T.C.
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INSTITUTE OF GRADUATE STUDIES

COMPARATIVE STUDY OF DIFFERENT MPPT ALGORITHMS ON 250KW GRID-CONNECTED PV SYSTEM

MASTER’S THESIS

Zainab LARABI

Department of Electrical & Electronic Engineering
Electrical & Electronic Engineering Program

JULY, 2023

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Thesis Advisor: Asst. Prof. Dr. ABBAS UĞURENVER

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DECLARATION

I hereby declare with the respect that the study "Comparative study of different MPPT algorithms on 250KW grid-connected PV system", which I submitted as a Master thesis, is written without any assistance in violation of scientific ethics and traditions in all the processes from the project phase to the conclusion of the thesis and that the works I have benefited are from those shown in the References. (27/07/2023)

Zainab LARABI

FOREWORD

First, I would like to express my endless gratitude to God for being who I am right now and helping me to find patience, strength within myself to complete this thesis.

I would also like to thank my family not only for encouraging me to go abroad for a master's degree but also for teaching me to chase my dreams and never give up.

I feel very fortunate to have Dr. ABBAS UĞURENVER as my supervisor and want to express my appreciation for guiding me within the whole research process in a patient and effective manner.

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Finally, I would like to acknowledge the important contribution of Istanbul Aydin University to my life, not only from an academic perspective but helping to meet great people that inspire, challenge, support and motivate me.

July, 2023 Zainab LARABI

COMPARATIVE STUDY OF DIFFERENT MPPT ALGORITHMS ON 250 KW GRID-CONNECTED SYSTEM

ABSTRACT

Photovoltaic systems are essential for producing low-cost electricity, but they can impact power quality due to non-linear loads, load imbalance, and harmonics. These issues can lead to device deterioration, affecting energy quality and performance. Photovoltaic systems are rapidly expanding annually and are quickly becoming an essential component of the energy balance in most regions and energy systems.

The critical function of solar energy management systems in solar PV deployment is to use the maximum power point tracking (MPPT) strategy. Accordingly, this thesis simulates the use of solar energy obtained from photovoltaic panels connected to the grid via converters and its operation at maximum power using Perturb & Observe (P&O) and Incremental Conductance (IC), and Fuzzy Logic (FL) control algorithms controlled by an MPPT.

A PV system that generates 250 kW and is connected to a grid needs 10 KV to be designed and simulated. Several components of the PV system such as solar panels, DC-DC converters, DC-AC inverters, and three-phase power grids were used to optimize performance and ensure the operation of the system in the presence of multiple components using MATLAB/ Simulink as a complete simulation study.

The objective is to increase the PV system's power efficiency. The numerical and electrical equations for the design have been presented. Grid-tied inverters with different types of maximum power point tracking systems (MPPT), voltage and current regulators, pulse width modulation (PWM), and phase lock loop (PLL) circuits have all been debated.

Keywords: PV system, MPPT, P&O, Incremental Conductance, Fuzzy Logic.

250 KW ŞEBEKE BAĞLANTILI SİSTEM ÜZERİNDE FARKLI MPPT ALGORİTMALARININ KARŞILAŞTIRMALI İNCELENMESİ

ÖZET

Fotovoltaik sistemler, düşük maliyetli elektrik üretmek için gereklidir, ancak doğrusal olmayan yükler, yük dengesizliği ve harmonikler nedeniyle güç kalitesini etkileyebilirler. Bu sorunlar, cihazın bozulmasına yol açarak enerji kalitesini ve performansını etkileyebilir. Fotovoltaik sistemler, yıllık hızlı bir oranda hızla genişlemekte ve çoğu bölge ve enerji sisteminde hızla enerji dengesinin temel bir bileşeni haline gelmektedir.

