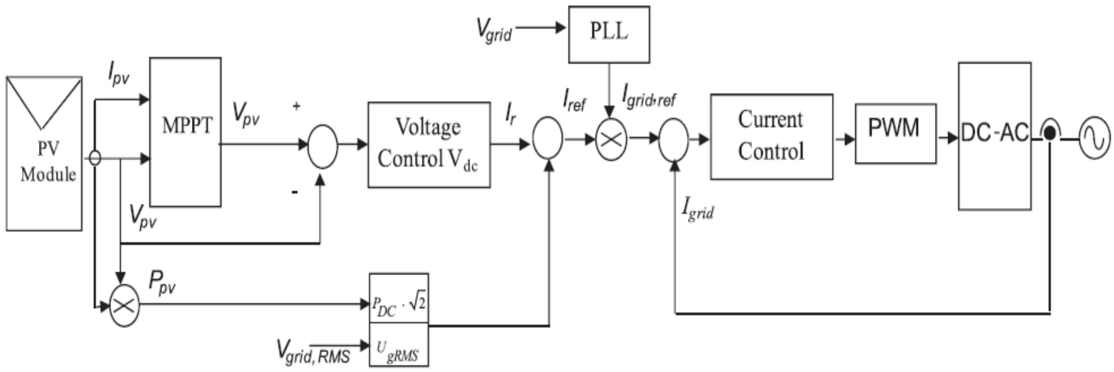

Figure 3. 18 Control structure for single phase without DC–DC converter.

The full bridge inverter connected to the grid across the LCL filter is shown in Figure 3.19. This power control structure is divided principally on the synchronize algorithm based on the Phase Locked Loop (PLL), a maximum power point (MPPT), the input power control of the continuous side and the injected current control into the grid. PLL is used for the synchronization of the inverter output current with the grid voltage, the power factor equal to the unity, also allowing for the generation of the sinusoidal and clean reference signal. The PI controller is used with the feed-forward technique of the grid voltage. As mentioned previously, the feed-forward technique improves the dynamic response. This guarantees the stability of perturbations in the system introduced by the feedback voltage and proposes an alternative solution for the poor performances of the PI controller, which includes the use of the proportional resonant controller PR [78].

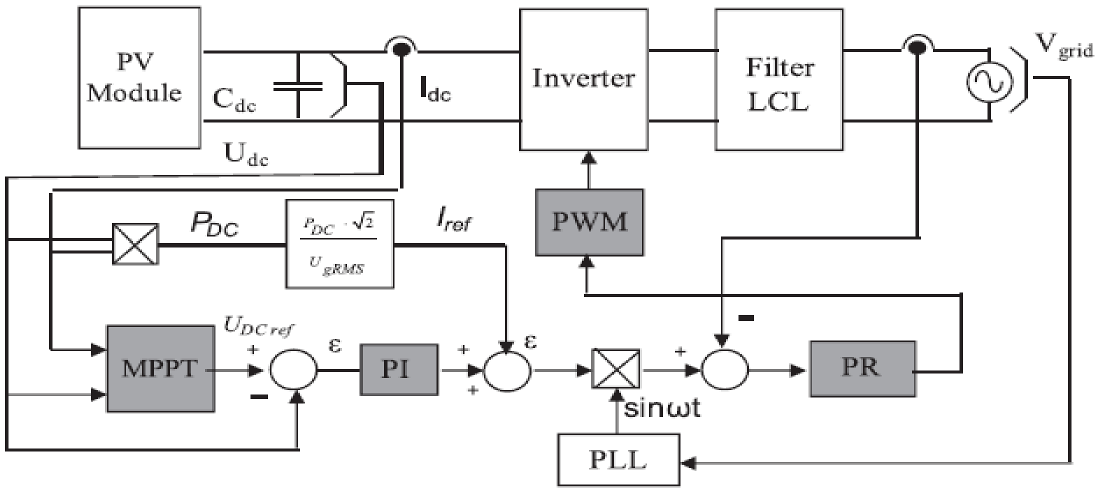

Figure 3. 19 Injected power control structure

Another control structure for single-stage photovoltaic (PV) inverter is proposed in [80]. The grid current controller implemented in two different ways, using the classical proportional integral (PI) and the novel proportional resonant (PR) controllers. An incremental conductance method has been used in order to track the MPPT of the PV characteristic. The PR+HC (harmonic compensator) controller gives better performances then the classical PI controller for the grid current loop. The PR controller is able to remove the steady-state error without using VFF, which makes it more reliable. By adding the selective HC to the PR controller, a very good rejection for the dominant harmonics can be obtained.

3.6.3 Control based on the shifting phase for grid connected photovoltaic inverter

The photovoltaic system consists of a photovoltaic generator (PVG), a maximum power point tracking (MPPT) block and a PWM single phase inverter (DC/AC) is shown in figure 3.20.The DC/DC converter is employed to boost the PV-array voltage to an appropriate level based on the magnitude of utility voltage, while the controller of the DC–DC converter is designed to operate as a maximum power point (MPP) that increases the economic feasibility of the PV system.

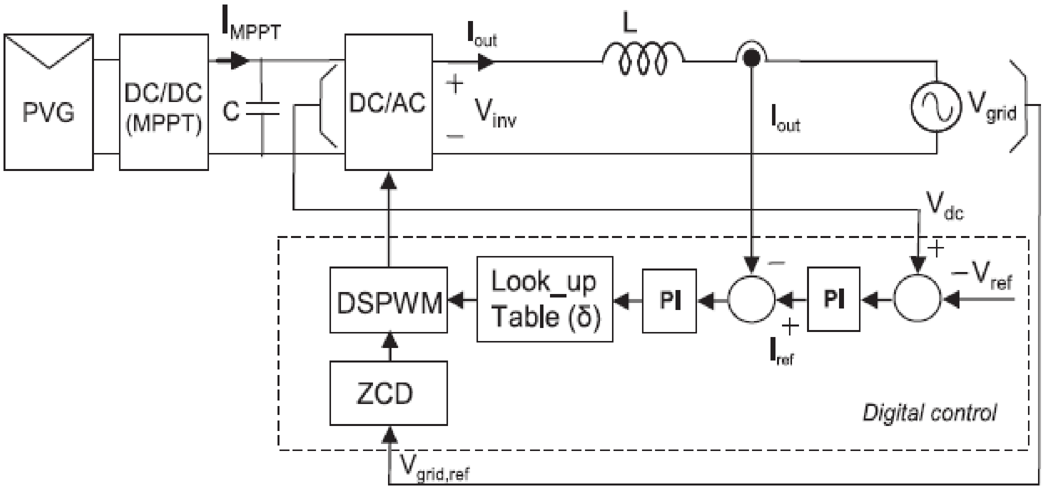

Figure 3. 20 Control structure based on the shifting phase for a single phase connected to the grid.

The control loop for the PWM inverter is assured by the output current control, the DC bus control and synchronizing to the grid, to inject power into the grid at all time. In this case the voltage at the Point of Common Coupling (PCC; the point where the load would be connected in parallel to the two sources), is not considering. The inverter is decoupled of the grid. The output voltage of the PWM inverter is already set by the utility PV modules. Therefore the inverter is current controlled to ensure only power injection into the grid. The power control is obtained by means of the inverter output voltage shifting phase, PCSP (Power Control Shifting Phase). In Figure 3.20 are represented a controller with two control loops: an inner one, that allows controlling the inverter output current and an outer one to control the DC bus(V_{DC}).

The reference of the output current (I_{ref})depends on the DC bus voltage (V_{DC}) and its reference(V_{ref}). A low pass filter is incorporate in order to ensure that high frequency switching noise present in the measured inverter output current signal does not pass through to the PI controller. The control structure is associated with proportional–integral (PI) controllers since they have a satisfactory behavior when regulating DC variables. In this case the output current I_{out} is not controlled varying the amplitude modulation index m_a, since it is considered constant, but by phase shifting the inverter output voltage with respect to the grid voltage. The adequate value of the phase shifting is obtained taking into account the zero crossing detector (ZCD) of the reference ($V_{grid,ref}$). The DSPWM (Digital Sinusoidal Pulse Width Modulation)generates the driving signals for the PWM inverter according to the switching pattern, with the corresponding phase shifting, in order to satisfy the current reference, I_{ref}. So the power factor is indirectly controlled. As a result, a certain amount of reactive power can be generated. The main advantage of this control strategy is its simplicity with respect to the computational requirements of the control circuit and hardware implementation. On the other hand, it allows reconfiguring the control in a fast and simple way in case that not only an active power needs to be injected but also a reactive one [78].Table 3.5, resume the advantage and inconvenient of each control structures for single phase topologies [57] [78].

Table 3. 5 Advantage and inconvenient of control structures for single phase inverters

Topologies	Advantage	Inconvenient
Single phase inverter with DC/DC converter	Fast Dynamic Instantaneous current control	Complex hardware circuit No full control of power factor
Single phase inverter without DC/DC converter	Simplicity of the conversion system Instantaneous current control Fast Dynamic	Complex hardware circuit No full control of power factor
Single phase inverter with PCSP	Simplicity Less circuitry Few resources Reactive power controlled	No full control of current No fast dynamics

3.6.4 Control structure for three-phase inverter connected to the grid

To study stationary and dynamic regimes in three-phase systems, the application of “vector control” (Park vector) is a powerful tool for the analysis and control of DC–AC converters, enabling abstraction of differential equations that govern the behavior of the three-phase system in independent rotating shafts. The main disadvantage of using this control method is that it introduces a nonlinear part, a rotation of axes (mathematical transformations), which requires a lot of computing power, an issue that is solved with existing microcontrollers and DSP.

3.6.4.1 dq control

The concept of decoupled active and reactive power control of three-phase inverter is realized in the synchronous reference frame or also called dq control by using the abc-dq transformation for converting the grid current and voltages into a rotating reference system with the grid voltage, these variable control values are transformed into continuous. In this way, the ac current is decoupled into active and reactive power components, Id and Iq, respectively. These current components are then regulated in order to eliminate the error between the reference and measured values of the active and reactive powers. In most cases, the active power current component, Id, is regulated through a DC-link voltage control aiming at balancing the active power flow in the system. As shown in Fig. 3.36, the power control loop is followed by a current control system. By comparing the reference and measured currents, the current controller should generate the proper switching states for the inverter to eliminate the current error and produce the desired ac current waveform.

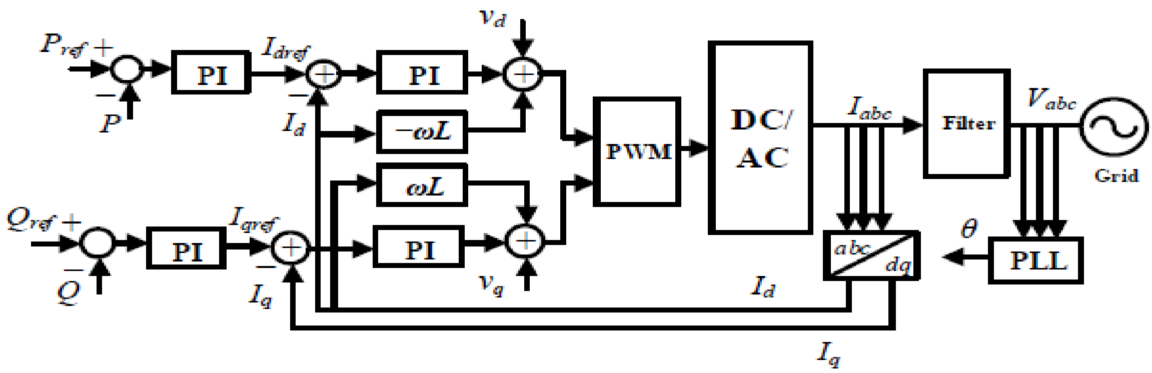

Figure 3. 21 General structure for dq control strategy

In the case that the reactive power has to be controlled, a reactive power reference must be imposed to the system. Linear PI controller is an established reference tracking technique associated with the d-q control structure due their satisfactory combinational performance. Eq. (3.6) states the transfer function on the d-q coordinate structure.

$$G_{PI}^{dq} = \begin{pmatrix} K_p + \frac{K_i}{s} & 0 \\ 0 & K_p + \frac{K_i}{s} \end{pmatrix} \qquad (3.6)$$

Where K_p is the proportional gain and K_i is the integral gain of the controller.

For improving the performance of PI controller in such a structure, as depicted in Fig. 3.36, cross-coupling terms and voltage feed forward are usually used. In any case, with all these improvements, the compensation capability of the low-order harmonics in the case of PI controllers is very poor. Proposes the use of PR+HC controller to improve the system dynamic response, harmonic distortion, eliminate steady state error and prevent the use of the feed-forward. The phase-locked loop (PLL) technique is usually used in extracting the phase angle of the grid voltages in the case of PV systems.

3.6.4.2 αβ–Control

In this case, the grid currents are transformed into a stationary reference frame using the abc-αβ module, as shown in Figure 3.22. The abc control is to have an individual controller for each grid current; characteristic to this controller is the fact that it achieves a very high gain around the resonance frequency, thus being capable of eliminating the steady-state error between the controlled signal and its reference. High dynamic characteristics of the Proportional Resonant Controller PR controller have been reported in different works, and which is gaining common popularity in the current control for networked systems, is an alternative solution for performance under the proportional integral PI controller. The basic operation of the controller PR, is based on the introduction of an infinite gain at the resonant frequency to eliminate the steady state error at this frequency between the control signal and the reference. It does not require the use of feed forward. The transfer matrix of the PR controller in the stationary reference frame is given by Eq. (3.7):

$$G_{PR}^{\alpha\beta} = \begin{pmatrix} K_p + \frac{K_i}{s^2+\omega^2} & 0 \\ 0 & K_p + \frac{K_i}{s^2+\omega^2} \end{pmatrix} \qquad (3.7)$$

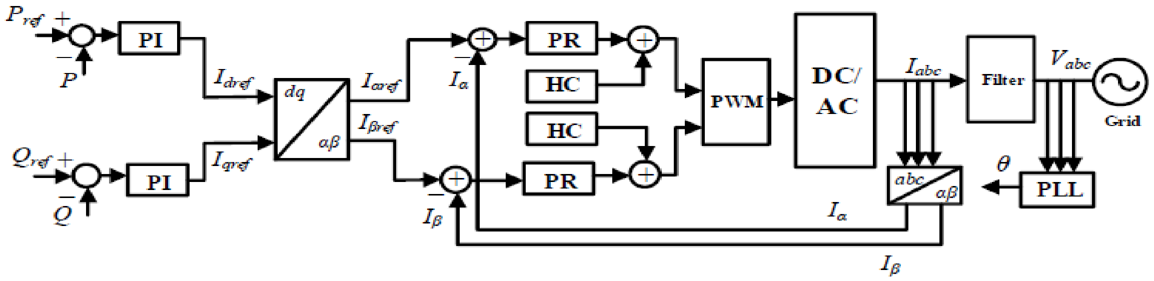

Figure 3. 22 General structure for αβ control strategy.

3.6.4.3 ABC control

ABC control is a structure where nonlinear controllers like hysteresis or dead beat are preferred due to their high dynamics. The performance of these controllers is proportional to the sampling frequency; hence, the rapid development of digital systems such as digital signal processors or field-programmable gate array is an advantage for such an implementation. A possible implementation of abc control is depicted in Figure 3.23, where the output of DC-link voltage controller sets the active current reference. Using the phase angle of the grid voltages provided by a PLL system, the three current references are created. Each of them is compared with the corresponding measured current, and the error goes into the controller. If hysteresis or dead-beat controllers are employed in the current loop, the modulator is not necessary. The output of these controllers is the switching states for the switches in the power converter. In the case that three PI or PR controllers are used, the modulator is necessary to create the duty cycles for the PWM pattern. The PI controller is widely used in conjunction with the dq control, but its implementation in the abc frame is also possible. The implementation of PR controller in abc is simple since the controller is already in a stationary frame and the implementation of three controllers is possible as expressed in Eq. (3.8) [78]:

$$G_{PR}^{abc} = \begin{pmatrix} K_p + \frac{K_i}{s^2+\omega^2} & 0 & 0 \\ 0 & K_p + \frac{K_i}{s^2+\omega^2} & 0 \\ 0 & 0 & K_p + \frac{K_i}{s^2+\omega^2} \end{pmatrix} \quad (3.8)$$

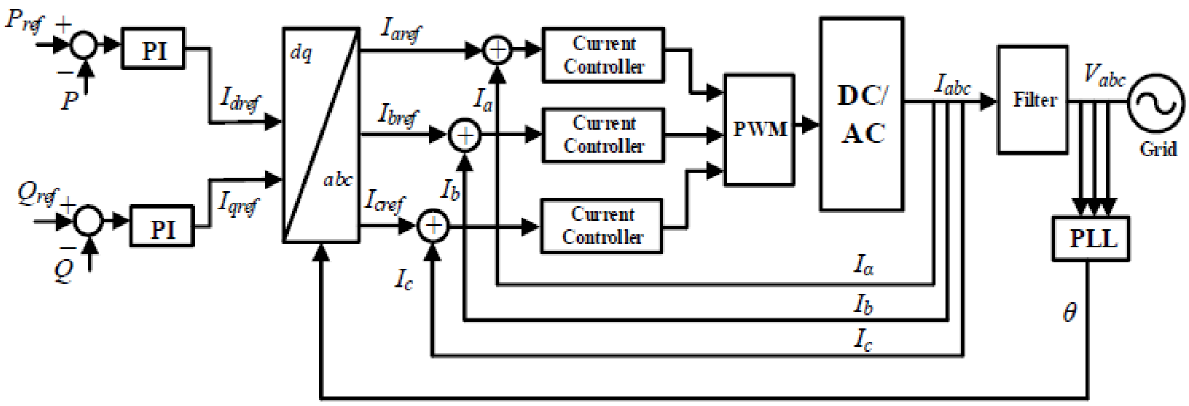

Figure 3. 23 General structure for abc control strategy.

Table 3. 6 Resume the advantage and inconvenient of control structures in three phase inverter

Topologies	Advantage	Inconvenient	Controller Type
dq control	Simplicity Controlling and filtering can be easier accomplished	The steady-state error is not removed Compensation capability of the low-order harmonics is very poor	PI
αβ control	The steady-state error is removed Around the resonance frequency, a very high gain is acquired High dynamic	Complex Hardware circuit No complete control of power factor	PR
abc control	-	The transfer function is complex	PI
	Simple transfer function	More complex than hysteresis and Deadbeat	PR
	High dynamic Rapid development	High complexity of the control for current regulation.	Hysteresis
	High dynamic. Simple control for current regulation. Rapid development	Implementation in high frequency microcontroller	Dead-Beat [57] [78].

3.7 Two phase representation of three-phase variables in the synchronously rotating reference frame

In three phase machines usually the behavior and performance are described and analyzed by their voltage and current equations. The coefficients of the differential equations which describes the dynamic behavior of the machines are time varying. For such a complex electrical machine analysis, mathematical transformations are often used to separate or decouple the variables and to solve equations involving time varying quantities by referring all variables to a common reference frame either stationary or rotating. Among the various methods available for transformation, the well-known are Clarke transformation and Park transformation. By proper selection of the reference frame, it is possible to simplify considerably the complexity of the mathematical machine model. While these transformations were initially developed for the analysis and simulation of ac machines, they are now extremely useful tools in the digital control of such machines. As digital control techniques are extended to the control of the currents, torque and flux of such machines, the need for compact, accurate machine models is obvious [81].

Clarke and Park transformations are used in high performance architectures in three phase power system analysis. Current and voltage are represented in terms of space vector which is represented in a stationary reference frame. A general rotating reference frame has then been introduced. Through the use of the Clarke transformation, the real and imaginary currents can be identified. The Park transformation is used to realize the transformation of those real and imaginary currents from the stationary to the rotating reference frame [82].

3.7.1 Switching states of voltage source inverter

The power devices of the voltage source inverter are assumed in ideal condition: the voltage across the switch is zero when the switches are conducting and there will be voltage across the switch when it is in open circuit in the blocking mode. Therefore, each inverter leg can be represented as an ideal switch. It gives the possibility to connect the three phase windings of the grid to positive or negative terminals of the dc link (V_{dc}). Thus the equivalent scheme for three-phase inverter and possible eight combinations of the switches in the inverter are shown in Figure 3.24.

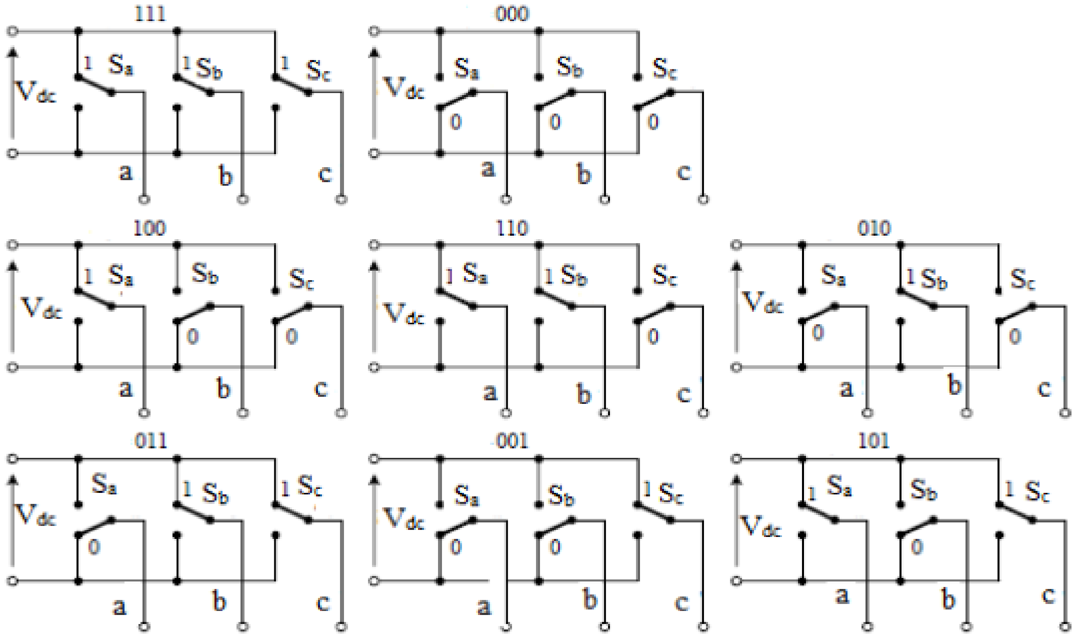

Figure 3. 24 Eight Possible Switching states of Voltage Source Inverter

The relation between the switching states and the inverter voltage outputs in terms of phase and line voltages is given in Table 3.7.