Güneş enerjisi yönetim sisteminin güneş PV dağıtımındaki temel işlevi, maksimum güç noktası izleme (MPPT) stratejisini kullanmaktır. Buna göre, bu tez, dönüştürücüler aracılığıyla şebekeye bağlı fotovoltaik panellerden elde edilen güneş enerjisinin kullanımını ve maksimum güçte çalışmasını Perturb & Observe (P&O) ve Artımlı İletkenlik (IC) ve Fuzzy Logic (FL) kontrol algoritmaları kullanılarak simüle etmektedir. bir MPPT'dir.

250 kW üreten ve bir şebekeye bağlı olan bir PV sisteminin tasarlanması ve simüle edilmesi için 10 KV'a ihtiyacı vardır. Güneş panelleri, DC-DC dönüştürücüler, DC-AC invertörler ve üç fazlı elektrik şebekeleri gibi PV sisteminin çeşitli bileşenleri, MATLAB/Simulink kullanılarak performansı optimize etmek ve sistemin birden fazla bileşen varlığında çalışmasını sağlamak için kullanıldı. tam bir simülasyon çalışması.

Amaç, PV sisteminin güç verimliliğini artırmaktır. Tasarım için sayısal ve elektriksel denklemler sunulmuştur. Farklı maksimum güç noktası izleme sistemleri (MPPT), voltaj ve akım regülatörleri, darbe genişlik modülasyonu (PWM) ve faz kilitleme döngüsü (PLL) devrelerine sahip şebekeye bağlı eviricilerin tümü tartışıldı.

Anahtar Kelimeler: PV sistemi, MPPT, P&O, Artımlı İletkenlik, Bulanık Mantık.

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ABBREVIATIONS

AC : Alternative Current

DC : Direct Current

FL : Fuzzy Logic

IC : Incremental Conductance

MPP : Maximum Power Point

MPPT : Maximum Power Point Tracking

PLL : Phase Locked Loop

P&O : Perturb & Observe

PV : PhotoVoltaic

VSI : Voltage Source Inverter

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I. INTRODUCTION

A. Background

In recent decades, meeting the world's energy needs has emerged as a significant political and societal concern. With electricity generation predominantly depending on once-seemingly limitless resources of energy including oil, gas, and coal, fulfilling rising global energy demands has become vital. As fossil fuel reserves decline and energy consumption continues to grow at an alarming pace, the need for renewable energy solutions is becoming more apparent. Renewable energy sources play an important role in the generation of electrical energy (Jurasz, Canales, Kies, Guezgouz, & Beluco, 2020). There are several renewable sources that are used to generate electrical energy such as wind energy, photovoltaic, geothermal, etc. Energy sources such as sun, wind or hydroelectric power are becoming increasingly popular, mainly because they do not cause any emissions and are available in unlimited quantities.

Photovoltaic energy is the most rapidily expanding renewable energy source, with a history that dates back to its use as a source of electricity for space satellites. Photovoltaic systems are a decent choice for electricity generation because photovoltaic systems are used to directly convert the energy that comes from the sun into an electrical energy by photovoltaic panels (Gao, Li, Zhou, & Ma, 2016). These panels consist of modules that have a semiconductor cell connected in different kind of ways. The current rating of the modules increases as the area of each cell increases and vice versa. A solar cell which is a semiconductor diode that contains a p-n junction that is exposed to light. These cells are made by mixing a thin film or sheet of solid silicon with electrodes. This process involves doping one of the surfaces of the silicon layer, which creates the p-n gap. When a short-circuited cell is exposed to light, charged particles are formed, which generate an electric current. The creation of these charges occurs when the energy of the photon that is absorbed by the semiconductor is sufficient to split the atomic electrons (Kamat, Tvrdy, Baker, & Radich, 2010). The semiconductor and the spectrum of the incident light are both important in this process.

Figure 1 provides a visual representation of the physical structure of a PV cell.

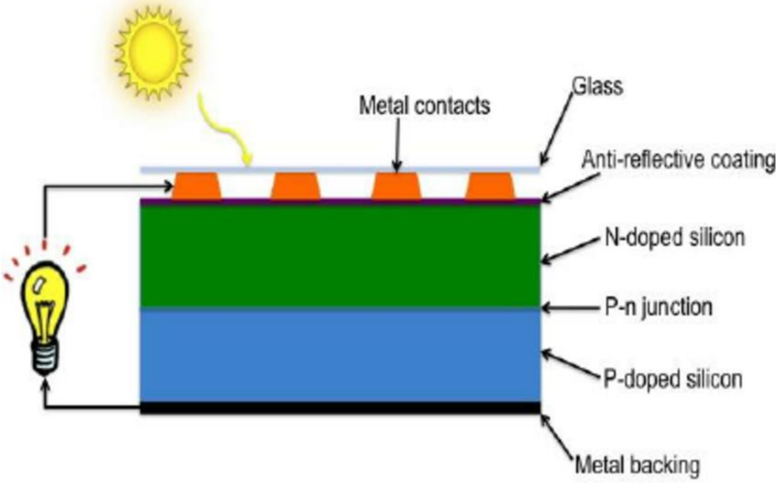


Figure 1 Solar cell structure

The Maximum Power Point Tracking (MPPT) controllers uses power electronic circuits to achieve maximum power (MP) functioning. Numerous MPPT algorithms have been developed over time to track MP in a variety of situations, including steady uniform irradiance, irradiance with rapid step changes, and partial shade. MPPT algorithms are classified into two types: direct and indirect (Kahla, Bechouat, Amieur, Feraga, & Sedraoui, 2019). Direct MPPT techniques, such as Incremental Conductance (IC) and Perturb and Observe (P&O), identify the MPP using data from a real-time system. Table 1 summarizes the various MPPT algorithms. In contrast, indirect MPPT techniques rely on system parameters such as short circuit current and open circuit voltage. These strategies are popular due of their simplicity. When using a greater step size, the controller can achieve the MPP faster, but this can result in larger steady-state oscillations. Smaller step sizes, on the other hand, can result in lower steady-state oscillations but may take longer to reach the MPP, resulting in more power loss.

Table 1 MPPT Algorithms

Items	**P&O**	**INC**	**ANN**	**FLC**
Dynamic response	Poor	Medium	High	Medium
Transient fluction	Bad	Bad	Good	Good
Steady oscillation	Large	Moderate	Zero	Small
Static error	High	High	Low	Low
Control accuracy	Low	Accurate	Accurate	Accurate
Tracking speed	Slow	Slow	Moderate	Fats
Overall efficiency	Medium	Medium	High	High
System complexity	Simple	Simple	Medium	Medium
Temperature characteristics	Poor	Poor	Good	Good

A control plan based on the MPPT method is required for the PV power conditioning system to ensure effective operating efficiency and optimal performance from the PV array. To drive the entire system, the phase-locked loop (PLL) combines line voltage and current, as well as frequency, phase angle, and amplitude. A PV system can divide based on the power converting stages. For example, it can be a single-stage that it will not require a DC/DC converter and MPPT control. Also, it can contain two stages which it will need a DC/DC (isolated or non-isolated) or DC/AC converter (Prajapati & Lairenlakpam, 2023). Between the PV generator and the grid system, a transformer will be needed to step up or step down the voltage levels and also it can work as a galvanic isolator. For example, In a DC/DC converter, a high-frequency generator it can be used to provide an isolation, resulting in a lower system dimension and storage. Grid-connected PV systems with distinct DC/DC converters for low and medium-power demands are becoming more common. The proposed multi-level topologies are commonly used in solar photovoltaics due to their improved performance, flexibility, lower conductivity, and reduced switching. This paper investigates a two-stage PV multilevel inverter featuring a DC/DC boost converter, a three-phase DC/AC inverter, and a fuzzy logic MPPT algorithm. The performance of the system is demonstrated in unbalanced grid voltage scenarios, and the usefulness of the proposed work is evaluated using MATLAB/Simulink software