Table 3. 7 Switching patterns and output vectors

Voltage vectors	Switching vectors			Line to neutral voltage			Line to line voltage		
	S_a	S_b	S_c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	1/3	2/3	0	-1	1
V_6	1	0	1	1/3	2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

The stator voltage components applied to the electrical machine are estimated using the switching states and dc link voltage (V_{dc}) as follows [81]:

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \frac{V_{dc}}{3} \begin{pmatrix} S_a & S_b & S_c \\ S_b & S_a & S_c \\ S_c & S_a & S_b \end{pmatrix} \begin{pmatrix} 2 \\ -1 \\ -1 \end{pmatrix} \quad (3.9)$$

3.7.2 Clarke's Transformation

The transformation of stationary circuits to a stationary reference frame was developed by E. Clarke [23]. The stationary two-phase variables of Clarke's transformation are denoted as α and β. As shown in figure3.25, α-axis and β-axis are orthogonal.

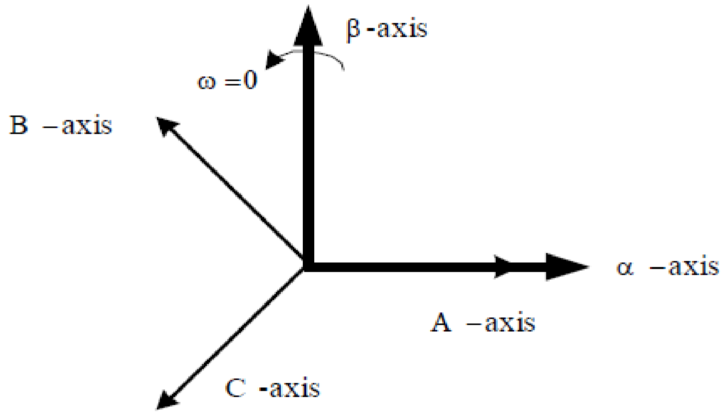

Figure 3. 25 Clarke's transformation

In order for the transformation to be invertible, a third variable, known as the zero-sequence component, is added. The resulting transformation is

$$[f_{\alpha\beta 0}] = T_{\alpha\beta 0}[f_{abc}] \quad (3.10)$$

Where $f_{\alpha\beta 0}$ represents voltage, current, flux linkages, or electric charge and the transformation matrix$T_{\alpha\beta 0}$is given by

$$T_{\alpha\beta 0} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3.11)$$

3.7.3 Park's Transformation

In the late 1920s, R.H. Park introduced a new approach to electric machine analysis. He formulated a change of variables which replaced variables such as voltages, currents, and flux linkages. Park's transformation is a well-known three-phase to two-phase transformation in synchronous machine analysis. Park's transformation is presented in figure 3.26.

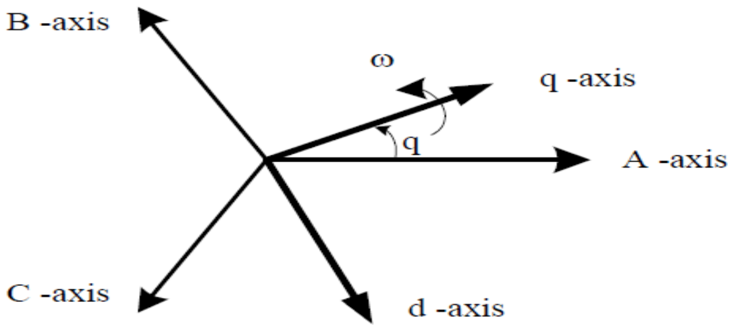

Figure 3. 26 Park's transformation.

The transformation equation is of the form

$$[f_{qd0}] = T_{qd0}(\theta)[f_{abc}] \tag{3.12}$$

And the dq0 transformation matrix $T_{dq0}(\theta)$ is defined as

$$T_{qd0}(\theta)=\frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta-\frac{2\pi}{3}\right) & \sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{3.13}$$

Where θ is the angular displacement of Park's reference frame and can be calculated by

$$\theta = \int_0^t \omega(\zeta)d\zeta + \theta(0) \tag{3.14}$$

Where
ζ is the dummy variable of integration

In the previous equations, the angular displacement θ must be continuous, but the angular velocity associated with the change of variables is unspecified. The frame of reference may rotate at any constant, varying angular velocity, or it may remain stationary. The angular velocity of the transformation can be chosen arbitrarily to best fit the system equation solution or to satisfy the system constraints. The change of variables may be applied to variables of any waveform and time sequence; however, we will find that the transformation given above is particularly appropriate for an a-b-c sequence [83].

3.8 Conclusion

In this chapter, a brief description of connection topologies and Kinds of grid-connected of PV systems. And basic MPPT techniques has been presented to find the maximum power output and summarized the various features of some techniques and the main characteristics of MPPT methods. We also presented the inverter control strategy "linear controllers and non-linear controllers" and their classifications. It has also been descripted the most common control structures for single phase and three-phase inverter.

Finally, were presented the types of mathematical transformations to represent three-phase variables in synchronous rotation into two phases by referring all variables to a common reference frame either stationary or rotating.

Chapter 4
Description of aspects related to the high integrations of renewable photovoltaic sources in the electricity distribution network in terms of energy quality

4.1 Introduction

Large-scale distributed PV generation impacts several aspects of the distribution system. Some of the most noticeable effects concern voltage, current profiles, power quality, protection, electric losses, reactive power management, power balancing, regulation, protection and operability of the system. Solar PV generation impacts can be steady state or dynamic (transient) nature. These impacts vary in severity as a function of the degree of penetration and location of solar PV distributed generation on the distribution feeder [48].On the other hand, instantaneous penetration levels, the fraction of electricity production from intermittent sources at a given instance, could be much higher for instance, in Portugal; instantaneous penetration levels have reached 100% in 2018. Such high penetration rates could threaten power grid stability as current control methods cannot handle high variability and uncertainty in the power generation. Similarly, PV rooftop systems also create bidirectional power flow which can degrade power quality. To match supply with demand in the presence of PV systems, a more responsive demand-side management (DSM) is required. In DSM, customer demand is monitored in real-time and flexible customer loads are curtailed in magnitude or shifted in time, hence managed in lieu of energy imbalance. Power systems around the globe are becoming more decentralized as the generation mix integrates distributed PV systems. One of the most popular applications of PV systems is the integration of PV modules at the low-voltage level such as rooftops, communities or micro grids, and distributed grid level.

Traditionally, network planning was based on regional or local peak demand forecasting over a planning horizon, and the goal was to make sure that no physical constraints were violated during the system operation. Hence, in most distribution networks there was little or no monitoring and control, demand was assumed to be unresponsive, and there were no distributed generators. This approach, fit-and forget, needs to be updated as situations like high solar power injections that happen a few times a year require active management approach. Otherwise, there would be a need for grid reinforcements which increase overall system cost.

The main body of the issues is related to power quality which is defined as the set of operating boundaries that allow specific electrical equipment to function in its intended manner without performance degradation [59].Optimal placement and sizing of DG in the distribution network will give the all benefits of DG like voltage profile improvement and reduce the system losses, improved power quality, relive T&D congestion, reduce reserve requirements and the associated costs etc… [60].

The photovoltaic’s systems can also impose several negative impacts on electrical networks, especially if their penetration level is high. These impacts are dependent on the size as well as the location of the photovoltaic’s system. Photovoltaic’s systems are classified based on their ratings into three different categorized, small systems rated at 10kW and less, intermediate PV systems rated 10kW to 500 kW, and large PV systems rated above 500 kW. The first two categories are usually installed at the distribution system and the last category is usually installed at the transmission system [36].

This chapter documents potential impacts caused by high-penetration PV scenarios.

4.2 Overload-Related Impacts

High penetrations of PV systems can cause the ampacity ratings of circuit elements to be exceeded in a number of ways. Perhaps most intuitively, the total generation from attached PV systems can overload circuit elements located between PV systems and load centers on a given circuit. Additionally, PV can mask load that can overload circuit elements if the PV disconnects.

Also, although load is often quite diverse, PV systems located relatively close to each other are generally fairly coincident (depending on their orientation). In such cases, multiple instances of PV systems that are sized to offset the attached load (e.g., in a residential subdivision) may overload circuit elements because of the coincident nature of the peak PV output relative to the diverse nature of the peak load. When examining overloads, consideration should be given to both normal system conditions and a contingency loss of circuit segments.

4.2.1 Ampacity Ratings

The location of PV can significantly impact the loading of feeder sections; therefore, it is necessary to verify that the feeder sections located between the PV and the substation have enough available capacity to distribute the PV's surplus power (after subtracting local and downstream load). At high penetrations, particularly during light load conditions with high PV output, the line section loading may increase as the PV contribution becomes larger than the native base load. The flow in some instances may increase above that of the peak native load (no PV output).

4.2.2 Cold Load Pickup

Cold load pickup takes place when a distribution circuit is reenergized after a long outage. In this situation, the loss of load diversity coupled with inrush currents can result in feeder current levels that may be much higher than the feeder's annual peak load. This may result in overloads and low voltages if the protection system does not trip first.

PV can exacerbate the cold load pickup problem by increasing the difference between the pre-fault measured load current and the post-fault cold load pickup current. Solar PV is typically tripped when a fault occurs. If the PV cannot reconnect to the system automatically after the fault is cleared (or system operators who could do so are not on standby), or if pre-fault generation levels are no longer available, the load picked up by the substation or the feeder's primary power source is a larger multiple of the pre-fault load compared to a scenario in which the feeder does not have solar PV.

Therefore, an assessment of the cold load pickup may be necessary when considering integrating large amounts of PV into the distribution system. Thus, again, determining the native load is of prime importance in designing circuits with high penetrations of PV.

4.2.3 Masked Load

Masked load refers to load that is hidden from upstream components by PV or other sources of generation. Because many forms of DG are not monitored and can be disconnected or otherwise absent without prior utility knowledge, it is important that the total load is considered in design and operation practices. For the purposes of this report, the load attached to the circuit is referred to as native load.

Figure 4.1 shows the measured load, native load, and PV generation for a peak load day. The native load (gray line) of this circuit is much higher than the measured flow (light blue line) on the circuit, because the measured circuit flow is the combination of the native load and the PV generation (dark blue line). If decisions are made based on the measurements instead of the native load calculations, significant overloads of circuit elements may occur if the PV disconnects unexpectedly. This example illustrates the issue with basing design and operation practices on measured load.

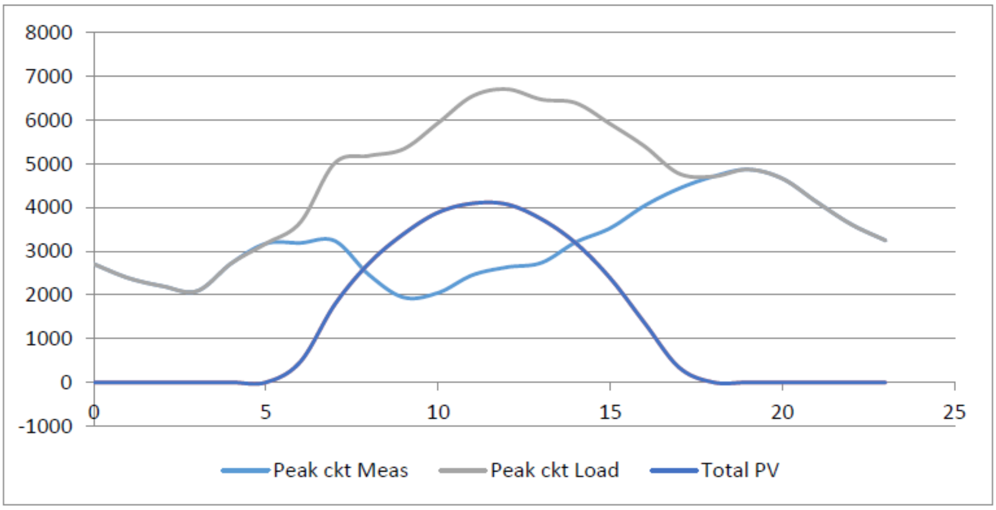

Figure 4. 1 Masked load—difference between measured load and native load on a peak load day

4.3 Voltage-Related Impacts

High penetrations of PV can impact circuit voltage in a number of ways. Voltage rise and voltage variations caused by fluctuations in solar PV generation are two of the most prominent and potentially problematic impacts of high penetrations of PV. These effects are particularly pronounced when large amounts of solar PV are connected near the end of long and lightly loaded feeders. Real and reactive power production from the PV system can impact the steady-state circuit voltage, and rise and fall of PV output can result in voltage fluctuations on the circuit. This, in turn, impacts power quality and voltage control device operation. Potential PV impacts on voltage are discussed below.

4.3.1 Feeder Voltage Profile

With the addition of another power source internal to the distribution circuit, the voltage profile along the circuit may improve when the PV is operating [61].

4.3.2 Overvoltage

Voltage rise is one of the major operational challenges for distributed PV deployment. In a typical distribution network, voltage levels at customer sites are allowed to flow within ±5% [59]. The extent to which voltage rise is experienced on a feeder depends on multiple factors, including the configuration of the feeder and the location of the PV and voltage control equipment, such as capacitor banks and voltage regulating transformers. Figure 4.2 shows an example of the impact of solar PV on the voltage profile of a feeder.

Pockets of high voltage can occur on the distribution circuit during low-load conditions, particularly in places that have a single large PV system or a cluster of PV systems. Voltages should stay below the permissible high-voltage thresholds; otherwise, they can reduce the life of electrical equipment and cause DG (including PV inverters) to trip off-line [61].

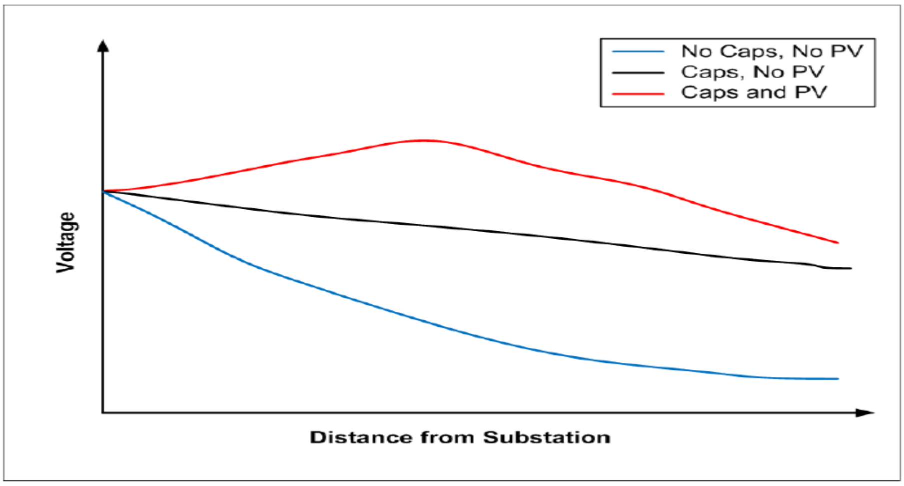

Figure 4. 2 Impact of solar PV on the voltage profile of a feeder

Reverse power flow leads to overvoltage along distribution feeders. In the Gunma project in Japan, it was noticed that when the sun light intensity is more than 5 kWh/m2, the voltage of individual inverters went up by 2%. Also, the difference between weekly household load and the weekends load demand could shift the voltage profile of the feeder by 1.5% to 2% above the maximum limit. A voltage analysis of distribution feeder in Canada showed that overvoltage along the feeder is highly sensitive to photovoltaic's system penetration level as well as to the point of interconnection of the PV cluster to the feeder; at high penetration levels, during light load conditions the voltage at the point of interconnection may increase by 2%-3% above the no load voltages especially when the PV cluster is located far from the distribution transformer [36].

4.3.3 Potential for Increased Substation Voltage

If a regulator or a load tap changer (LTC) transformer is not available at the substation, feeder head voltage may start to rise above acceptable limits. Even with the availability of substation regulation, studies should determine whether sufficient headroom (regulation room) exists to allow the regulator or the LTC to maintain the voltage within permissible limits over the entire load spectrum.

4.3.4 Voltage Flicker

The Institute of Electrical and Electronics Engineers (IEEE) Standard 1453TM-2011 explains voltage flicker as follows:

Voltage fluctuations on electric power systems sometimes give rise to noticeable illumination changes from lighting equipment. The frequency of these voltage fluctuations is much less than the 50 Hz or 60 Hz supply frequency; however, they may occur with enough frequency and magnitude to cause irritation for people observing the illumination changes.

Variations in PV output resulting from cloud cover or shading can cause fluctuations in customer service voltage. Although not common, these voltage violations can cause flicker, which may be irritating to customers and may also result in malfunctioning appliances. Maximum PV power generation on a particular feeder should be constrained to prevent unacceptable flicker; this could set an upper limit on the total connected PV capacity on that feeder. Solar PV impact studies should be performed to assess the potential of voltage flicker due to high penetrations of solar PV.

4.3.5 Automatic Voltage Regulation Equipment

Voltage regulation practices used in radial power distribution systems have traditionally been designed with the assumption that the substation is the only power source in the system, which implies that all flow is outward from the substation toward the end of the feeder. Voltage on such feeders is typically regulated by the LTC at the substation, voltage regulators at the start of the feeders and sometimes distributed throughout the feeders, and switched capacitor banks distributed throughout the feeders. The control settings of these devices are coordinated to maintain the desired voltage profile along the feeder.

After PV is added to the distribution system, the assumption that the substation is the only power source no longer holds true, and the problems of voltage rise/fall and flicker associated with solar PV as discussed earlier can lead to frequent operation of LTCs, voltage regulators, and switched capacitor banks, resulting in additional step-voltage changes. Further, more frequent operation of these devices may shorten their life cycles and increase maintenance requirements.

Voltage regulation equipment that uses line drop compensation to control the feeder voltage profile can be particularly affected by the addition of large amounts of solar PV concentrated at the front of a feeder or immediately after a midline voltage regulator. This is because high concentrations of solar PV at the start of a feeder can mask the actual load current and result in inadequate voltage compensation by the regulator [61].

4.4 Reverse Power Flow Impacts

In distribution system, the power flow is usually unidirectional from the medium voltage system to the Low Voltage system. However, at a high penetration level of photovoltaic's systems, there are moments when the net production is more than the net demand, especially at noon, and as a result, the direction of power flow is reversed, and power flows from the low voltage side to the medium Voltage side. This reverse power flow results in overloading of the distribution feeders and excessive power losses. Reverse flow of power has also been reported to affect the operation of automatic voltage regulators installed along distribution feeders as the settings of such devices need to be changed to accommodate the shift in load center. Reverse power flow may have adverse effects on online tap changers in distribution transformers especially if they are from the single bridging resistor type [36].If voltage regulators are bidirectional, modifications to the regulator control may still be necessary to accommodate the reverse flow.

4.4.1 Substation and Bulk System Impacts

Impacts depend on factors such as penetration level, aggregated output characteristics, and system characteristics (e.g., amount and type of other generation sources). Most common concerns include increases in cost because of regulation, ramping generation, scheduling generation, and unit commitment, which may degrade balancing authority area performance and wear and tear on regulating units.

4.4.1.1 Reverse Power Flow to Adjacent Circuits

Protection concerns, arising from significant reverse power flows, such as exceeding interruption ratings of circuit protection elements and sympathetic tripping of adjacent circuits are two of many ways in which distribution-connected PV or other forms of DG-caused fault current contributions lead to problems on the distribution system.

4.4.1.2 Reverse Power Flow through the Substation Transformer

Reverse power flows resulting from PV generation could possibly cause reverse power relays at a substation to operate, disconnecting the associated circuit. The resulting outages ultimately reduce system reliability.

4.4.2 Temporary and Transient Overvoltage

IEEE C62.82.1-2010 defines temporary overvoltage (TOV) as follows:

An oscillatory phase-to-ground or phase-to-phase overvoltage that is at a given location of relatively long duration (seconds, even minutes) and that is undammed or only weakly damped.

Temporary overvoltage's usually originate from switching operations or faults (e.g., load rejection, single-phase fault, fault on a high-resistance grounded or ungrounded system) or from nonlinearities (e.g., Ferro resonance effects, harmonics), or both. They are characterized by the amplitude, the oscillation frequencies, the total duration, or the decrement.

The above definition mentions load rejection as a potential cause of TOV. Because isolation of a section with PV caused by the operation of an upstream sectionalizing device is similar to a load-rejection scenario, it is important to study the potential for TOV in sections in which the amount of connected PV is close to or greater than the nominal load. Figure 4.3 shows an example of TOV due to load rejection where the waveforms shown are a PV inverters AC output voltage, AC output current and DC input voltage during a load rejection event.

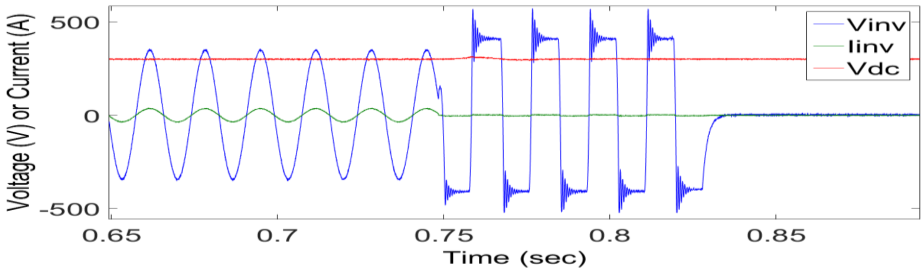

Figure 4. 3 Example of TOV due to load rejection

In contrast to TOV, transient overvoltage is defined by IEEE C62.82.1-2010 as follows:

A short-duration highly damped, oscillatory or non-oscillatory overvoltage, having a duration of a few milliseconds or less. Transient overvoltage is classified as one of the following types: lightning, switching, and very fast front, short duration.

The example waveform in figure 4.4 shows a diagram of a transient overvoltage and depicts that transient overvoltage is of much shorter duration than the TOV.

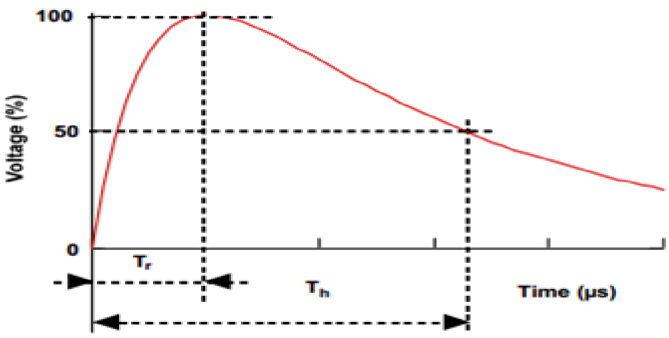

Figure 4. 4 Example of transient overvoltage

If the operation of upstream sectionalizing devices (such as fuses or recloses) results in the formation of an island with PV as an active power source, TOV may result, particularly when load in the islanded section is lower than the PV output. Depending on the magnitude of overvoltage and how fast a PV inverter trips after the detection of overvoltage, it is possible that other equipment installed on the islanded segment may be damaged.

The operation of a protective device or other switchable device that isolates an amount of load with an aggregate amount of PV in excess of the load may result in an overvoltage condition. Studies that show reverse flow through a protective device should alert the planning engineer to this possibility, because there is more generation than load on the section beyond the protective device.

4.4.3 Automatic Voltage Regulation Equipment

A “runaway tap changer” may be encountered with large penetrations of solar PV. This situation can occur in feeders in which the regulator is set such that it reverses the direction of voltage regulation with reversal in the direction of power flow. When this happens, the voltage regulator attempts to regulate the voltage on the substation side of the regulator. In the absence of solar PV, such a control setting of the voltage regulator helps in voltage regulation if the auto loop feature of the distribution system operates; however, if power reversal happens because of the presence of solar PV and not because of the operation of the auto loop, the voltage regulator may start regulating the voltage of the section on its substation side and try to bring the substation voltage to the set point voltage. The substation is a strong source and will not respond to the change in tap settings, and the regulator will keep changing the tap position until it reaches its limits, at which stage it is possible that the output on the PV side of the regulator may experience higher or lower than permissible voltages, depending on the direction in which the taps are moved [61].

4.5 Phase unbalance

Inverters used in small residential photovoltaic system installations are mostly single phase inverters. If these inverters are not distributed evenly among different phases, phase unbalance may take place shifting the neutral voltage to unsafe values and increasing the voltage unbalance.

4.6 Power quality problems

Power quality issues are one of the major impacts of high photovoltaic’s penetration level on distribution networks [36].Power quality assumes growing importance in low, medium, or high voltage facilities. The main problems regarding power quality are high harmonic distortions and voltage levels [52]. Approximately 70% to 80% of all power quality (PQ) issues related problems can be attributed to faulty connection and/or wiring. Power frequency disturbances, harmonic electromagnetic interface, transient, and lower power factor are the other categories of PQ problems [62].

4.6.1 Frequency fluctuation

Frequency is one of the most important factors in power quality. Any imbalance between the produced and the consumed power may lead to frequency fluctuation. The small size of PV systems causes the frequency fluctuation to be negligible compared with other renewable energy based resources. However, this issue may become more severe by increasing the penetration levels of PV systems.

Frequency fluctuation may change the winding speed in electro motors and may damage generators.

4.6.2 Harmonics

Harmonic distortion is a serious power quality problem [63]. Harmonic distortion of voltage and current waveform is a growing issue due to the high penetration of PV generation. Distortion occurs due to the conversion of DC power that is generated by PV panels into AC power system is done via inverters which are the main source of harmonics. Injected harmonics can cause increased power losses due to heating, shorten equipment lifetime, lead to power outages [59]parallel and series resonances and false operation of protection devices that may reduce the reliability of power systems [63].

However, voltage harmonics are usually within limits if the networks stiff enough with low equivalent series impedance. Current harmonics, on the other hand, are produced by high pulse power electronic inverters and usually appear at high orders with small magnitudes. An issue with higher order current harmonics is that they may trigger resonance in the system at high frequencies. This situation occurred in the holiday park in the Netherlands where the 11th and15th voltage harmonics exceeded the permissible limits due to resonance between the grid inductance and the inverter high capacitance.

4.6.3 Electromagnetic interference problem

The high switching frequency of Photovoltaic system inverters may result in electromagnetic interference with neighboring circuits such as capacitor banks, protection devices, converters and DC links leading to mal-function of these devices [36].

4.6.4 Output power fluctuation

The fluctuation of the output power of PV systems is one of the main factors that may cause severe operational problems for the utility network. Power fluctuation occurs due to variations in solar irradiance caused by the movement of clouds and may continue for minutes or hours, depending on wind speed, the type and size of passing clouds, the area covered by the PV system, and the PV system topology. Power fluctuation may cause power swings in lines, over- and under loadings, unacceptable voltage fluctuations, and voltage flickers [63].

4.6.5 Increased reactive power

Photovoltaic’s system inverters normally operate at unity power factor for two reasons. The first reason is that current standards, according to IEEE 929-2000, do not allow Photovoltaic’s system inverters to operate in the voltage regulation mode. The second reason is that owners of small residential PV systems in the incentive programs are revenue only for their kilowatt-hour yield, not for their kilovolt-ampere hour production. Thus, they prefer to operate their inverters at unity power factor to maximize the active power generated and accordingly, their return. As a result, the active power requirements of existing loads are partially met by PV systems, reducing the active power supply from the utility. However, reactive power requirements are still the same and have to be supplied completely by the utility. A high rate of reactive power supply is not preferred by the utilities because in this case distribution transformers will operate at very low power factor. Efficiency of transformers decreases as their operating power factor decreases, as a result, the overall losses in distribution transformers will increase reducing the overall system efficiency.

4.7 Islanding Detection and Operation

Grid-connected PV systems may experience more frequent abnormal operating conditions such as voltage shutdown, short-circuit or equipment failure. In order to avoid large-scale blackouts and system failures, a portion of the network is disconnected from the main grid, but distributed PV generators continue to provide power and maintain the scheduled voltage and frequency within the operating limits (Teoh and Tan 2011). Two types of islanding exist:

planned (intentional) and unplanned (unintentional) modes. As the name suggests, intentional islanding is planned and typically used for maintenance purposes. During the maintenance, the PV system provides power. Unplanned islanding mode, on the other hand, can be severe as loss of grid synchronization may lead to instabilities. Therefore, islanding detection techniques are critical. Detection methods can be classified into two groups: remote techniques and local methods [59].

4.8 System Protection Impacts

High penetrations of PV can change the fault current levels and also make it necessary to review the protection coordination currently implemented in the distribution network. The addition of PV increases the fault current levels at all points on the system; therefore, it is important to verify that the maximum fault current through each protective device does not exceed its interrupting rating. Typically, utilities require the interrupting rating to exceed the maximum fault current by a safety margin of approximately 10%, but any applicable margins for this area should be considered. In addition, direct-current offsets that occur when the X/R ratio of the thevenin impedance is high should also be considered. Some manufacturers specify their interrupting ratings at an X/R ratio of 15 or less. Equipment interruption ratings in most cases are given for the symmetrical fault level and list the maximum X/R ratio. Fault current contribution from PV is typically approximately 1.1 times the rated current.

For fault sensing the circuit should be checked to verify that all the protective devices can sense faults within their respective protective zones. If the PV is connected via a delta-wye transformer or even a wye-wye transformer in cases when the utility side of the transformer is ungrounded, then ground faults upstream of the PV may result in high voltages on the unfaulted phases. This is typically a utility concern, because it can affect other customers. The utility is normally obligated to address the problem by informing the PV owner of the issue. Once informed, it should become the PV owner’s responsibility to install equipment to detect overvoltage and isolate the PV. Overvoltage’s caused by ungrounded secondary systems or inverters are not addressed in this document and are the responsibility of the PV owner. Fault contribution from PV may cause a fuse to blow that would have otherwise remained intact. If reclosing times are too fast after a fault, the PV may still be online and have lost synchronism with the utility system. Practices should be reviewed to ensure that reclosing does not cause conditions to be out of synchronism. This is true for any generating source, including synchronous, induction, and PV connected to the system. If automatic reclosing is used, some utilities have increased the open time between breaker or recloser closings to ensure that PV has been shut down by the local protective systems. Voltage sensing on the PV side of the breaker or recloser can help ensure that no PV source is online when the breaker or recloser is closed. IEEE 1547 requires that PV systems be shut down and isolated within 2 s or less during island conditions. A strict reading of the standard shows that PV should disconnect faster than 2 s when the utility uses automatic reclosing times less than 2s. This requirement is independent of the islanding detection requirement. When DG such as PV continues to serve load via a utility’s lines when it is isolated from the utility source, an island condition has occurred. PV may not be designed to maintain voltage and frequency for customers in the absence of a utility source and poses a threat to equipment connected to the island. Additionally, an island condition may present a hazard to utility workers in the area. For these reasons, islands are typically prohibited, except in special cases when an island has been preplanned to provide service continuity. When an islanded condition occurs that is not preplanned, it is often referred to as an unintentional island.

Under voltage may cause the PV to trip off-line for voltage sags during temporary faults. Voltage sags may be as short as a fraction of a cycle and up to 1 s or 2 s long. Currently, inverters compliant with UL 1741 are required to detect under voltage and disconnect from the grid. Planning and protection design personnel should be aware of this effect, which causes loss of generation from the PV system. It may be desirable for PV to ride through voltage sags by extending the trip times to the maximum permissible. Also, fast automatic reconnection may be desirable as determined by the local utility. Advanced PV inverters may have functionality that includes low-voltage ride-through so that PV generation can come back online quickly and/or ride through voltage sags without being tripped for adjacent fault conditions.

4.9 Circuit Configurations

4.9.1 Normal System Configuration

A PV system should be evaluated for its normal configuration. A normal system configuration is also referred to as the "as-built" system configuration. The as-built configuration should be evaluated throughout the entire load spectrum of the circuit to assess the effects of the PV addition.

4.9.2 Abnormal System Configuration

A PV system should also be evaluated for abnormal configurations. Abnormal configurations are the various reconfigurations that are possible involving adjacent circuits. These include potential planned circuit reconfigurations of which a PV system may or may not be a part, such as auto loops, two feeds to a single customer, single contingencies, and switching plans. Ideally, abnormal configurations should be evaluated throughout the entire load spectrum of the circuits involved to assess the effects of the addition of PV. Operating restrictions should be noted, including cases when the PV must stay offline. Note that the criteria (such as for overvoltage's, overloads, etc.) for abnormal system configurations may differ (they may be somewhat more relaxed) from that used for normal system configurations.

4.9.3 Future/Planned System Configurations

PV installations should be analyzed for known future configurations as well. The future/planned configuration should be evaluated throughout the entire load spectrum of that circuit to assess potential criteria violations resulting from the addition of PV.

4.9.4 Contingency Conditions

Contingency conditions refer to abnormal system conditions that may arise because of events such as loss of load, tripping of a line, or failure of protective devices. The need to analyze the impact of PV during normal, abnormal circuit configurations and also during contingency conditions [61].

4.10 Conclusion

This chapter documents potential impacts caused by high-penetration PV scenarios such as overload impacts, voltage impacts, reverse power flow impacts, phase unbalance, power quality problems, Islanding detection and operation and system protection impacts.

Finally, we descripted the circuit configurations normal and abnormal system configuration.

Chapter 5
Study the impacts of the candidate geographical locations on the performance of PV system and choose the best location

5.1 Introduction

The meteorological is different from one place to another, which affects the productivity of the photovoltaic system. Therefore, it is very important to use a simulation tool for photovoltaic's to select all components and to know the energy produced according to the geographical location and choose the best operating for Photovoltaic system. This Chapter study the impacts of geographical location on the output of energy from PV system (5 MW) particularly applied in the PVsyst program of Skikda (Algeria) and Atbara (Sudan), to compare yearly energy output in order to select the best site and connect with the grid.

The comparison was done using four methods for controlling the PV array (fixed tilt, seasonal tilt, tracking horizontal, tracking vertical). The network was designed in PVsyst program by using (Latitude, Longitude, Elevation, Time Zone) of Skikda and Atbara and then selected all components of PV system.

The results of Simulation show the total quantity of electrical yearly energy produced by PV system in Atbara is greater than Skikda, about 18.66%, 16.49%, 18.60%, and 8.93% of the energy injected into grid in Skikda for fixed tilt, seasonal tilt, tracking horizontal and tracking vertical respectively.

5.2 Impacts of the geographical location on the performance of PV system - Skikda (Algeria) and Atbara (Sudan) case study

Currently, several stand-alone PV systems as water pumping, lighting and telecommunications are installed in Algeria and Sudan. But these standalone PV systems can be used only to provide power for remote loads that do not have any access to power grids while grid connected applications are used to provide energy for local loads and for the exchange power with utility grids.

There are many simulation programs that are using to analyze the PV system. In this study, simulation of the PV system is performed using PVsyst to analyze the operation of the system based on geographical location. The total amount of electric power generated annually by the PV array in Skikda and Atbara are compared. So as to select the best place in terms of the production of high yearly energy to connect with the grid.

5.2.1 Parameter Selection and System Configuration

Simulation of the PV system means determining the amount of energy needed to operate the system and the number of photovoltaic modules needed to generate power. The photovoltaic system (PV) must generate sufficient power to cover the power consumption of loads (lights, appliances, equipment). The size and configuration of the solar array is then optimized to match the power output of the system with the power consumption of the system. The energy production from PV system depends on meteorological conditions, photovoltaic modules type, characteristics of PV inverter and the directional of PV modules. The system being modeled using the PVsyst program shown in Figure 5.1. It consists of a PV array feeding inverter that feeds current into the grid.

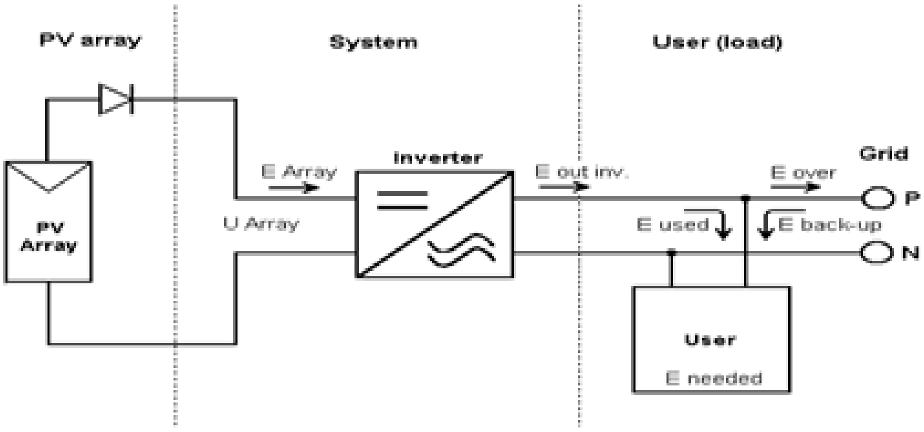

Figure 5. 1 A graphical image of the PV system connected to the grid.

5.2.2 Geographical location and meteorological data of Skikda and Atbara

This work is done based on real meteorological data and geographical location. These data are provided by «Weather Underground» site is available on the Internet to provide meteorological data and geographical location for any place in the world [85]. The modules must be fixed at an appropriate tilt angle to allow the system to operate at high efficiency. Generally, solar radiation data is given in the form of universal radiation on a horizontal surface. If the angle shown on the horizontal surface of the photovoltaic panels changes, the global irradiation received by the PV panels will also change.

Figure 5.2 and Figure 5.3 shows the geographical parameters for the selected sites of Skikda and Atbara.

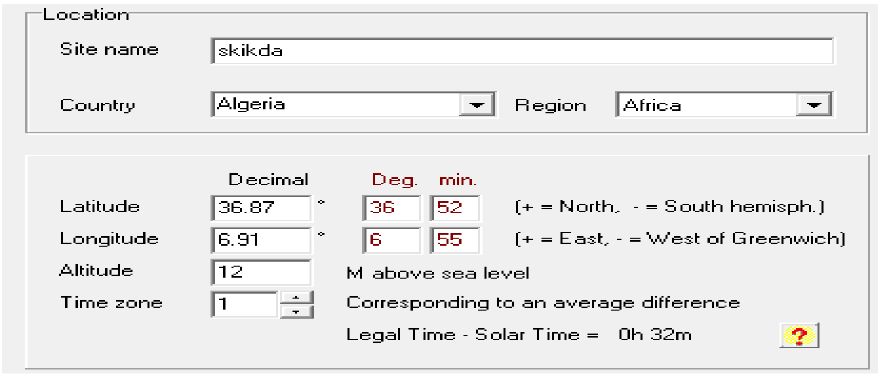

Figure 5. 2 Geographical parameters location of Skikda

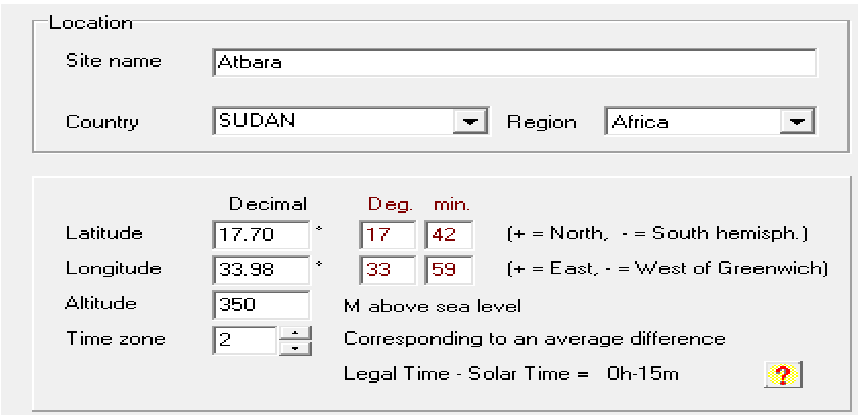

Figure 5. 3 Geographical parameters location of Atbara

Figure 5.4 and figure 5.5 shows the global and diffuse solar irradiation and temperature, monthly and yearly values of Skikda and Atbara.

	Global Irrad. kWh/m².mth	Diffuse kWh/m².mth	Temper. °C
January	71.3	33.4	12.7
February	89.6	39.6	12.8
March	130.8	56.0	14.4
April	156.6	66.4	16.6
May	196.5	75.7	20.6
June	208.2	75.0	24.7
July	226.6	72.6	27.5
August	195.0	69.2	27.8
September	140.7	59.0	24.8
October	104.5	48.2	22.1
November	74.1	35.1	17.9
December	64.8	30.5	14.3
Year	**1658.7**	**660.8**	**19.7**

Figure 5. 4 Global and Diffuse irradiation and Temperature of Skikda

	Global Irrad. kWh/m².mth	Diffuse kWh/m².mth	Temper. °C
January	158.7	49.7	22.1
February	161.0	50.8	23.1
March	195.9	63.0	26.3
April	208.2	64.3	29.7
May	206.5	71.5	30.1
June	201.9	68.9	31.2
July	200.9	72.3	30.4
August	195.3	71.6	30.7
September	183.0	65.2	32.5
October	170.2	61.5	30.9
November	153.6	51.0	27.1
December	147.9	48.7	23.6
Year	**2183.0**	**738.6**	**28.1**

Figure 5. 5 Global and Diffuse irradiation and Temperature of Atbara

5.2.3 Solar PV Horizon profile

Photovoltaic solar modules produce electricity only when sunshine is available. The output power of the PV system is affected by temperature, weather conditions and sunshine during the day. Sun path chart is a simple graphical way to represent the motion of the Sun, depending on projection used following sun path charts, various Sun Path charts are used, and the horizon profile can be manually defined by a set of (Azimuth/Height) points in degrees. After setting the horizon line (azimuth set of points, height) in PVSYST simulator, we can get the solar path in Skikda and Atbara. Figure 5.6 and Figure 5.7 shows horizon line drawing of solar of Skikda and Atbara from 6h00 AM to 6h00 PM, so 12 hours of sunshine. Our system can receive the solar light, and out this time, solar can be behind the plane, this depends for solar height and horizon line drawing.

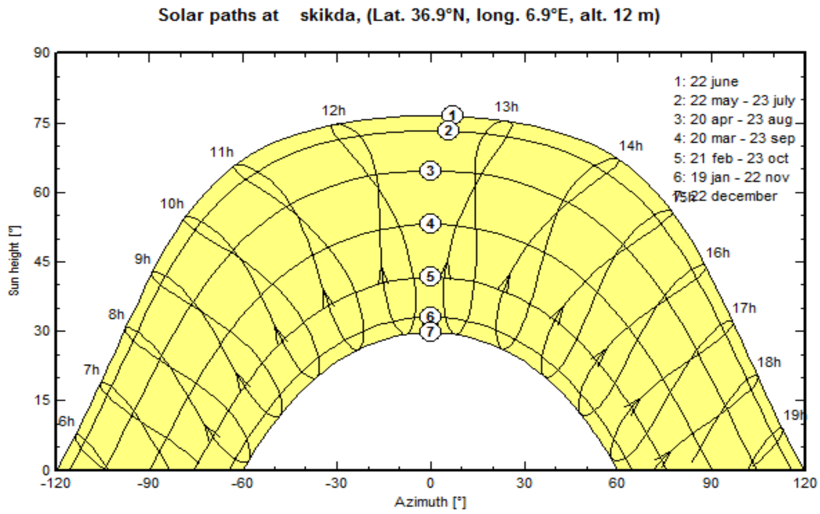

Figure 5. 6 Horizon line drawing of solar of Skikda

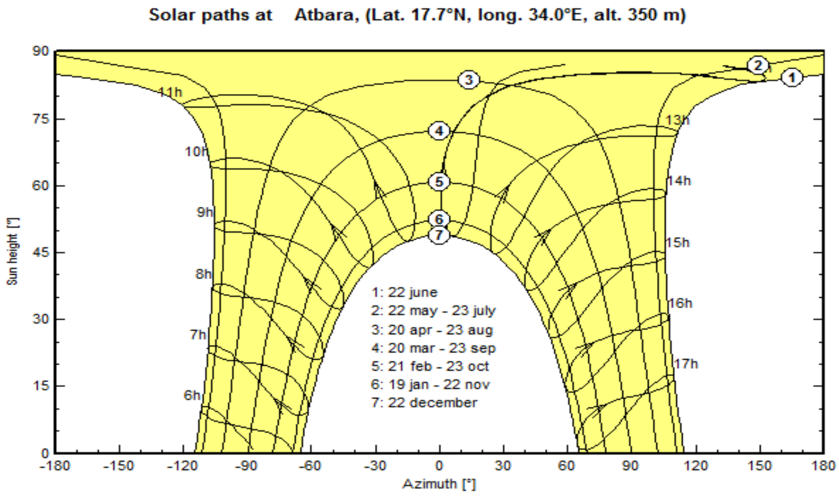

Figure 5. 7 Horizon line drawing of solar of Atbara.

5.3 PV module selection

There are several types of PV modules and inverters in PVsyst program, depending into power, technology and manufacturer. The system to be studied is consists of 20000 photovoltaic solar modules. Manufacturer is Viessmann_Vitavolt300_Typ_RC, polycrystalline silicon.

Nominal power 250W_p, P_{mpp}=249.50W_p.

V_{oc} =70.40V, V_{mpp} = 57.10V, I_{mpp} = 4.37A, I_{sc}= 4.78A.

Where:
P_{mpp}: Maximum power point.
V_{oc}: Open circuit voltage.
V_{mpp}: Maximum power point voltage.
I_{mpp} : Maximum power point current.
I_{sc} : Short circuit current of PV module.

Figure 5.8 shows the PV system definition, It contains the specifications of both solar panels and PV inverters.

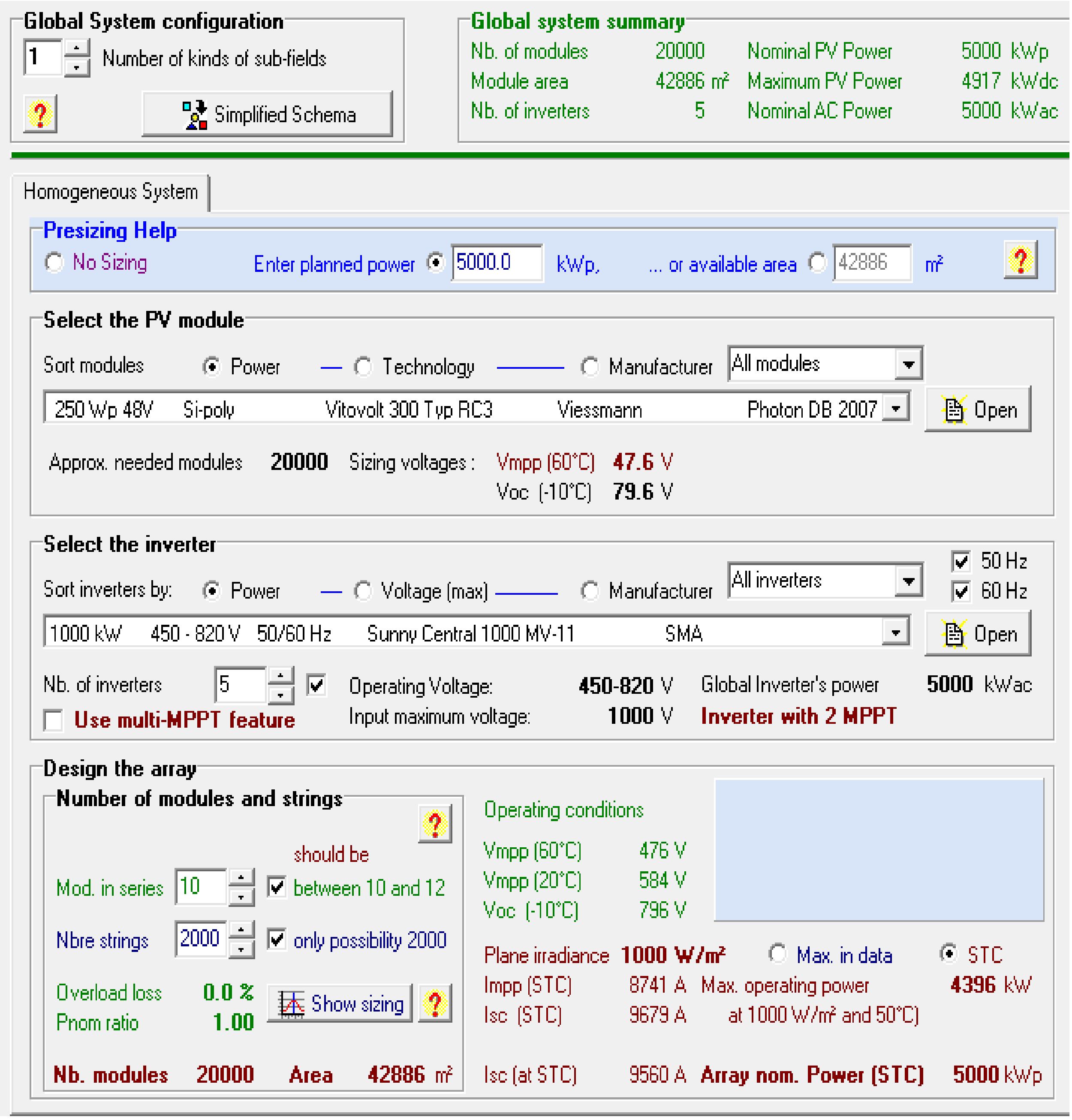

Figure 5. 8 PV system definition

It is very important to identify the characteristics curves of solar panels, to know the effect of temperature and radiation on its performance because they are the most important effects. Figure 9 shows the characteristics of the selected photovoltaic module.

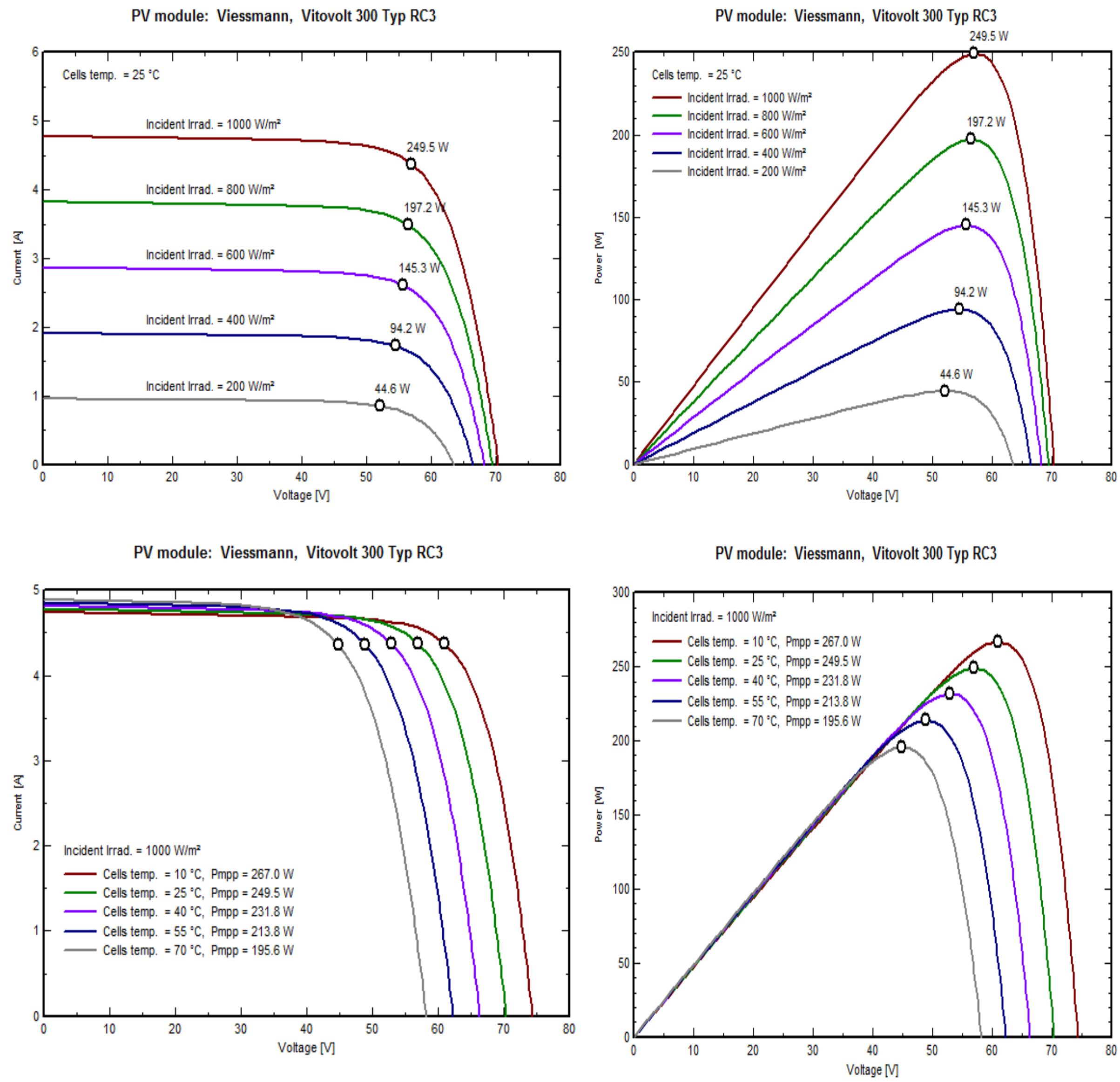

Figure 5. 9 Technical characteristics of the photovoltaic module

5.4 Inverters selection

The grid connecting photovoltaic systems is accomplished through an inverter, which converts DC energy produced from photovoltaic units to AC energy. Inverter is one of the main components along with PV string in grid connected PV system. The main components of solar plants are modules and inverters. If any of them fails, the result will affect the energy produced. The simulation model was developed in the PVsyst program, the system consists of 5 inverters, whose characteristics are shown in figure 5.10.

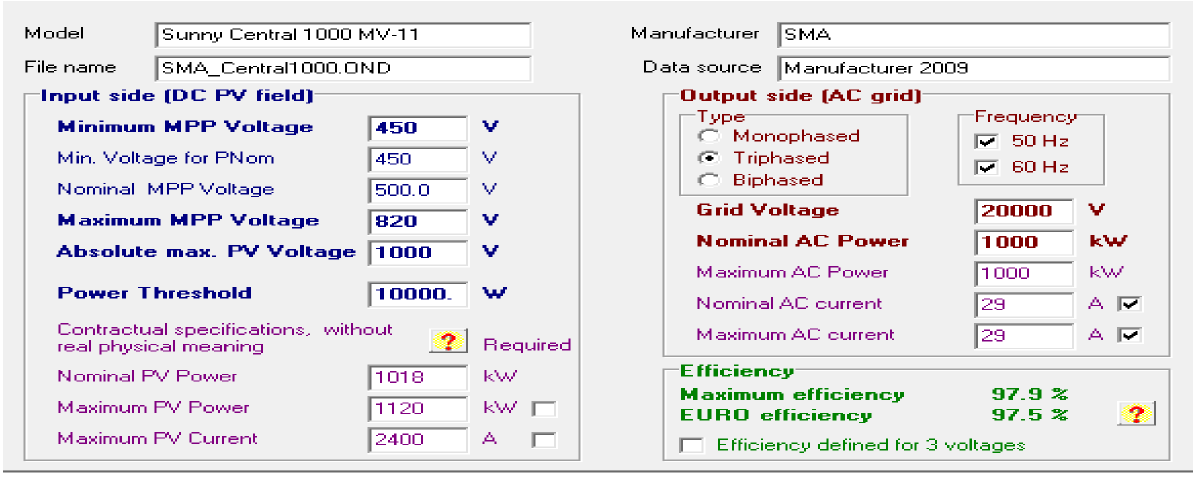

Figure 5. 10 Technical characteristics of the inverter used.

5.5 Simulation results

The designer of PV system by using PVsyst program enables to design the system configuration in addition to predicting generation of energy based on the meteorological data of site installation.

5.5.1 Tilt angle results

The inclination angle or tilt angle can be adjusted by PVsyst program to obtain highest irradiance on the PV module. Figure 5.11 to figure 5.18 shows the best tilt angle, for the four methods applied to control PV array (fixed tilt, seasonal tilt, tracking horizontal, tracking vertical) are obtained from PVsyst if the system was placed in Skikda or Atbara.

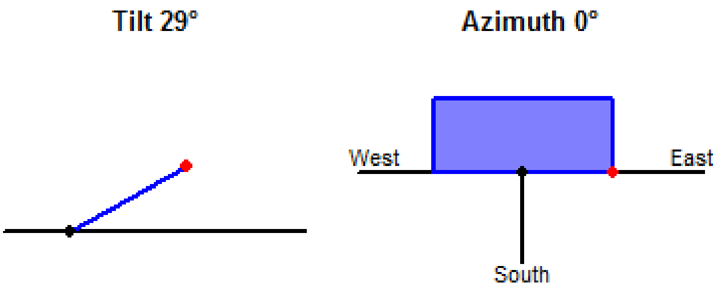

Figure 5. 11 Fixed tilt on Skikda

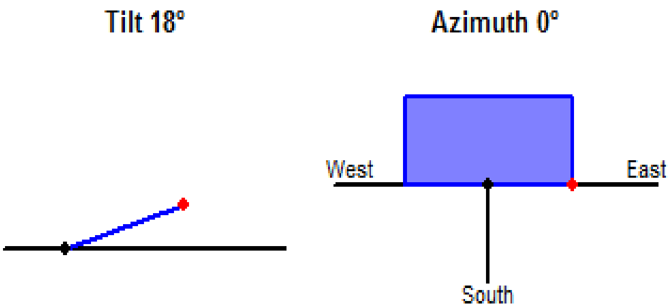

Figure 5. 12 Fixed tilt on Atbara

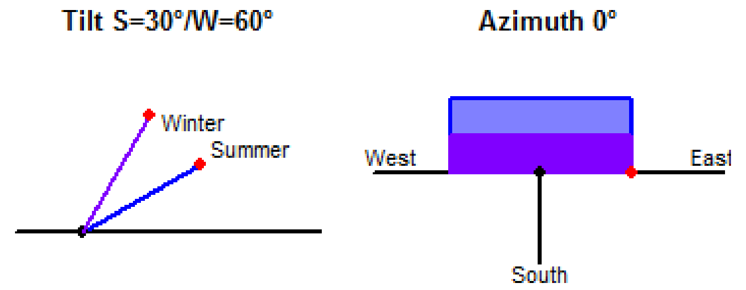

Figure 5. 13 Seasonal tilt adjustment on Skikda

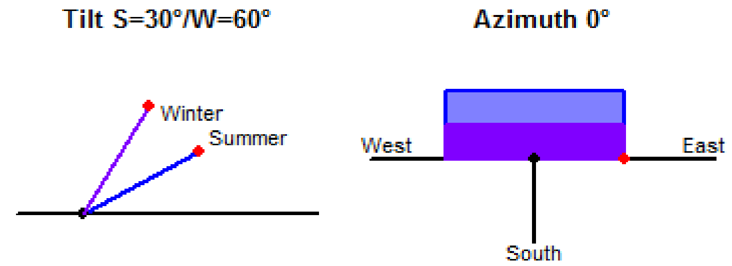

Figure 5. 14 Seasonal tilt adjustment on Atbara

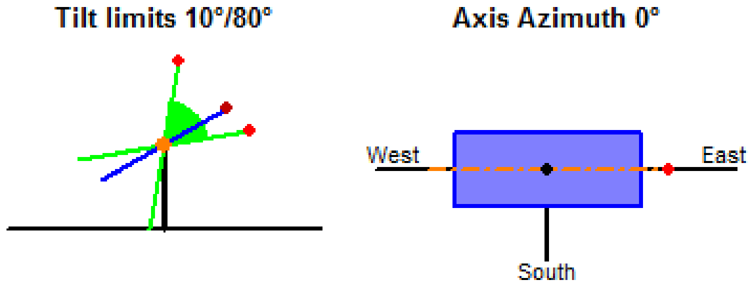

Figure 5. 15 Tracking horizontal axis e-w on *Skikda*

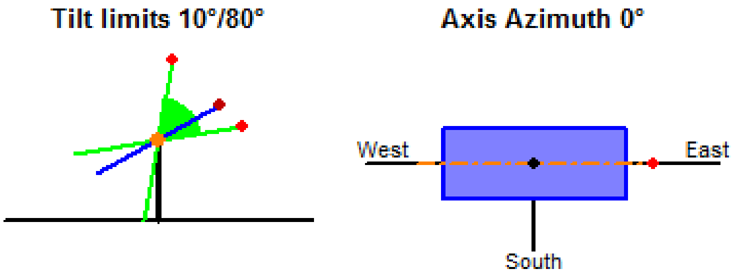

Figure 5. 16 Tracking horizontal axis e-w onAtbara

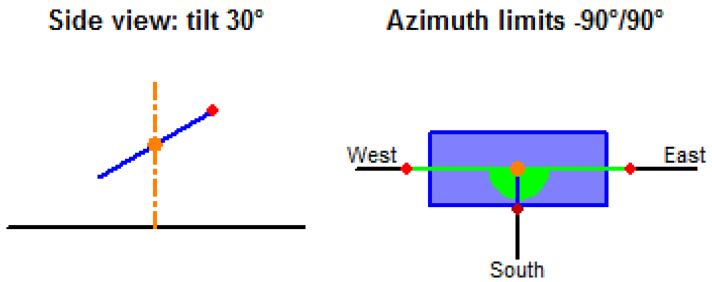

Figure 5. 17 Tracking vertical axis on Skikda

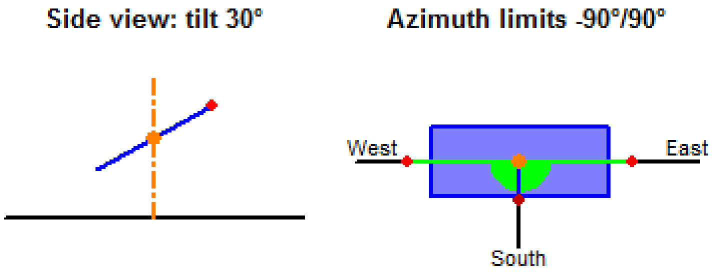

Figure 5. 18 Tracking vertical axis on Atbara

5.5.2 The yearly results

The results of simulation show the effective energy at the output of array, available energy at inverter output, energy injected into grid, global incident in cool-plane and average ambient temperature yearly per month of the selected system if it was placed in Skikda or Atbara.

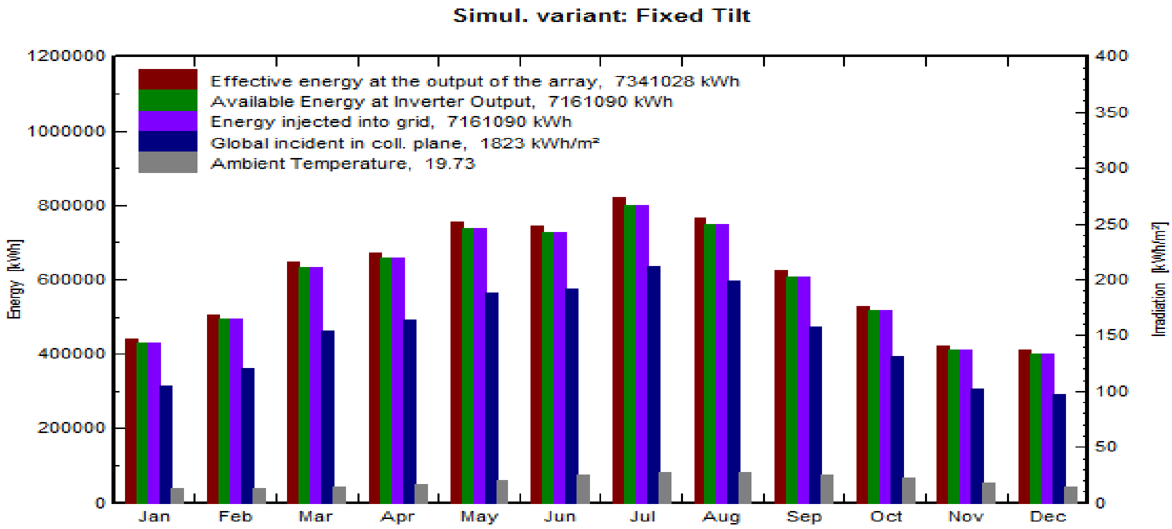

Figure 5. 19 Results of simulation fixed tilt on Skikda

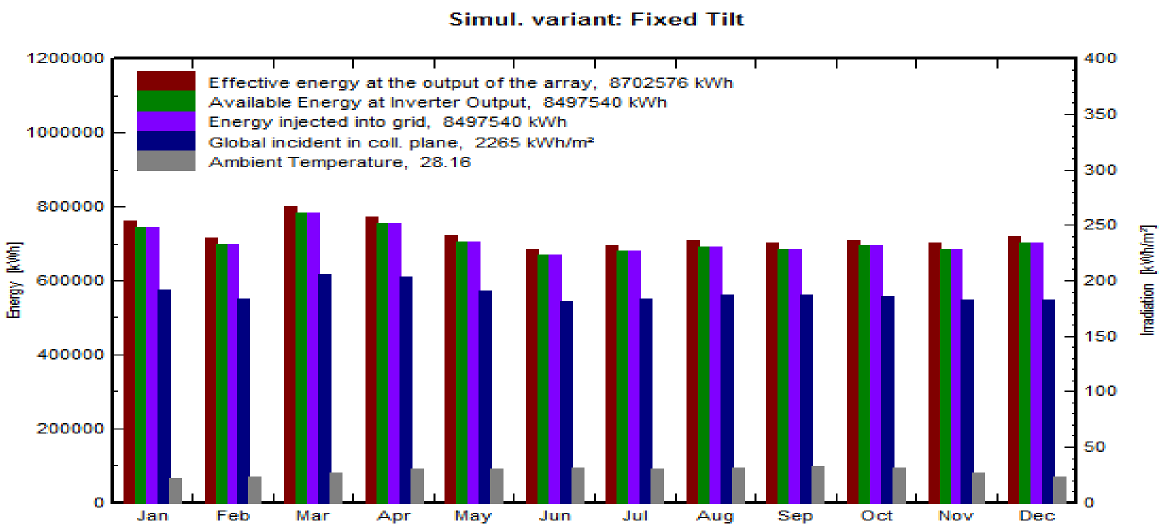

Figure 5. 20 Results of simulation fixed tilt on Atbara

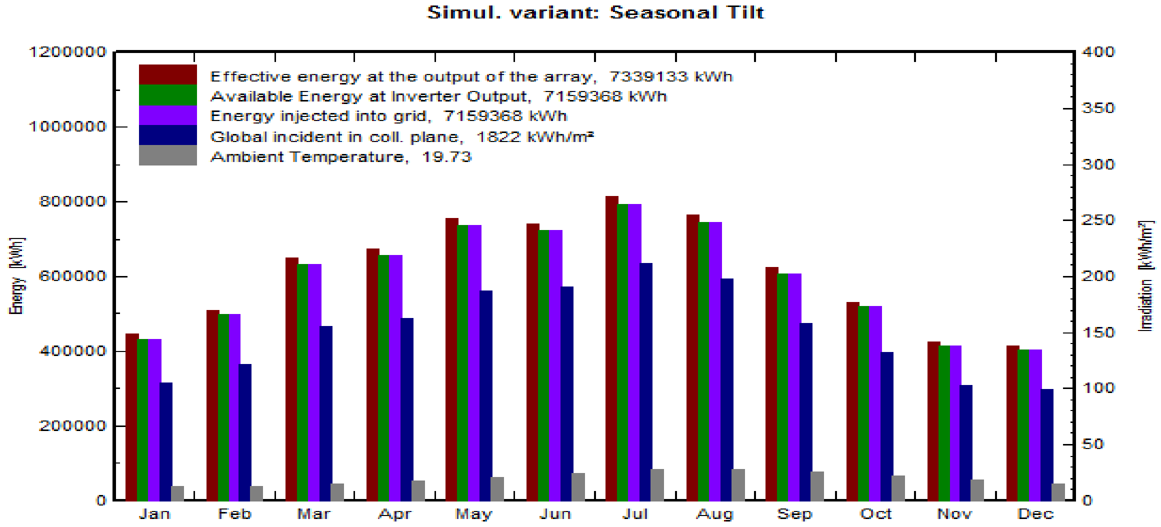

Figure 5. 21 Results of simulation seasonal tilt on Skikda

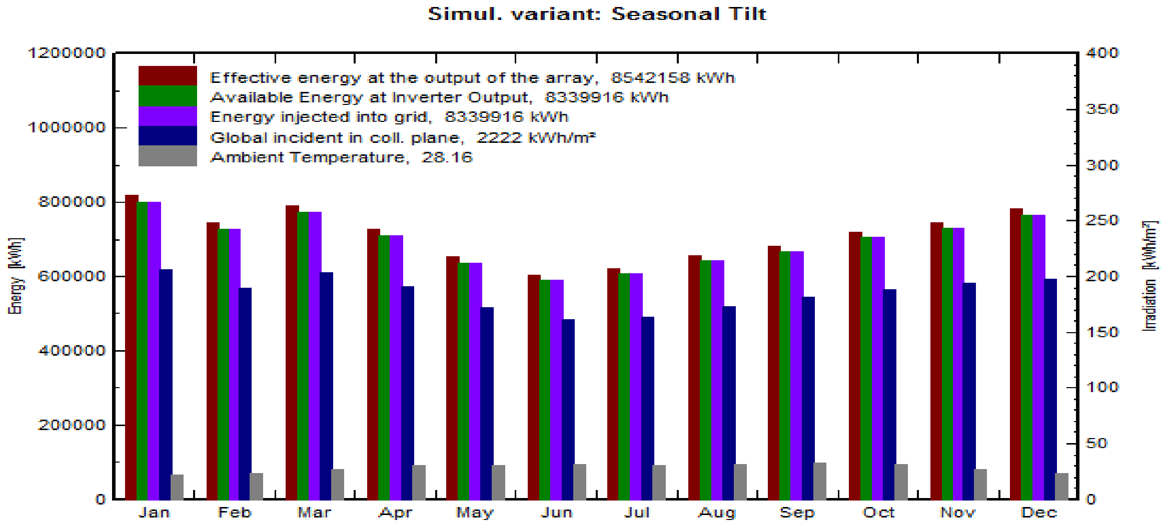

Figure 5. 22 Results of simulation seasonal tilt on Atbara

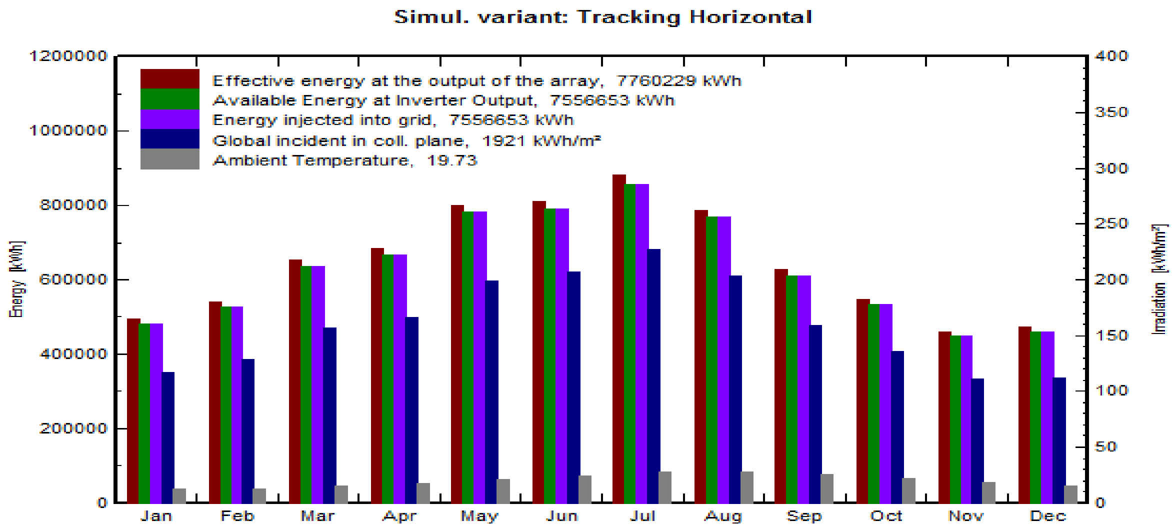

Figure 5. 23 Results of simulation tracking horizontal on Skikda

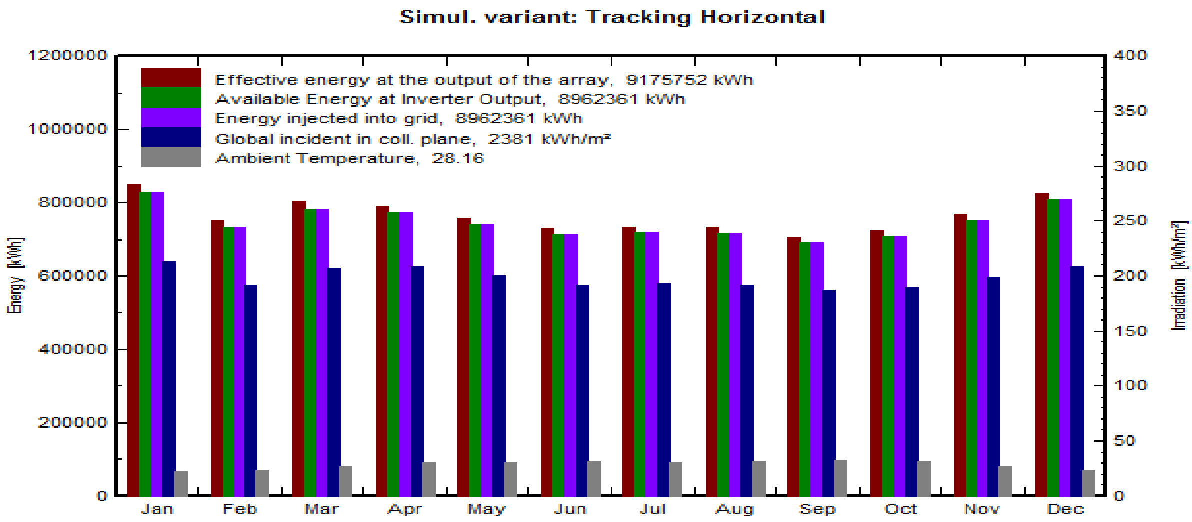

Figure 5. 24 Results of simulation tracking horizontal on Atbara

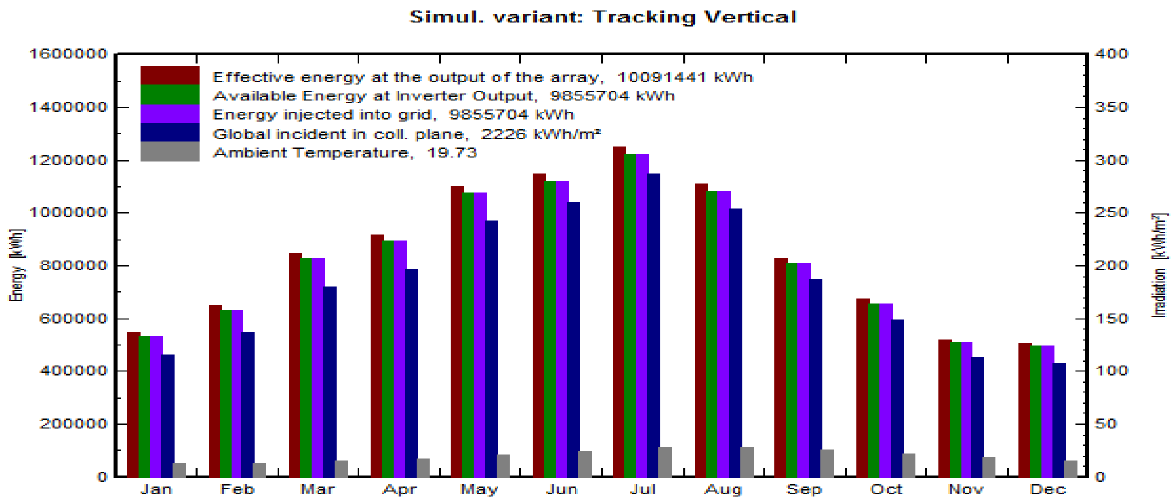

Figure 5. 25 Results of simulation. Tracking vertical on Skikda

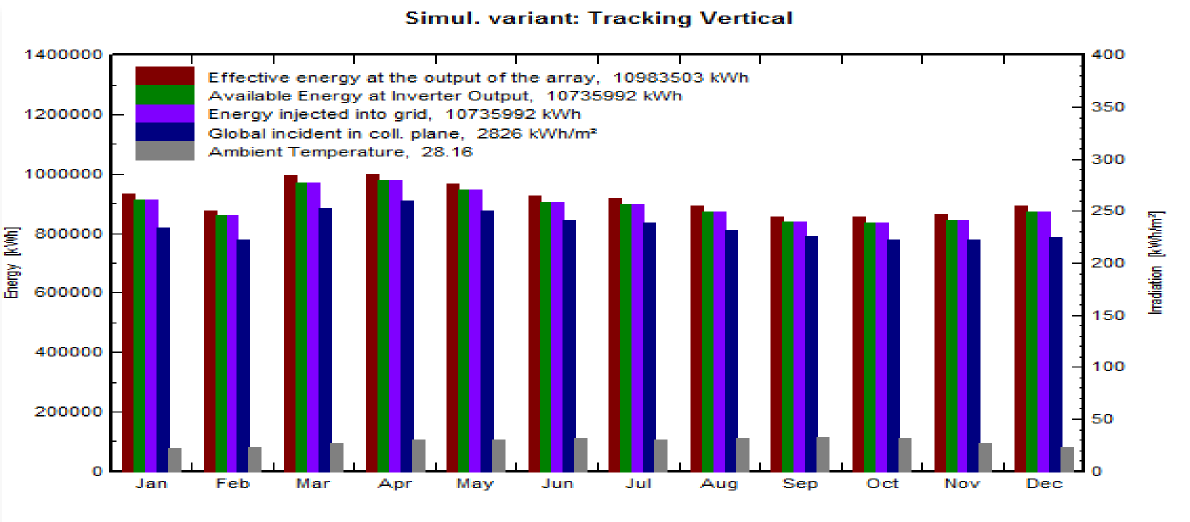

Figure 5. 26 Results of simulation. Tracking vertical on Atbara

5.6 Comparison the simulation results

The performance of PV system simulated by PVsyst program in Skikda and Atbara is different according to the geographical location. The results of output array above showed that Atbara is better than Skikda and can be explained as follows:

- The average temperature per year of Skikda is lower than average temperature per year of Atbara, this decreases about 29.94% from the average temperature per year found in Skikda.
- The global incident in coll (annual solar radiation falling on PV module) in Atbara is greater than Skikda, this increase about 24.24%, 21.95%, 23.94% and 26.95% of annual solar radiation falling on PV module in Skikda for fixed tilt, seasonal tilt, tracking horizontal and tracking vertical respectively.
- The effective energy at the output of the array in Atbara is greater than Skikda, this increase about 18.55%, 16.39%, 18.24%, and 8.80% of effective energy at the output of the array in Skikda for fixed tilt, seasonal tilt, tracking horizontal and tracking vertical respectively.
- The energy injected into grid in Atbara is greater than Skikda, this increase about 18.66%, 16.49%, 18.60%, and 8.93% of the energy injected into grid in Skikda for fixed tilt, seasonal tilt, tracking horizontal and tracking vertical respectively.

5.7 Conclusion

In this chapter, we studied the impacts of geographical locations on the performance of the photovoltaic system if it is installed in Skikda on Algeria and Atbara on Sudan. Although the average annual temperature in Atbara is about 42.73% higher than the average annual temperature in Skikda. It is known that the increase in temperature negatively affects the performance of the photovoltaic system.. But the simulation by using PVsyst program, shows the total electrical annual energy production from PV system (5 MW) in Atbara higher than in Skikda. The annual solar radiation, which is falling on the PV module in Atbara is greater than Skikda, So that annual energy at Atbara largest.

Therefore, it is important to use simulation of PV model to identify the PV system performance in order to predict the annual energy generation before connecting to grid according to meteorological conditions.

Chapter 6
Study and analyzing the impacts on energy quality to integrate decentralized Photovoltaic to grid. Sudan case study

6.1 Introduction

In most Sudanese cities, instability in electricity supply is a growing problem, and this problem can be solved by using renewable energies, especially solar photovoltaic energy because Sudan receives abundant amounts of solar radiation throughout the year. Any two different cities do not receive the same sunlight at the same time, and this affects the production of the PV system, because the production of energy for solar panels directly related to the amount of radiation received in the project site. Therefore, it is very necessary to use a photovoltaic simulation tool to determine all the components and know the energy produced according to the geographical location.

This chapter including two cases studies, the first case study presented the productive energy from PV (5MW) to connect with the grid in ten different areas (Portsudan, Alobied, Omdurman, Atbara, Dongola, Madani, Elginina, Alnhood, Kadogli, Nyala) in Sudan, these areas were proposed by the Sudanese Hydro Generation and Renewable Company, General Administration of Renewable Energies ,Solar Power Management. In order to know the productivity of the panel's if they are placed in these areas.

The system was planned by using fixed tilt method to control the PV array in PVsyst program by using (Latitude, Longitude, Altitude, Time Zone) of all the ten areas. This study was focused on global incident in coll and available energy at inverter output. The simulation results explain the best position of PV (5MW) between the ten areas Portsudan city. The PV system which has been selected in this area produces an annual energy of 8566750 KWh by global incident in coll 2283 KWh/m^2, it is the highest annual energy generated by the photovoltaic system. Cities were arranged according to their highest productivity.

The second case study, analyzing the impacts on energy quality to integrate (20MW) decentralized Photovoltaic in Portsudan to grid.

6.2 A comparison study of PV (5MW) based on PVsyst program for evaluation productive energy to connect with the grid. Sudan case study.

There are different types of power generation in Sudan, such as hydro, steam and gas Turbines, diesel and combined cycle. Sudan is a promising country which has a huge potential and natural resources. The sun is a major source of energy on the surface of the earth .Sudan is characterized by a good geographical location for the use of solar energy. Sudan has large open areas of land without the use of the PV option connected to the grid[86].The application of new and renewable energy sources now available in Sudan is a key issue in strategic future energy planning as an alternative to conventional fossil energy to provide a portion demand of local energy[87].

I hope in the near future Sudan will be able to replace all power generation that cause pollution in the environment to renewable energy such as solar energy and wind to reduce greenhouse gases emission. There are many simulations used to study the performance of PV system. In this study, the PV system was simulated by using PVsyst program to analyze operation of the system, a according to geographical location data of the system .The total annually energy productivity generated from the PV system in all 10 areas in Sudan was compared .So as to choose the best place in terms of high annual energy production to connect it with the network. And arrange the stations according to the highest productivity.

6.2.1 System definition.

Photovoltaic system simulation means studying, sizing and analyzing data for complete PV systems. The photovoltaic power production depends on meteorological conditions, the type of photovoltaic units, the photovoltaic inverter and the direction of photovoltaic units. Information about available area or planned power is useful to choose PV module and inverter technology. The system that is designed using the PVsyst program is shown in figure 6.1. It consists of a PV array feeding inverter that feeds the power into the grid. The grid connected systems must be identified by geographical location of site, selecting optimization tilt plane by the program, to reduce the loss of irradiation received by PV array and increase the output power.

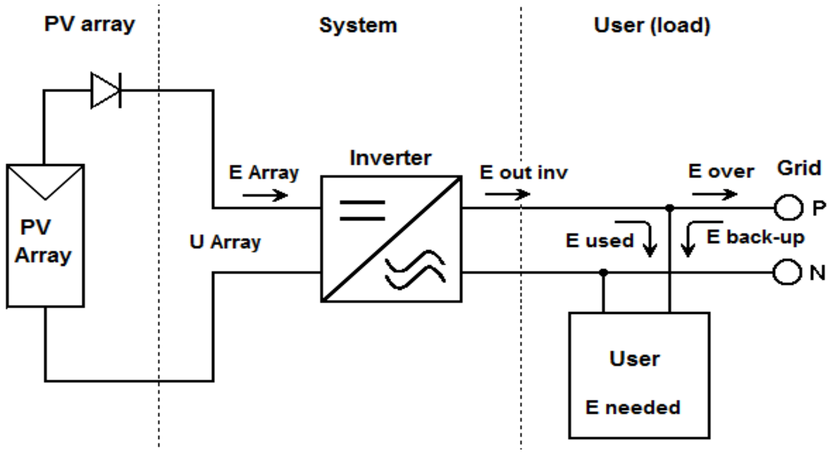

Figure 6. 1 PV system connected to the grid

6.2.2 Geographical location of cities

This work is based on real meteorological data and geographical location (latitude, longitude, altitude and time zone). This data is provided by the «Underground Weather» available website on the Internet to provide meteorological data and geographical location to everywhere in the world [85]. Table 6.1 show the geographical location of (Portsudan, Alobied, Omdurman, Atbara, Dongola, Madani, Elginina, Alnhood, Kadogli, Nyala) in Sudan.

Table 6. 1 Geographical location of cities

Area	latitude	longitude	altitude
Portsudan	19.36°N	37.13° E	13m
Alobied	13.17°N	30.23° E	573.94m
Omdurman	15.62°N	32.53° E	385.87m
Atbara	17.70°N	33.98° E	350m
Dongola	19.17°N	30.48° E	225.86m
Madani	14.40°N	33.50° E	411.78m
Elginina	13.45°N	22.43° E	800m
Alnhood	12.68°N	28.41° E	571m
Kadogli	11.10°N	29.43° E	499m
Nyala	12.05°N	24.88° E	673m

6.3 PV module and Inverter selection

The PVsyst program contains many types of PV modules and Inverters according to power, technology and manufacturer. The system which is going to be study, contain 20000 photovoltaic solar modules, 10 PV modules in series and 2000 strings in parallel. The main components that work together with PV the inverter in PV system connected to grid [25]. If any of them fail, the result affects of the energy produced [26]. The developing system consists of 5 inverters. Table 6.2 shows general parameters for PV system simulation.

Table 6. 2.General parameters for PV system simulation

Parameters	Input/Values
System type	Grid connected
Field type	Fixed tilted plane
PV modules	Polycrystalline, Vitavolt300_Typ_RC_Viessmann.
nominal power	250 W_p
maximum power point (P_{mpp})	249.50 W_p
open circuit voltage (V_{oc})	70.40V
maximum power point voltage (V_{mpp})	57.10V
maximum power point current (I_{mpp})	4.37A
short circuit current of PV module (I_{sc})	4.78A
Inverter	Sunny central 1000MV-11
Inverter unit power	1000 kW

It is very important to identify the characteristics curves of solar module. To know the effect of temperature and radiation on their performance because they are the most important effects. Figure 6.2 to Figure 6.5 below show the characteristics of the photovoltaic module selected.

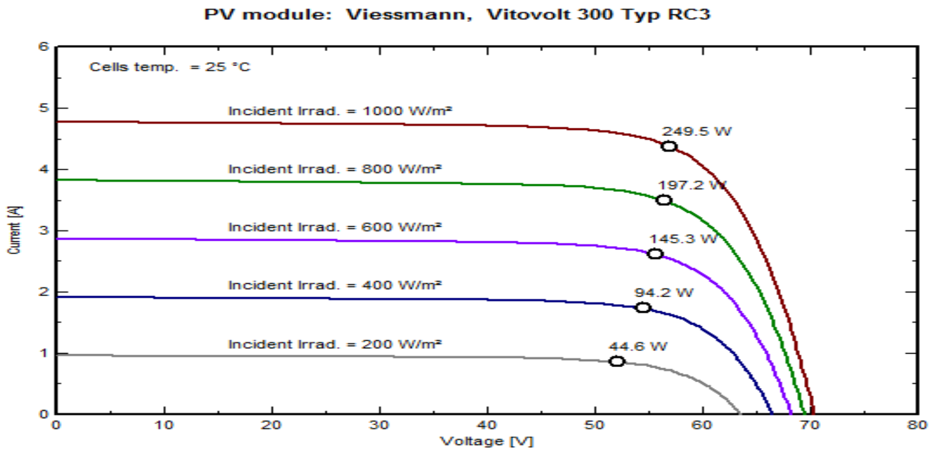

Figure 6. 2 I-V characteristics module at a constant temperature 25 ° C.

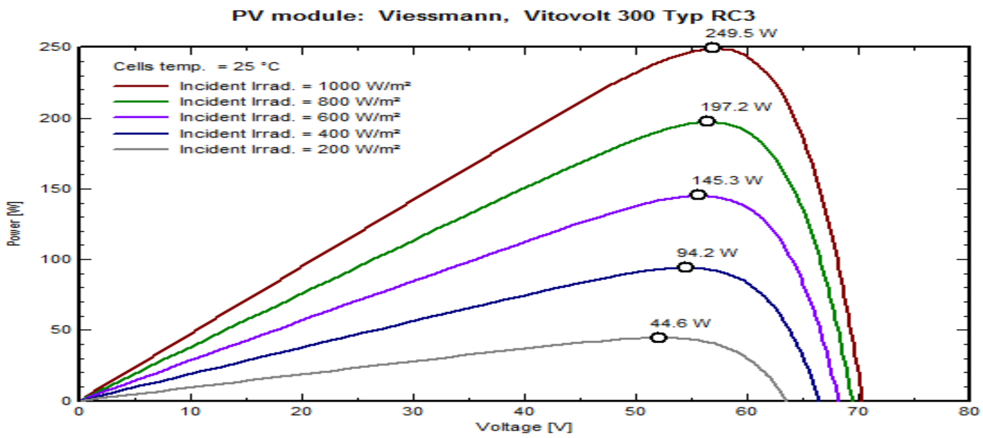

Figure 6. 3 P-V characteristics module at a constant temperature 25 ° C.

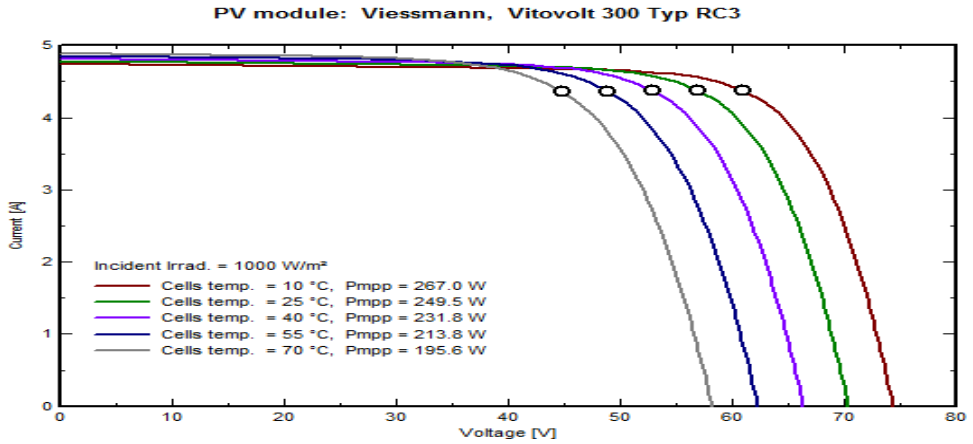

Figure 6. 4 I-V characteristics module at a constant radiation 1000 W/m^2

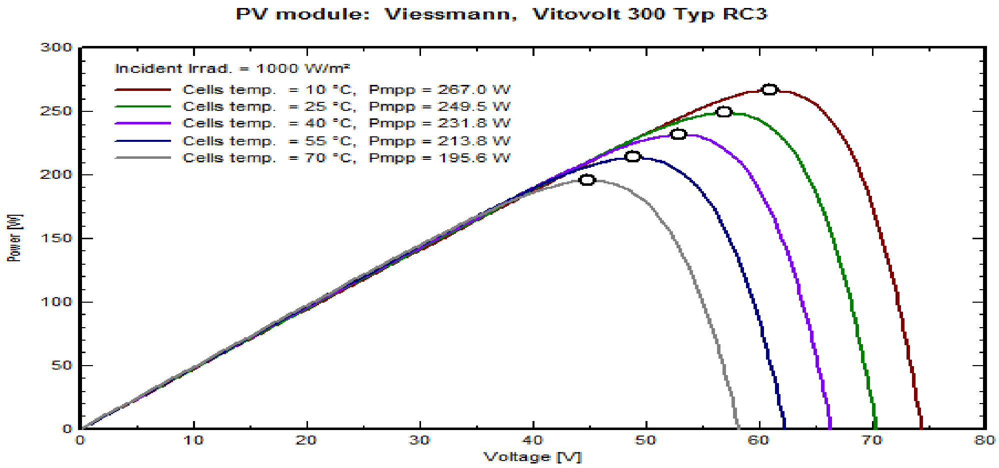

Figure 6. 5 P-V characteristics module at a constant radiation 1000 W/m^2

It is also necessary to know the technical characteristics of the inverter shown in Figure 6. 6.

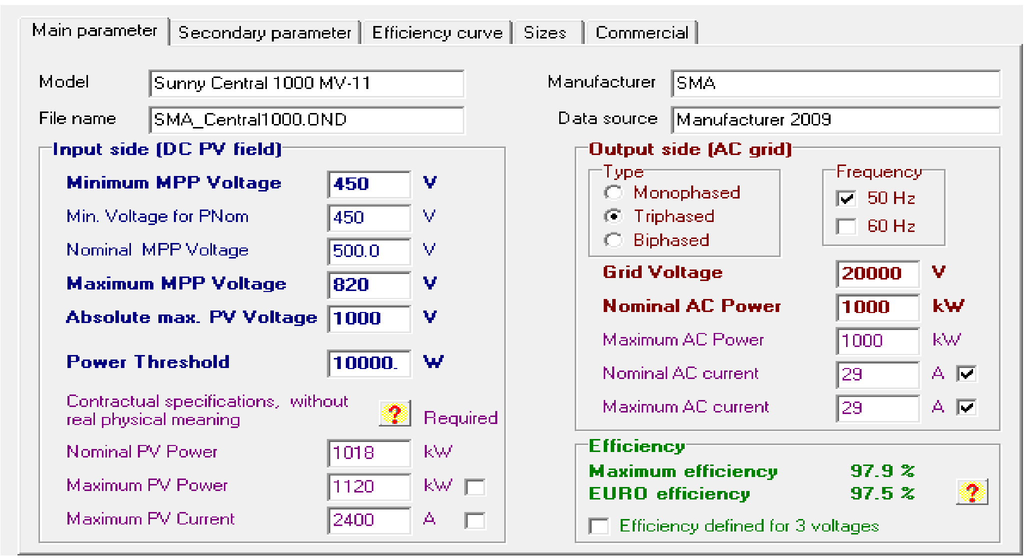

Figure 6. 6 Technical characteristics of inverter selected.

6.4 Results of simulation

The PVsyst program using by engineers and researchers, because PVsyst program provides levels of study of the PV system, which correspond to almost the different stages in development of the real project. The tilt angle or inclination angle is adjusted through the PVsyst program to obtain the highest irradiance on the PV module. There are several results that can be obtained using the program, but this work was focused on global incident (full irradiance received by the tilted plane per year) and expected power generation from PV system (available energy at inverter output per year) based on meteorological data for site installation. Figure 6.7 to Figure 6.16 shows the global incident and available energy at inverter output per year of Portsudan, Alobied, Omdurman, Atbara, Dongola, Madani, Elginina, Alnhood, Kadogli, and Nyala by using fixed tilted plane method for controlling the PV array.

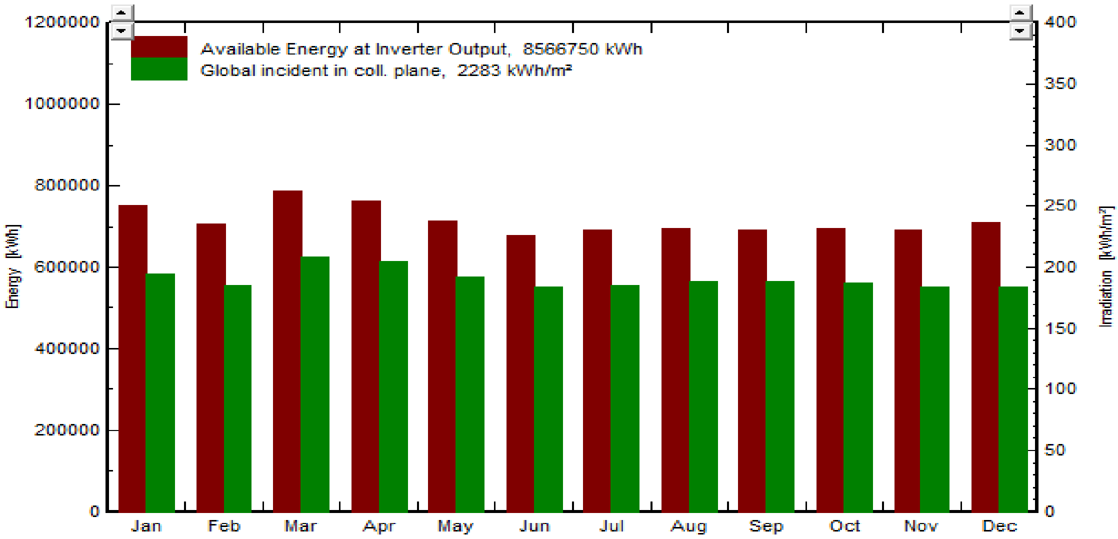

Figure 6. 7 Results of simulation on Portsudan

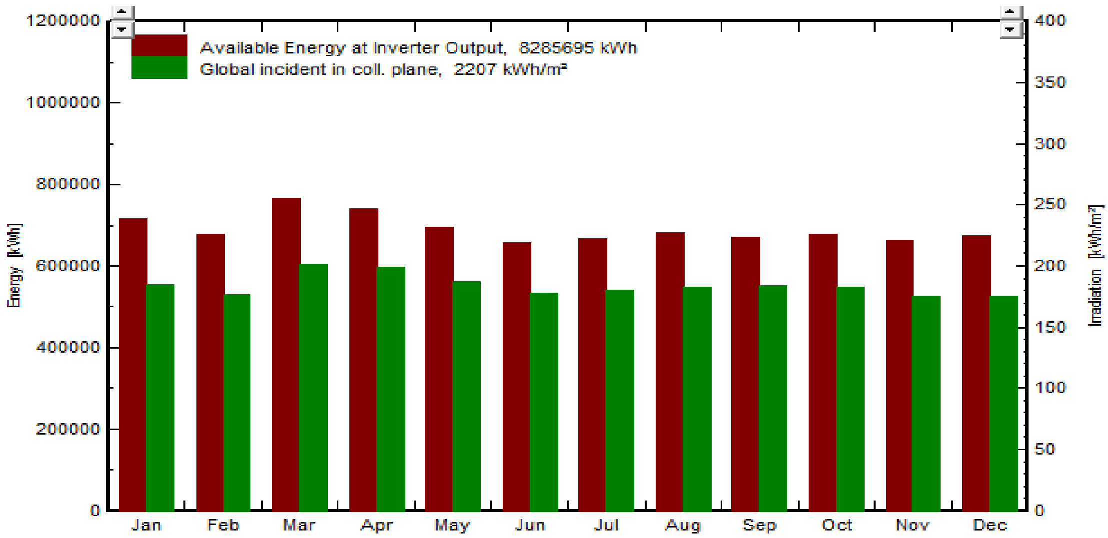

Figure 6. 8 Results of simulation on Alobied

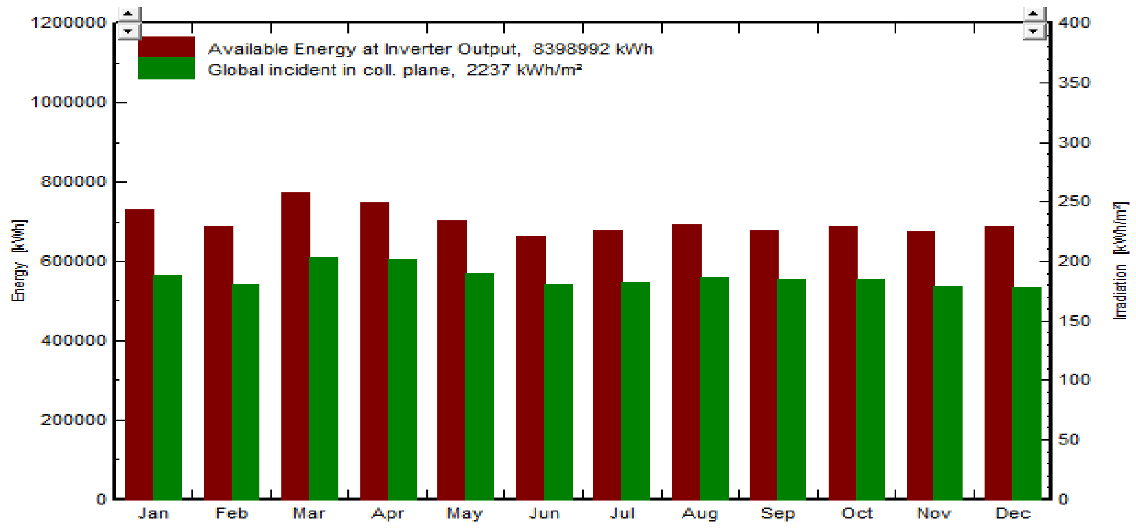

Figure 6. 9 Results of simulation on Omdurman

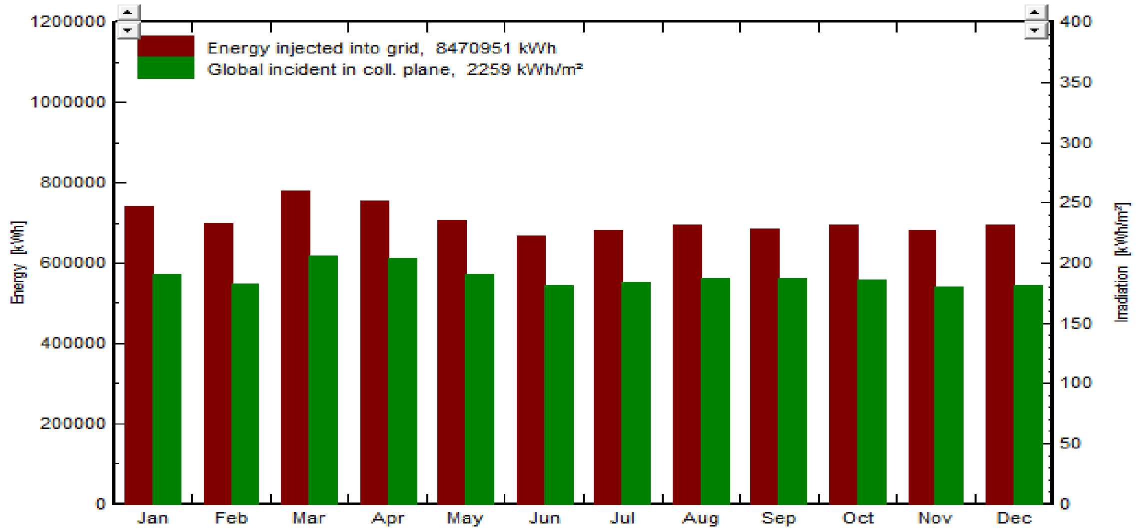

Figure 6. 10 Results of simulation on Atbara

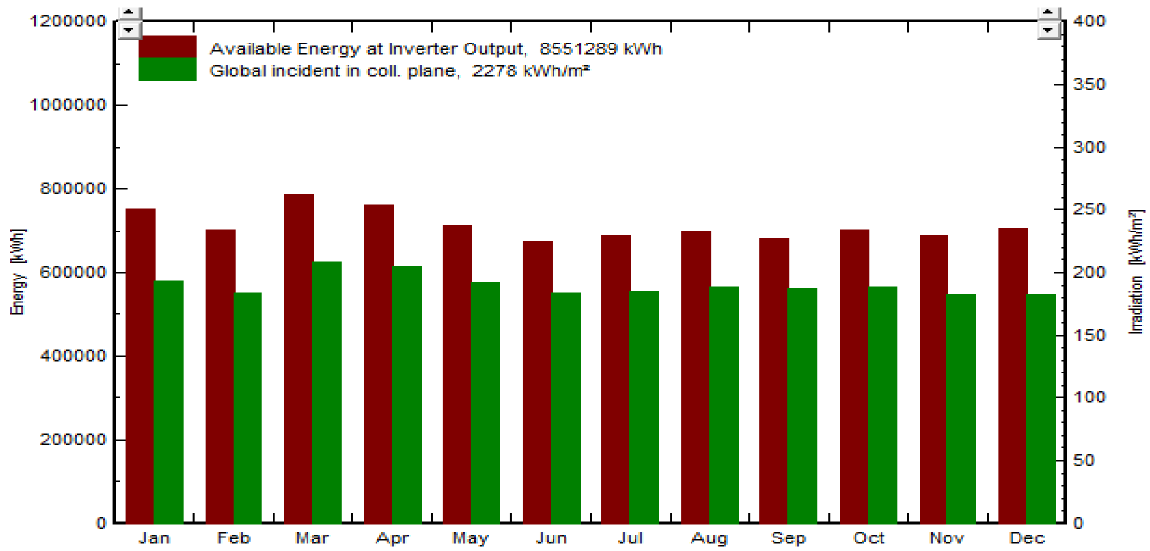

Figure 6. 11 Results of simulation on Dongola

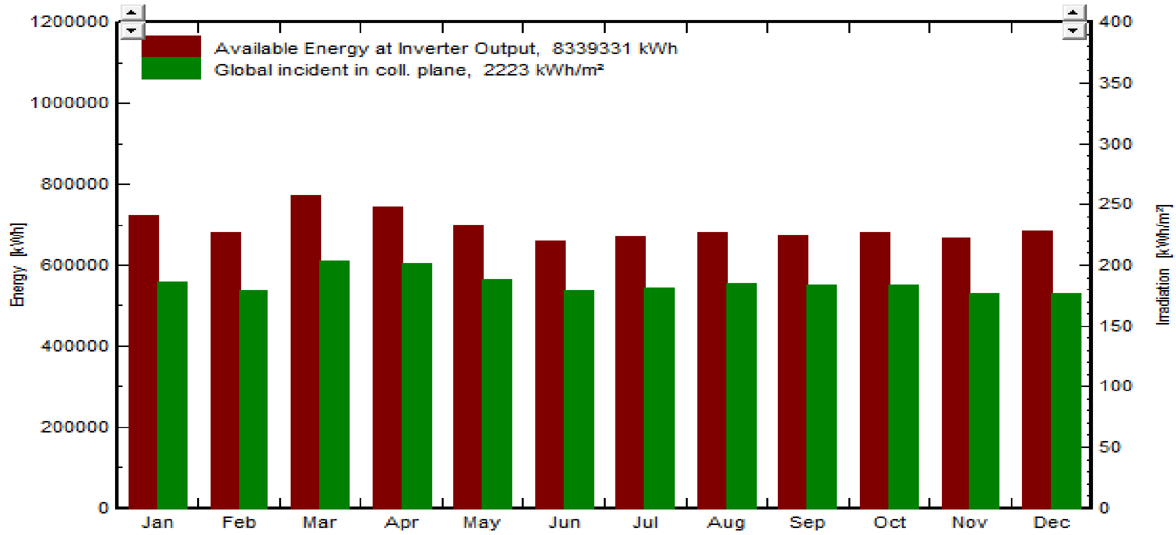

Figure 6. 12 Results of simulation on Madani

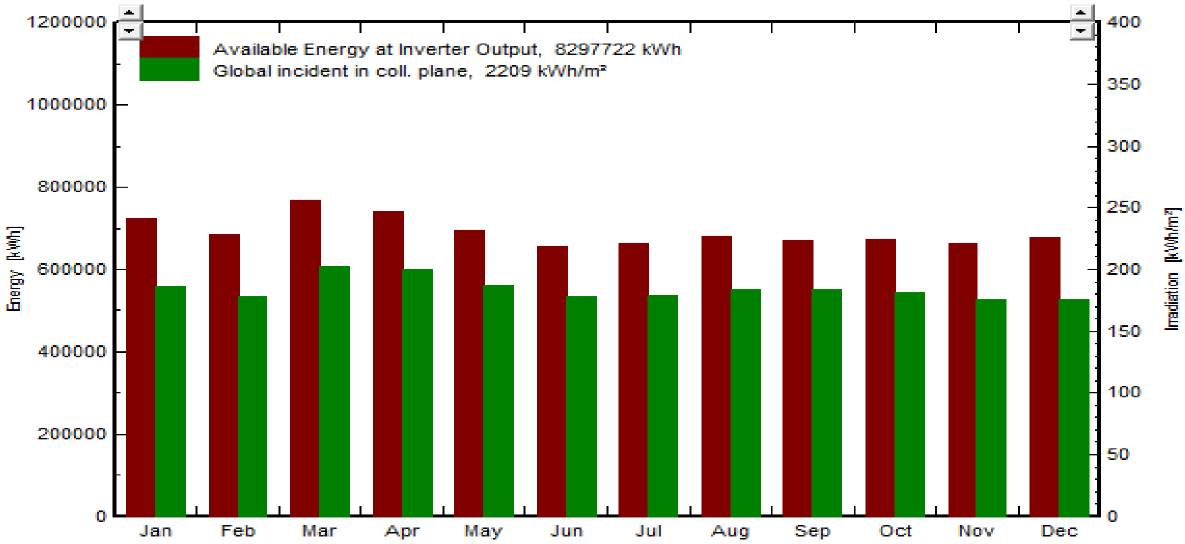

Figure 6. 13 Results of simulation on Elginina

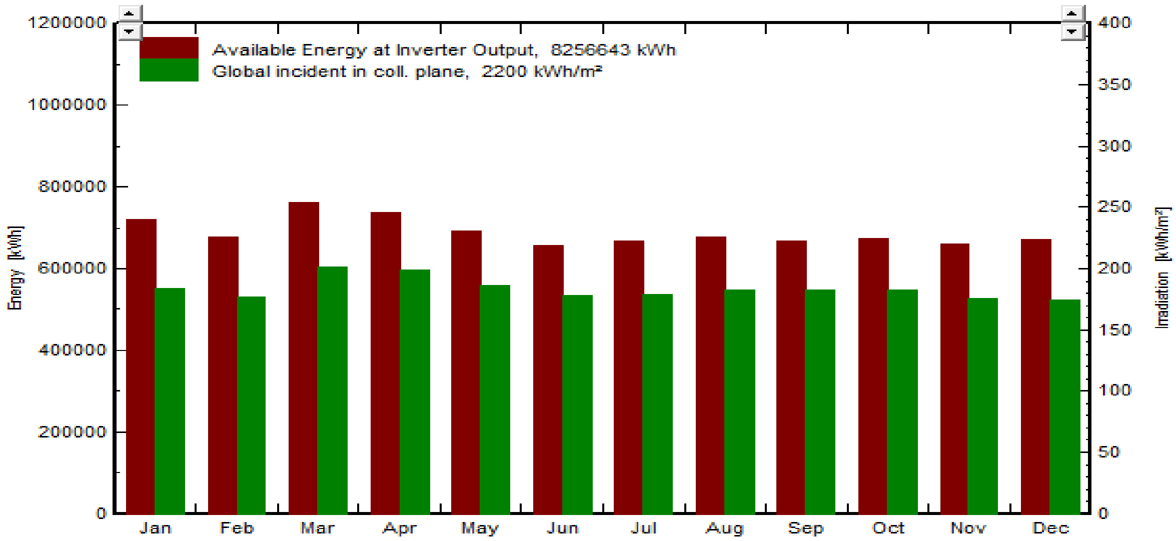

Figure 6. 14 Results of simulation on Alnhood

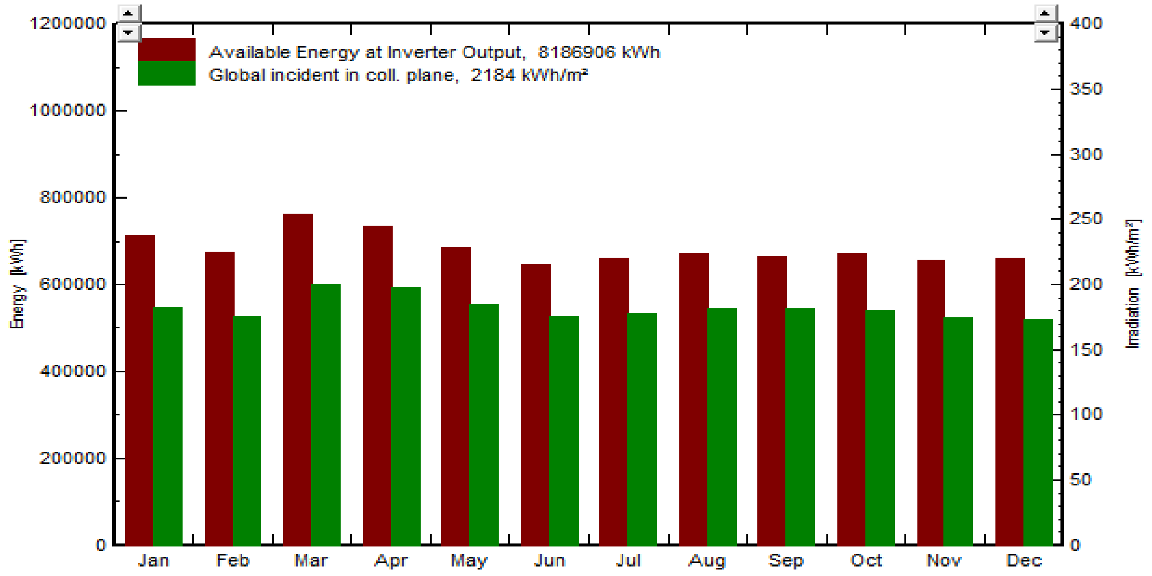

Figure 6. 15 Results of simulation on Kadogli

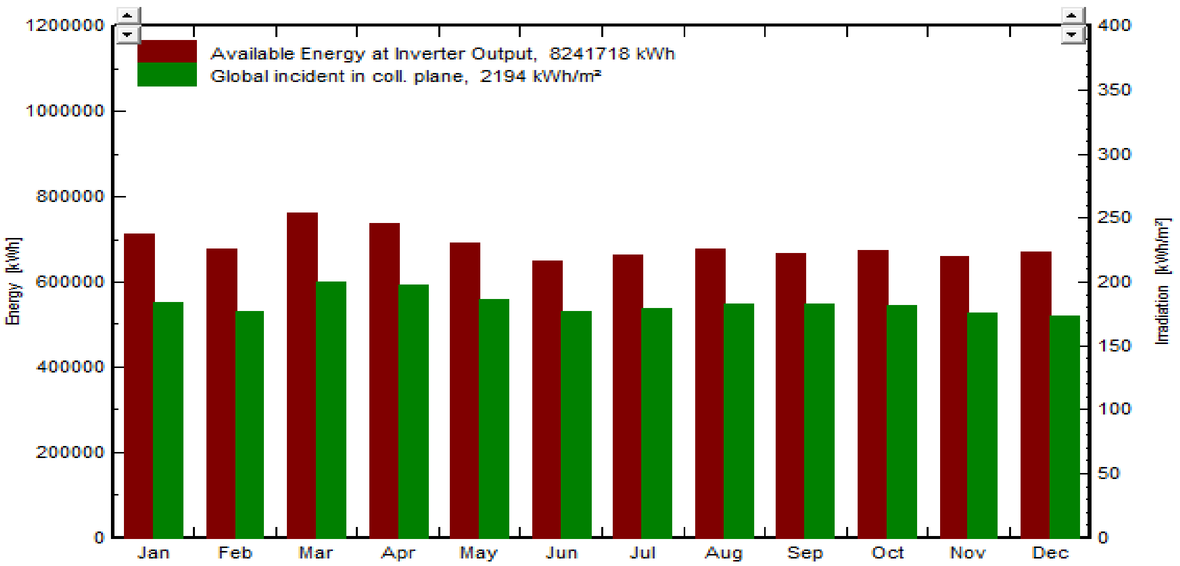

Figure 6. 16 Results of simulation on Nyala

6.5 Comparison results

The performance of the photovoltaic system simulated by the PVsyst program varies in the 10 different cites selected in Sudan by geographical location. The highest productivity from photovoltaic panels on ten cites was obtained in Portsudan 8566750 KWh. Table 3 below shows the area, annual generation of the area, percentage from total generation and arranging areas In terms of high generation.

Table 6. 3 Comparison results

Area	Annual generation of the area (KWh)	Percentage from total generation	Arranging areas In terms of high generation
Portsudan	8566750	10.24779931%	First
Alobied	8285695	9.911593016%	Seventh
Omdurman	8398992	10.04712223%	Fourth
Atbara	8470951	10.13320171%	Third
Dongola	8551289	10.2293044%	Second
Madani	8339331	9.975753983%	Fifth
Elginina	8297722	9.925980068%	Sixth
Alnhood	8256643	9.876840155%	Eighth
Kadogli	8186906	9.793418697%	Tenth
Nyala	8241718	9.85898643%	Ninth
Total generation	83595997		

The Figure 6.17 below shows the generation of the solar power station if it is installed in each of the ten regions in Sudan that have been selected.

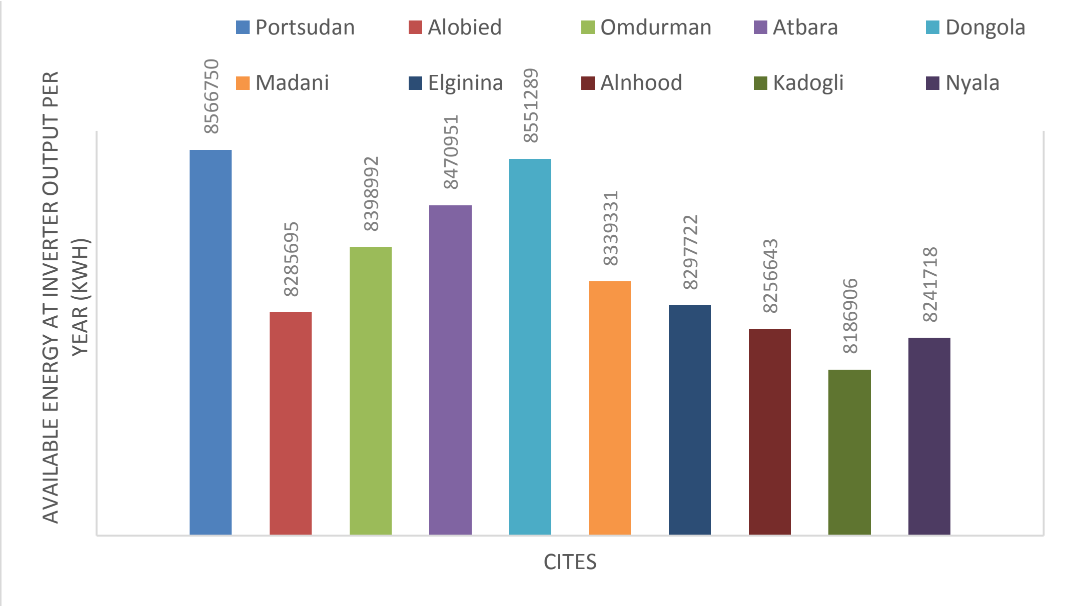

Figure 6. 17 The generation of PV system in ten cites

6.6 Analyzing the impacts on energy quality to integrate (20MW) decentralized Photovoltaic in Portsudan to grid.

Portsudan is a port city in eastern Sudan, and the capital of the Red Sea State. It has an area of 218,887 km² and a population of 1,895,104 people it is 499.5 km away from the Nile River State, Atbara in northern Sudan, and 842.0 km away from the capital of Sudan, Khartoum, in central Sudan. Port Sudan has an international airport, a petroleum refinery, and modern docking facilities that handle the bulk of the country's external trade and it is the only sea port with a coastline of 780 km. It is fed with electricity from the Atbara transformer station, which is fed from the city of Meroe by hydro-generation in northern Sudan and is 292 km away from the city of Atbara. The generation of Port Sudan city is covered by generators by a Turkish ship on the Red Sea coast.

6.6.1 PV system configuration

The tilt of PV panels can be adjusted by PVsyst program to obtain highest irradiance on the PV module. And in Portsudan adjusted at 19º, Azimuth of PV panels 180º then the total photovoltaic power output 94 MWh per day and global tilted irradiation 6.043 kWh/m2 per day. The total photovoltaic power output of average hourly profiles and monthly averages are shown in figure 6.18 and figure 6.19. The PV data selected to integrate the grid of mars 2021. Figure 6.20 below shows the single line diagram of Portsudan power station.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6				0	0	0	0	0	0	0	0	
6 - 7	0	1	2	3	3	3	2	2	2	2	2	1
7 - 8	4	4	6	7	6	6	5	5	6	7	5	4
8 - 9	7	7	10	10	10	9	8	8	9	10	9	7
9 - 10	10	10	13	13	12	11	10	10	12	12	10	9
10 - 11	11	13	15	15	14	13	12	12	14	14	12	10
11 - 12	12	14	16	15	14	13	12	12	14	14	12	11
12 - 13	12	14	15	15	13	13	12	12	13	14	12	10
13 - 14	11	13	14	13	12	11	10	11	12	12	10	9
14 - 15	9	10	11	10	9	9	8	8	9	9	8	7
15 - 16	6	7	7	7	6	6	5	5	6	5	4	4
16 - 17	1	3	3	3	3	3	3	2	2	1	1	1
17 - 18		0	0	0	0	0	0	0	0			
18 - 19												
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	82	95	110	111	102	95	88	88	98	99	84	73

Figure 6. 18 Average hourly profiles of total photovoltaic power output [MWh]

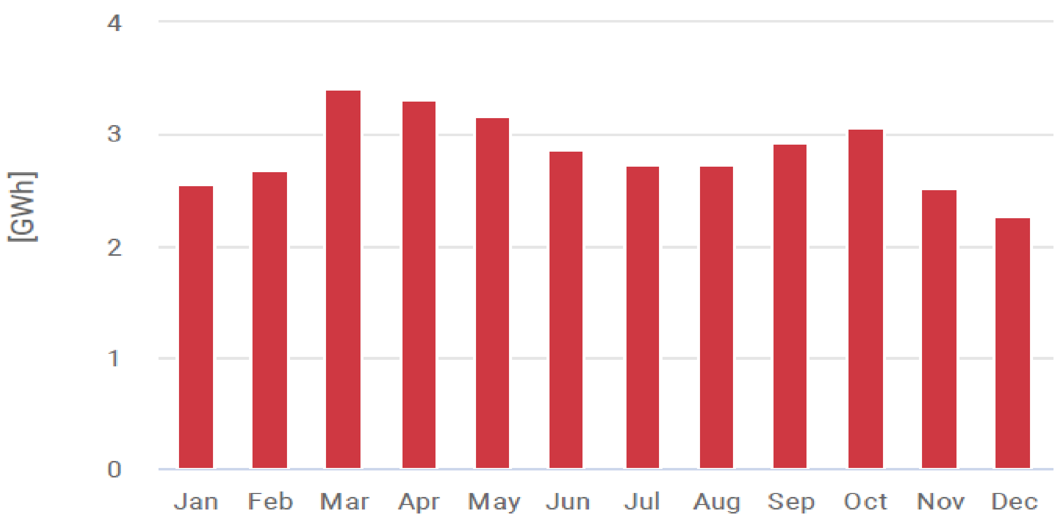

Figure 6. 19 Monthly averages total photovoltaic power output [GWh]

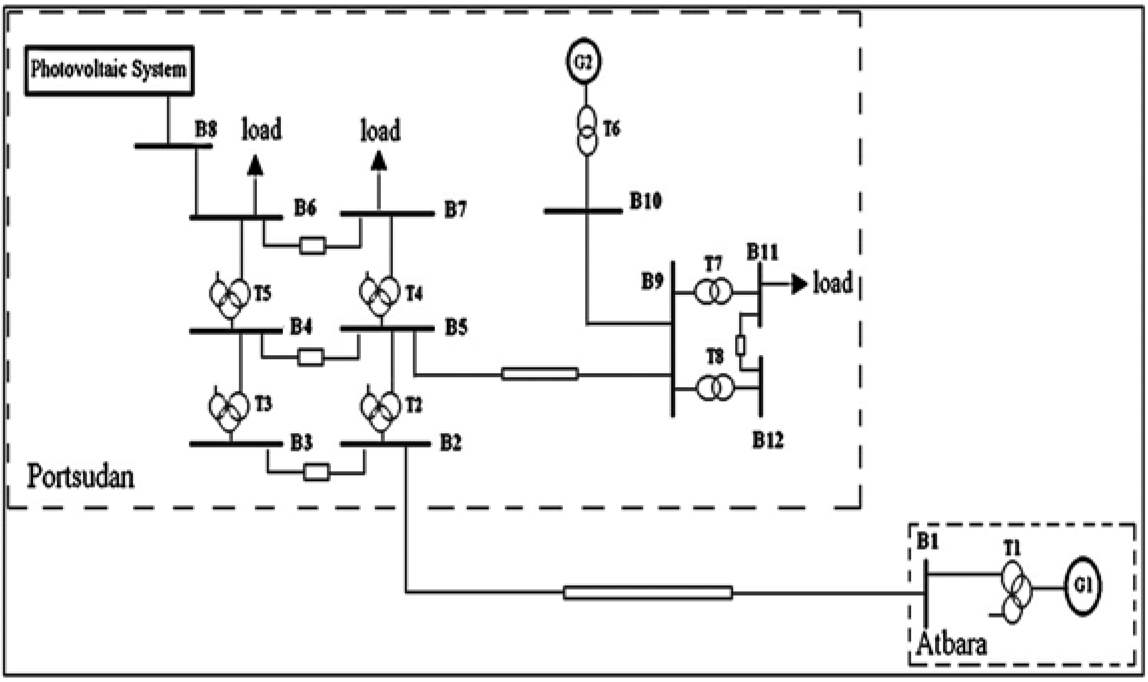

Figure 6. 20 Single line diagram of Portsudan power station

6.6.2 Data analysis using matlab program

The system contain 12 buses and 8 transformers, one transformer 300/300/75 MVA (T_1) in Atbara and six in Portsudan four 100/100/40 MVA (T_2, T_3, T_4, T_5) and three 30 MVA (T_6, T_7, T_8). All data of Portsudan station (R, X and Bc) convert to per unit and shows in linedata_org program.

6.6.2.1 SYS_Data program

```
%  Column 2: Bus type: 0 = PQ, 2 = PV, 1 = Swing
 busdata_org = [
%Bus Type Pd(MW) Qd(MVAR) Pg(MW) Qg(MVAR) Vset(pu) Bsh(pu)
   1    1    0.0     0.0     88.8    18.3    1.0    0.03;
   2    0    0.0     0.0     0.0     0.0     0.0    0.0;
   3    0    0.0     0.0     0.0     0.0     0.0    0.0;
   4    0    0.0     0.0     0.0     0.0     0.0    0.0;
   5    0    0.0     0.0     0.0     0.0     0.0    0.0;
   6    0    70.6    23.1    0.0     0.0     0.0    0.01;
   7    0    70.6    23.1    0.0     0.0     0.0    0.0;
   8    2    0.0     0.0     20.0    0.0     1.0    0.0;
   9    0    0.0     0.0     0.0     0.0     0.0    0.0;
  10    2    0.0     0.0     68.0    33.7    1.0    0.0;
  11    0    7.0     2.3     0.0     0.0     0.0    0.0;
  12    0    0.0     0.0     0.0     0.0     0.0    0.0;
];
Qmax=inf(length(busdata_org),1);
Qmin=-1*Qmax;
busdata(:,1:2)=busdata_org(:,1:2);
busdata(:,3)=busdata_org(:,7);
busdata(:,4)=0.0;
r=0;  %Increase in load
```

```
busdata(:,5)=(1+r)*busdata_org(:,3); % load Pd
busdata(:,6)=(1+r)*busdata_org(:,4); % Load Qd
busdata(:,7)=busdata_org(:,5);
busdata(:,8)=busdata_org(:,6);
busdata(:,9)=Qmin;
busdata(:,10)=Qmax;
busdata(:,11)=busdata_org(:,8);
%                               Line code
%        Bus bus   R      X     1/2 B   = 1 for lines
%        nl  nr  p.u.   p.u.   p.u.     > 1 or < 1 tr. tap at bus nl
% linedata=[1   2   0.0192   0.0575   0.02640    1
linedata_org = [
% From  To  R(pu)     X(pu)      Bc(pu)    Line Limit
     1       2    0.0705    0.3738     0.3534       90;
     2       3    0.0         0.0001     0.0             90;
     3       4    0.0106    0.159       0.0             90;
     2       5    0.0106    0.159       0.0             90;
     4       5    0.0         0.0001     0.0             90;
     4       6    0.0083    0.1245     0.0             90;
     5       7    0.0083    0.1245     0.0             90;
     6       7    0.0         0.0001     0.0             90;
     8        6   0.0         0.0001       0.0           20;
     5        9   0.0023    0.0095       0.0704      90;
    10        9   0.0         0.001         0.0           90;
    9        11  0.0083    0.1245       0.0           30;
    9        12  0.0083    0.1245       0.0           30;
   11        12  0.0         0.0001       0.0           30;
];
linedata(:,1:5)=linedata_org(:,1:5);
linedata(:,6)=1; % Tap setting
```

6.6.2.2 ybus program

This program obtains the bus Admittance Matrix for power flow solution

```
j=sqrt(-1); i = sqrt(-1);
nl = linedata(:,1); nr = linedata(:,2); R = linedata(:,3);
X = linedata(:,4); Bc = j*linedata(:,5); a = linedata(:, 6);
nbr=length(linedata(:,1)); nbus = max(max(nl), max(nr));
Z = R + j*X; y= ones(nbr,1)./Z;        %branch admittance
for n = 1:nbr
if a(n) <= 0
a(n) = 1; else end
Ybus=zeros(nbus,nbus);     % initialize Ybus to zero
% formation of the off diagonal elements
for k=1:nbr;
Ybus(nl(k),nr(k))=Ybus(nl(k),nr(k))-y(k)/a(k);
Ybus(nr(k),nl(k))=Ybus(nl(k),nr(k));
end
end
% formation of the diagonal elements
for  n=1:nbus
```

```
for k=1:nbr
if nl(k)==n
Ybus(n,n) = Ybus(n,n)+y(k)/(a(k)^2) + Bc(k);
elseif nr(k)==n
Ybus(n,n) = Ybus(n,n)+y(k) +Bc(k);
else, end
end
end
clear Pgg
```

6.6.2.3 busout program

This program prints the power flow solution in a tabulated form on the screen.

```
disp(tech)
fprintf('                    Maximum Power Mismatch = %g \n', maxerror)
fprintf('                           No. of Iterations = %g \n\n', iter)
head =['    Bus  Voltage  Angle    ------Load------    ---Generation---   Injected'
       '    No.  Mag.     Degree     MW       Mvar       MW       Mvar       Mvar '
       '                                                                          '];
disp(head)
for n=1:nbus
fprintf(' %5g', n), fprintf(' %7.3f', Vm(n)),
fprintf(' %8.3f', deltad(n)), fprintf(' %9.3f', Pd(n)),
fprintf(' %9.3f', Qd(n)),  fprintf(' %9.3f', Pg(n)),
fprintf(' %9.3f ', Qg(n)), fprintf(' %8.3f\n', Qsh(n))
end
fprintf('      \n'), fprintf('    Total              ')
fprintf(' %9.3f', Pdt), fprintf(' %9.3f', Qdt),
fprintf(' %9.3f', Pgt), fprintf(' %9.3f', Qgt), fprintf(' %9.3f\n\n', Qsht)
```

6.6.2.4 Newton Raphson program

Power flow solution by Newton-Raphson method

```
ns=0; ng=0; Vm=0; delta=0; yload=0; deltad=0;
nbus = length(busdata(:,1));
kb=[];Vm=[]; delta=[]; Pd=[]; Qd=[]; Pg=[]; Qg=[]; Qmin=[]; Qmax=[];  % Added (6-8-00)
Pk=[]; P=[]; Qk=[]; Q=[]; S=[]; V=[]; % Added (6-8-00)
for k=1:nbus
n=busdata(k,1);
kb(n)=busdata(k,2); Vm(n)=busdata(k,3); delta(n)=busdata(k, 4);
Pd(n)=busdata(k,5); Qd(n)=busdata(k,6); Pg(n)=busdata(k,7); Qg(n) = busdata(k,8);
Qmin(n)=busdata(k, 9); Qmax(n)=busdata(k, 10);
Qsh(n)=busdata(k, 11);
if Vm(n) <= 0
Vm(n) = 1.0; V(n) = 1 + j*0;
else delta(n) = pi/180*delta(n);
V(n) = Vm(n)*(cos(delta(n)) + j*sin(delta(n)));
end
P(n)=(Pg(n)-Pd(n))/basemva;
Q(n)=(Qg(n)-Qd(n)+ Qsh(n))/basemva;
S(n) = P(n) + j*Q(n);
end
for k=1:nbus
```

```
if kb(k) == 1, ns = ns+1; else, end
if kb(k) == 2
ng = ng+1; else, end
ngs(k) = ng;
nss(k) = ns;
end
Ym=abs(Ybus); t = angle(Ybus);
m=2*nbus-ng-2*ns;
maxerror = 1; converge=1;
iter = 0;
%%%% added for parallel lines (Aug. 99)
mline=ones(nbr,1);
for k=1:nbr
for m=k+1:nbr
if((nl(k)==nl(m)) && (nr(k)==nr(m)));
mline(m)=2;
elseif ((nl(k)==nr(m)) && (nr(k)==nl(m)));
mline(m)=2;
else, end
end
end
% Start of iterations
clear A  DC   J  DX
while maxerror >= accuracy && iter <= maxiter % Test for max. power mismatch
for ii=1:m
for k=1:m
A(ii,k)=0;      %Initializing Jacobian matrix
end, end
iter = iter+1;
for n=1:nbus
nn=n-nss(n);
lm=nbus+n-ngs(n)-nss(n)-ns;
J11=0; J22=0; J33=0; J44=0;
for ii=1:nbr
if mline(ii)==1   % Added to include parallel lines (Aug. 99)
if nl(ii) == n || nr(ii) == n
if nl(ii) == n ,  l = nr(ii); end
if nr(ii) == n , l = nl(ii); end
J11=J11+ Vm(n)*Vm(l)*Ym(n,l)*sin(t(n,l)- delta(n) + delta(l));
J33=J33+ Vm(n)*Vm(l)*Ym(n,l)*cos(t(n,l)- delta(n) + delta(l));
if kb(n)~=1
J22=J22+ Vm(l)*Ym(n,l)*cos(t(n,l)- delta(n) + delta(l));
J44=J44+ Vm(l)*Ym(n,l)*sin(t(n,l)- delta(n) + delta(l));
else, end
if kb(n) ~= 1  && kb(l) ~=1
lk = nbus+l-ngs(l)-nss(l)-ns;
ll = l -nss(l);
% off diagonalelements of J1
A(nn, ll) =-Vm(n)*Vm(l)*Ym(n,l)*sin(t(n,l)- delta(n) + delta(l));
if kb(l) == 0  % off diagonal elements of J2
A(nn, lk) =Vm(n)*Ym(n,l)*cos(t(n,l)- delta(n) + delta(l));end
```

```
if kb(n) == 0  % off diagonal elements of J3
A(lm, ll) =-Vm(n)*Vm(l)*Ym(n,l)*cos(t(n,l)- delta(n)+delta(l)); end
if kb(n) == 0 && kb(l) == 0  % off diagonal elements of  J4
A(lm, lk) =-Vm(n)*Ym(n,l)*sin(t(n,l)- delta(n) + delta(l));end
else end
else , end
else, end
end
Pk = Vm(n)^2*Ym(n,n)*cos(t(n,n))+J33;
Qk = -Vm(n)^2*Ym(n,n)*sin(t(n,n))-J11;
if kb(n) == 1
P(n)=Pk; Q(n) = Qk; end   % Swing bus P
if kb(n) == 2
Q(n)=Qk;
if Qmax(n) ~= 0
Qgc = Q(n)*basemva + Qd(n) - Qsh(n);
if iter <= 7                  % Between the 2th & 6th iterations
if iter > 2               % the Mvar of generator buses are
if Qgc  < Qmin(n),       % tested. If not within limits Vm(n)
Vm(n) = Vm(n) + 0.01;    % is changed in steps of 0.01 pu to
elseif Qgc  > Qmax(n),   % bring the generator Mvar within
Vm(n) = Vm(n) - 0.01;end % the specified limits.
else, end
else,end
else,end
end
if kb(n) ~= 1
A(nn,nn) = J11;  %diagonal elements of J1
DC(nn) = P(n)-Pk;
end
if kb(n) == 0
A(nn,lm) = 2*Vm(n)*Ym(n,n)*cos(t(n,n))+J22;  %diagonal elements of J2
A(lm,nn)= J33;        %diagonal elements of J3
A(lm,lm) =-2*Vm(n)*Ym(n,n)*sin(t(n,n))-J44;  %diagonal of elements of J4
DC(lm) = Q(n)-Qk;
end
end
DX=A\DC';
for n=1:nbus
nn=n-nss(n);
lm=nbus+n-ngs(n)-nss(n)-ns;
if kb(n) ~= 1
delta(n) = delta(n)+DX(nn); end
if kb(n) == 0
Vm(n)=Vm(n)+DX(lm); end
end
maxerror=max(abs(DC));
if iter == maxiter && maxerror > accuracy
fprintf('\nWARNING: Iterative solution did not converged after ')
fprintf('%g', iter), fprintf(' iterations.\n\n')
fprintf('Press Enter to terminate the iterations and print the results \n')
```

```
converge = 0; pause, else, end
end
if converge ~= 1
tech= ('                    ITERATIVE SOLUTION DID NOT CONVERGE'); else,
tech=('                Power Flow Solution by Newton-Raphson Method');
end
V = Vm.*cos(delta)+j*Vm.*sin(delta);
deltad=180/pi*delta;
i=sqrt(-1);
k=0;
for n = 1:nbus
if kb(n) == 1
k=k+1;
S(n)= P(n)+j*Q(n);
Pg(n) = P(n)*basemva + Pd(n);
Qg(n) = Q(n)*basemva + Qd(n) - Qsh(n);
Pgg(k)=Pg(n);
Qgg(k)=Qg(n);     %june 97
elseif  kb(n) ==2
k=k+1;
S(n)=P(n)+j*Q(n);
Qg(n) = Q(n)*basemva + Qd(n) - Qsh(n);
Pgg(k)=Pg(n);
Qgg(k)=Qg(n);  % June 1997
end
yload(n) = (Pd(n)- j*Qd(n)+j*Qsh(n))/(basemva*Vm(n)^2);
end
busdata(:,3)=Vm'; busdata(:,4)=deltad';
Pgt = sum(Pg);  Qgt = sum(Qg); Pdt = sum(Pd); Qdt = sum(Qd); Qsht = sum(Qsh);
```

6.6.2.5 Lineflow program

This program is used in conjunction with lf gauss or lf Newton for the computation of line flow and line losses.

```
SLT = 0;
fprintf('\n')
fprintf('                        Line Flow and Losses \n\n')
fprintf('     --Line--  Power at bus & line flow    --Line loss--  Transformer\n')
fprintf('     from  to    MW      Mvar     MVA       MW      Mvar      tap\n')
for n = 1:nbus
busprt = 0;
for L = 1:nbr;
if busprt == 0
fprintf('   \n'), fprintf('%6g', n), fprintf('      %9.3f', P(n)*basemva)
fprintf('%9.3f', Q(n)*basemva), fprintf('%9.3f\n', abs(S(n)*basemva))
busprt = 1;
else, end
if nl(L)==n      k = nr(L);
In = (V(n) - a(L)*V(k))*y(L)/a(L)^2 + Bc(L)/a(L)^2*V(n);
Ik = (V(k) - V(n)/a(L))*y(L) + Bc(L)*V(k);
Snk = V(n)*conj(In)*basemva;
Skn = V(k)*conj(Ik)*basemva;
```

```
SL  = Snk + Skn;
SLT = SLT + SL;
elseif nr(L)==n  k = nl(L);
In = (V(n) - V(k)/a(L))*y(L) + Bc(L)*V(n);
Ik = (V(k) - a(L)*V(n))*y(L)/a(L)^2 + Bc(L)/a(L)^2*V(k);
Snk = V(n)*conj(In)*basemva;
Skn = V(k)*conj(Ik)*basemva;
SL  = Snk + Skn;
SLT = SLT + SL;
else, end
if nl(L)==n | nr(L)==n
fprintf('%12g', k),
fprintf('%9.3f', real(Snk)), fprintf('%9.3f', imag(Snk))
fprintf('%9.3f', abs(Snk)),
fprintf('%9.3f', real(SL)),
if nl(L) ==n & a(L) ~= 1
fprintf('%9.3f', imag(SL)), fprintf('%9.3f\n', a(L))
else, fprintf('%9.3f\n', imag(SL))
end
else, end
end
end
SLT = SLT/2;
fprintf('   \n'), fprintf('    Total loss                        ')
fprintf('%9.3f', real(SLT)), fprintf('%9.3f\n', imag(SLT))
```

6.6.2.6 Analysis1 program

This program is used to integrate PV 20MW to grid and computation of line flow and line losses.

```
clear all; clc;
load Renewable_DataPV20MW; %% PV power Data
%%
point(1)=max(PV20MW);
point(2)=mean(PV20MW);
point(3)=min(PV20MW);
%%%%%%%%%%%%%%%%%%%
basemva = 100;
accuracy = 0.001;
accel = 1.8;
maxiter = 10000;
r=0.00; %% Load Shedding
busdata(8,7)=point(3);  %% inject renewable point
lfybus                        % form the bus admittance matrix
lfnewton             % Load flow solution by Newton-Raphson method
busout             % Prints the power flow solution on the screen
lineflow         % Computes and displays the line flow and losses
```

6.6.2.7 Analysis2 program

This program is used to plot real power in MW (Slack, PV20MW, Ship, Slack+PV20MW+Ship).

```
clear all;clc;
load Renewable_DataPV20MW; %% PV20MW power Data
%%%%%%%%%%%%%%%%
basemva = 100;
accuracy = 0.001;
accel = 1.8;
maxiter = 1000;
r=0.0; %% Increase in load
for RDL=1:length(WTP)
busdata(8,7)=WTP(RDL);%% inject renewable point
lfybus                    % form the bus admittance matrix
lfnewton          % Load flow solution by Newton-Raphson method
V(RDL,:)=Vm;
P_sys(RDL,:)=Pg;
Q_sys(RDL,:)=Qg;
end;
PG1=P_sys(:,1);
PG2=P_sys(:,8);
PG3=P_sys(:,10);
PGt=PG1+PG2+PG3;
PG=[PG1,PG2,PG3,PGt];
%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
plot(PG1,'b');
hold on
plot(PG2,'g');
hold on
plot(PG3,'y');
hold on
plot(PGt,'r');
xlim([1 24])
legend('Slack','PV20MW','Ship','Slack+PV20MW+Ship')
title('Generated Real Power')
xlabel('Sampling every 5 minutes during single day')
ylabel('Real power in MW)
```

6.7 Simulation results

The real power in MW (Slack, PV20MW, Ship, Slack+PV20MW+Ship) shows in figure 6.21

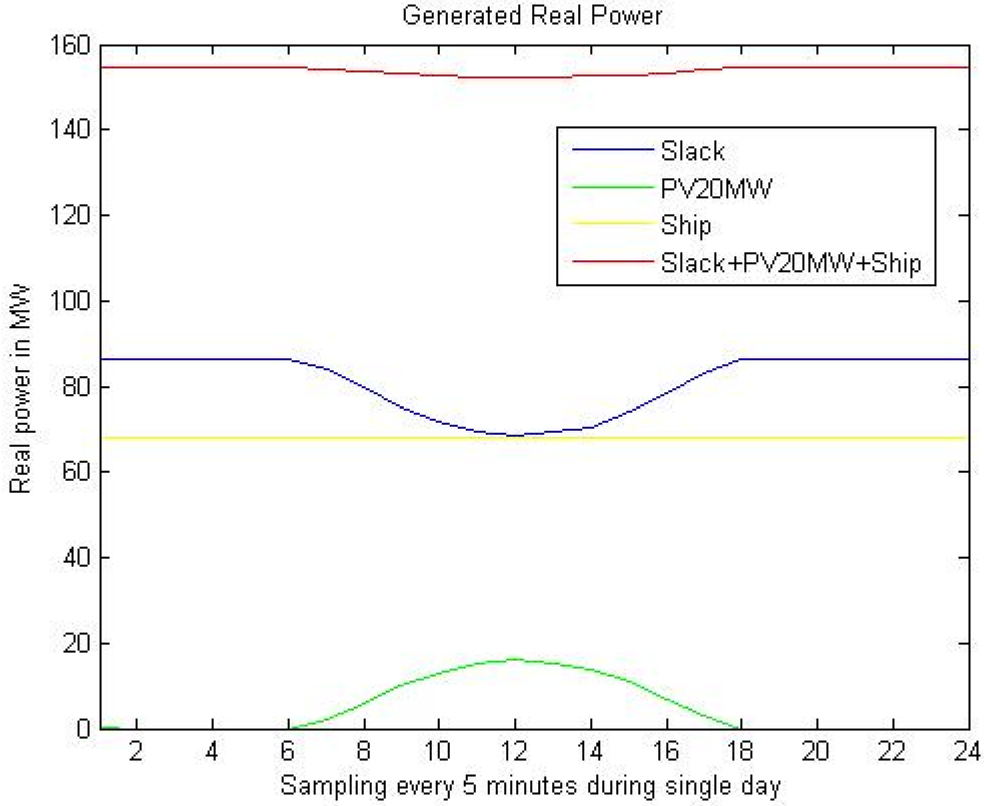

Figure 6. 21 Real power in MW (Slack, PV20MW, Ship, Slack+PV20MW+Ship)

1. Load flow of old system without PV system.

Power Flow Solution by Newton-Raphson Method

Maximum Power Mismatch = 4.98257e-12 No. of Iterations = 1

Bus No.	Voltage Mag.	Angle Degree	Load MW	Load Mvar	Generation MW	Generation Mvar	Injected Mvar
1	1.050	0.000	0.000	0.000	86.402	-42.952	0.030
2	1.053	-17.138	0.000	0.000	0.000	0.000	0.000
3	1.053	-17.140	0.000	0.000	0.000	0.000	0.000
4	1.043	-20.500	0.000	0.000	0.000	0.000	0.000
5	1.043	-20.499	0.000	0.000	0.000	0.000	0.000
6	1.000	-25.209	70.600	23.100	0.000	0.000	0.010
7	1.000	-25.209	70.600	23.100	0.000	0.000	0.000
8	1.000	-25.209	0.000	0.000	0.000	-7.924	0.000
9	1.050	-20.263	0.000	0.000	0.000	0.000	0.000
10	1.050	-20.228	0.000	0.000	68.000	50.924	0.000
11	1.048	-20.485	7.000	2.300	0.000	0.000	0.000
12	1.048	-20.485	0.000	0.000	0.000	0.000	0.000
Total			148.200	48.500	154.402	0.049	0.040

Line Flow and Losses

--Line-- from	to	Power at bus & line flow MW	Mvar	MVA	--Line loss-- MW	Mvar	Transformer tap
1		86.402	-42.922	96.475			
	2	86.402	-42.922	96.475	4.784	-52.771	
2		0.000	0.000	0.000			
	1	-81.618	-9.850	82.210	4.784	-52.771	
	3	40.806	4.934	41.103	0.000	0.002	
	5	40.812	4.916	41.107	0.162	2.424	
3		0.000	0.000	0.000			
	2	-40.806	-4.933	41.103	0.000	0.002	
	4	40.806	4.933	41.103	0.162	2.423	
4		0.000	0.000	0.000			
	3	-40.644	-2.509	40.722	0.162	2.423	
	5	-30.417	-31.653	43.898	-0.000	0.002	
	6	71.061	34.162	78.846	0.474	7.114	
5		0.000	0.000	0.000			
	2	-40.651	-2.492	40.727	0.162	2.424	
	4	30.417	31.655	43.900	-0.000	0.002	
	7	71.088	34.185	78.881	0.475	7.120	
	9	-60.854	-63.348	87.842	0.144	-14.820	
6		-70.600	-23.090	74.280			
	4	-70.587	-27.048	75.591	0.474	7.114	
	7	-0.013	-3.966	3.966	0.000	0.000	
	8	0.000	7.924	7.924	0.000	0.000	
7		-70.600	-23.100	74.283			
	5	-70.613	-27.066	75.623	0.475	7.120	
	6	0.013	3.966	3.966	0.000	0.000	
8		0.000	-7.924	7.924			
	6	-0.000	-7.924	7.924	0.000	0.000	
9		0.000	0.000	0.000			
	5	60.998	48.528	77.947	0.144	-14.820	
	10	-68.000	-50.859	84.915	0.000	0.065	
	11	3.502	1.166	3.691	0.001	0.015	
	12	3.500	1.165	3.688	0.001	0.015	
10		68.000	50.924	84.955			
	9	68.000	50.924	84.955	0.000	0.065	
11		-7.000	-2.300	7.368			
	9	-3.501	-1.150	3.686	0.001	0.015	
	12	-3.499	-1.150	3.683	0.000	0.000	

12		0.000	0.000	0.000		
	9	-3.499	-1.150	3.683	0.001	0.015
	11	3.499	1.150	3.683	0.000	0.000
Total loss					6.202	-48.411

2. Load flow of system with integrated PV system using the mean value of PV (4.667MW). Total loss is decreases from 6.202MW to 5.549 MW.

Power Flow Solution by Newton-Raphson Method

Maximum Power Mismatch = 0.000498058

No. of Iterations = 2

Bus No.	Voltage Mag.	Angle Degree	Load MW	Load Mvar	Generation MW	Generation Mvar	Injected Mvar
1	1.050	0.000	0.000	0.000	81.044	-44.009	0.030
2	1.055	-16.075	0.000	0.000	0.000	0.000	0.000
3	1.055	-16.077	0.000	0.000	0.000	0.000	0.000
4	1.043	-19.227	0.000	0.000	0.000	0.000	0.000
5	1.043	-19.226	0.000	0.000	0.000	0.000	0.000
6	1.000	-23.773	70.600	23.100	0.000	0.000	0.010
7	1.000	-23.773	70.600	23.100	0.000	0.000	0.000
8	1.000	-23.773	0.000	0.000	4.667	-9.006	0.000
9	1.050	-18.988	0.000	0.000	0.000	0.000	0.000
10	1.050	-18.952	0.000	0.000	68.000	48.558	0.000
11	1.048	-19.210	7.000	2.300	0.000	0.000	0.000
12	1.048	-19.210	0.000	0.000	0.000	0.000	0.000
Total			148.200	48.500	153.711	-4.457	0.040

Line Flow and Losses

--Line-- from	to	Power at bus & line flow MW	Mvar	MVA	--Line loss-- MW	Mvar	Transformer tap
1		81.044	-43.979	92.208			
	2	81.082	-43.961	92.233	4.220	-55.891	
2		0.000	0.000	0.000			
	1	-76.862	-11.930	77.783	4.220	-55.891	
	3	38.429	5.973	38.890	0.000	0.001	
	5	38.433	5.956	38.892	0.144	2.163	
3		0.000	0.000	0.000			
	2	-38.429	-5.972	38.890	0.000	0.001	
	4	38.429	5.972	38.890	0.144	2.162	
4		0.000	0.000	0.000			
	3	-38.285	-3.810	38.474	0.144	2.162	
	5	-30.418	-30.518	43.088	0.000	0.002	
	6	68.702	34.328	76.801	0.450	6.747	

5		0.000	0.000	0.000		
	2	-38.289	-3.794	38.477	0.144	2.163
	4	30.418	30.520	43.089	0.000	0.002
	7	68.731	34.350	76.837	0.450	6.753
	9	-60.859	-61.075	86.221	0.139	-14.846
6		-70.600	-23.090	74.280		
	4	-68.252	-27.581	73.615	0.450	6.747
	7	2.319	-4.497	5.060	0.000	0.000
	8	-4.667	8.988	10.127	-0.000	0.000
7		-70.600	-23.100	74.283		
	5	-68.281	-27.597	73.647	0.450	6.753
	6	-2.319	4.497	5.060	0.000	0.000
8		4.667	-9.006	10.143		
	6	4.667	-8.988	10.127	-0.000	0.000
9		0.000	0.000	0.000		
	5	60.998	46.230	76.537	0.139	-14.846
	10	-68.00	-48.560	83.559	0.000	0.063
	11	3.502	1.166	3.691	0.001	0.015
	12	3.500	1.165	3.688	0.001	0.015
10		68.000	48.558	83.558		
	9	68.000	48.624	83.596	0.000	0.063
11		-7.000	-2.300	7.368		
	9	-3.501	-1.150	3.686	0.001	0.015
	12	-3.499	-1.150	3.683	0.000	0.000
12		0.000	0.000	0.000		
	9	-3.499	-1.150	3.683	0.001	0.015
	11	3.499	1.150	3.683	0.000	0.000
Total loss					5.549	-52.816

3. Load flow of system with integrated PV system using max value of PV (16MW). Total loss is decreases from 5.549MW to 4.152MW.
   Power Flow Solution by Newton-Raphson Method
   Maximum Power Mismatch = 6.43215e-06
   No. of Iterations = 3

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar	Injected Mvar
1	1.050	0.000	0.000	0.000	68.351	-45.978	0.030
2	1.058	-13.552	0.000	0.000	0.000	0.000	0.000
3	1.058	-13.554	0.000	0.000	0.000	0.000	0.000
4	1.044	-16.203	0.000	0.000	0.000	0.000	0.000
5	1.044	-16.201	0.000	0.000	0.000	0.000	0.000
6	1.000	-20.352	70.600	23.100	0.000	0.000	0.010

7	1.000	-20.352	70.600	23.100	0.000	0.000	0.000
8	1.000	-20.351	0.000	0.000	16.000	-11.431	0.000
9	1.050	-15.957	0.000	0.000	0.000	0.000	0.000
10	1.050	-15.921	0.000	0.000	68.000	43.563	0.000
11	1.048	-16.179	7.000	2.300	0.000	0.000	0.000
12	1.048	-16.179	0.000	0.000	0.000	0.000	0.000
Total			148.200	48.500	152.351	-13.846	0.040

Line Flow and Losses

--Line--		Power at bus & line flow			--Line loss--		Transformer
from	to	MW	Mvar	MVA	MW	Mvar	tap
1		68.351	-45.948	82.360			
	2	68.352	-45.948	82.360	3.019	-62.548	
2		0.000	0.000	0.000			
	1	-65.333	-16.601	67.409	3.019	- 62.548	
	3	32.666	8.307	33.706	0.000	0.001	
	5	32.667	8.293	33.703	0.107	1.612	
3		0.000	0.000	0.000			
	2	-32.666	-8.306	33.705	0.000	0.001	
	4	32.666	8.306	33.705	0.107	1.612	
4		0.000	0.000	0.000			
	3	-32.558	-6.694	33.239	0.107	1.612	
	5	-30.419	-28.020	41.357	0.000	0.002	
	6	62.978	34.713	71.911	0.394	5.909	
5		0.000	0.000	0.000			
	2	-32.560	-6.681	33.238	0.107	1.612	
	4	30.419	28.021	41.358	0.000	0.002	
	7	63.011	34.732	71.949	0.394	5.915	
	9	-60.870	-56.072	82.760	0.128	-14.899	
6		-70.600	-23.090	74.280			
	4	-62.584	-28.804	68.894	0.394	5.909	
	7	7.984	-5.717	9.819	0.000	0.000	
	8	-16.000	11.431	19.664	0.000	0.000	
7		-70.600	-23.100	74.283			
	5	-62.616	-28.817	68.929	0.394	5.915	
	6	-7.984	5.717	9.819	0.000	0.000	
8		16.000	-11.431	19.664			
	6	16.000	-11.431	19.664	0.000	0.000	
9		0.000	0.000	0.000			
	5	60.998	41.173	73.593	0.128	-14.899	
	10	-68.000	-43.504	80.725	0.000	0.059	

	11	3.502	1.166	3.691	0.001	0.015
	12	3.500	1.165	3.688	0.001	0.015
10		68.000	43.563	80.757		
	9	68.000	43.563	80.757	0.000	0.059
11		-7.000	-2.300	7.368		
	9	-3.501	-1.150	3.686	0.001	0.015
	12	-3.499	-1.150	3.683	0.000	0.000
12		0.000	0.000	0.000		
	9	-3.499	-1.150	3.683	0.001	0.015
	11	3.499	1.150	3.683	0.000	0.000
Total loss					4.152	-62.305

In actual system in the fact the overvoltage occur in transmission line between Atbara and Portsudan and this appear in three cases above in bus 2 and 3, the voltage levels above the range ±5%. The voltage levels at customer sites are within ±5% in all cases.

6.8 Conclusion

This chapter including two cases studies, the first case studied represents the simulation using the PVsyst program for PV system (5 MW) to connected grid installed in ten different cities in Sudan, with this program the PV system was designed and obtained the expected annual energy production for each region. The simulation program, show the total electrical annual energy production from PV system (5 MW) in Portsudan is highest energy. Cities were arranged according to their highest productivity Portsudan, Dongola, Atbara, Omdurman, Madani, Elginina, Alobied, Alnhood, Nyala and last Kadogli.

Finally, the second case studied show that the integrated of PV 20MW in the grid of Portsudan decreases the losses of active and reactive power. If the PV system is injected the mean value of PV to grid, then the losses active and reactive power of system decreases from 6.202MW , -48.411Mvar to 5.549MW, -52.816Mvar respectively. The losses are lower to 4.152MW, -62.305Mvar if the grid is injected by the max value of PV system.

Chapter 7
Conclusion and Recommendations

7.1 Conclusion

The case study 1 represents the simulation by using PVsyst program, with this program the PV system (5 MW) was designed and obtained the expected yearly energy production. The photoelectric system was simulated with the same photovoltaic module and inverters, that was applied of Skikda and Atbara in PVsyst program, but the results of the photoelectric system is not similar according to the effect meteorological conditions on photovoltaic modules. Despite the average temperature per year in Atbara higher about 42.73% than Skikda. The temperature really limits the PV system performance, and the increase in heat is a sign of deterioration in photovoltaic cells. But the simulation by using PVsyst program, shows the total electrical yearly energy production in Atbara higher than in Skikda.

In Case Study 2, the expected annual energy production of the PV system in ten different cities in Sudan was compared, to be connected to the grid. Sudan is characterized by a good geographical location for use solar energy because Sudan receives abundant amounts of solar radiation throughout the year. The ten cities were proposed by the Sudanese Hydro Generation and Renewable Company, General Administration of Renewable Energies, Solar Power Management. The simulation program, show the total electrical annual energy production from PV system (5MW) in Portsudan is highest energy 8566750 KWh by global incident in coll 2283 KWh/m^2. Cities were arranged according to their highest productivity Portsudan, Dongola, Atbara, Omdurman, Madani, Elginina, Alobied, Alnhood, Nyala and last Kadogli. To determine the economic value of the system, you must know the total energy produced for this system. It is therefore important in accordance with meteorological conditions, to use photoelectric simulation to determine the performance of the PV system in order to predict annual power generation before it is connected to the grid.

In case study 3 the integrated of PV 20MW in the grid of Portsudan decreases the losses. If the PV system is injected the mean value of PV (4.667MW) to grid, then the losses of system decreases 10.53% of total losses of system without PV. If the PV system is injected the max value of PV (16MW) to grid, then the losses of system decreases 30.05% of total losses of system without PV system. There is no overvoltage by integrated PV to grid. I hope that in the near future Sudan will be able to establish solar power plants and connect to the grid to solve the problem of discontinuity of electrical supply and reduce greenhouse gases emission.

7.2 Recommendations

- Search for the maximum permissible penetration level of Integration the decentralized Photovoltaic to grid of Portsudan.
- Study of the reliability and compatibility of the supply system with the strong penetration of photovoltaic sources.
- Study working scenarios in degraded modes of PV systems: partial shading, short circuits, and problems of intensive tripping.
- Proposed solution to problems of reverse power flow, frequency problems due to the imbalance between supply and demand and finally protection problems.

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