B. Motivation

Solar, wind, and geothermal energy have significant advantages over traditional energy sources. They are environmentally friendly and have a low environmental impact. Furthermore, they can provide a consistent source of energy, particularly in rural areas where access to traditional energy sources is limited. Because of its availability, low cost, and ease of maintenance, solar energy has become a popular alternative (Abdullah-Al-Mahbub et al., 2022). MPPT algorithms have gained popularity in renewable energy systems, notably solar systems, due to their greater performance as compared to standard controllers. Fuzzy logic controllers can effectively handle nonlinear and complicated systems, making them a viable alternative for renewable energy systems (Lamamra, Batat, & Mokhtari, 2020). Furthermore, because of their low cost and excellent functionality, these controllers are an appealing option for manufacturers to incorporate into their applications. Overall, the expansion and development of renewable energy sources, especially solar energy, is critical in tackling the global energy issue and minimizing the environmental impact of energy production. Fuzzy logic controllers, for example, can improve the productivity and performance of general renewable energy systems, making them more viable and accessible to a larger range of consumers.

C. Problem and objectives of the research

Because of the growing increase of solar energy, the problem of integrating a photovoltaic system into the electricity grid has become increasingly significant. One of the most significant issues is the intermittent nature of solar power generation, which can result in swings in power output and consequent system instability. Furthermore, the inclusion of renewable energy sources such as solar power can provide technical and economic issues for power system operators, such as the requirement to maintain system stability and reliability. To overcome these issues, advanced control and synchronization algorithms are required to ensure that the electricity of the PV system is properly synchronized with the grid and that the system runs efficiently and reliably. Before these algorithms are applied in real-world systems, simulation models can be used to test and optimize them.

The goal of this project's literature search and simulations is to provide a better understanding of the issues involved in integrating a grid-connected photovoltaic system, as well as potential solutions and best practices for tackling them. The project can contribute to the development of more advanced and reliable solar energy systems that can assist to lessen the world's reliance on fossil fuels and minimize the consequences of climate change by building a highly efficient model for a grid-connected PV system.

To attain these objectives, the research will be conducted in the following stages:

- Conduct research on the grid-connected photovoltaic system and its elements in the literature.
- Modeling of the PV array for a grid-connected system using Matlab/Simulink.
- Design of an optimal MPPT system and the boost converter.
- Design and test the performance of a three-phase grid-connected inverter for PV systems in order to achieve a high power factor and high power quality of its injected electricity to the grid utility.
- The development and execution of modern power control switching schemes electronic components in a solar system's DC-DC converter and inverter.
- Implementation of the power electronic converter/inverter power synchronizing procedure with the public grid.
- Modeling of active and reactive electrical control algorithms.

D. Thesis outline

The thesis consists of five chapters organized as follows:

Chapter 1: This chapter provides some background information as well as general information regarding PV system technology and its uses in daily living. It provides an overview of the literature on PV modeling, MPPT, and grid-connected PV power systems. It also describes the thesis's objectives and the substance of its chapters.

Chapter 2: This chapter covers material from the literature on PV grid-connected systems, and their modeling, as well as some fundamental principles of solar energy, including PVs and their types, equivalent circuits, and features.

Chapter 3: This chapter covers the modeling and simulation of a PV array grid-connected model,an MPPT controller, a boost DC-DC converter, and an AC/DC inverter, the load, the utility grid, and mathematical Modeling.

Chapter 4: This chapter presents the simulation results of the whole grid-connected PV system model, as well as some remarks.

Chapter 5: This chapter highlights the suggested future study topics connected to thesis work and discusses the key findings taken from the thesis as a whole.

II. LITERATURE REVIEW

A. Introduction

Photovoltaic solar energy is created by converting solar radiation directly into electrical energy. This energy conversion is accomplished by the use of a photovoltaic (PV) cell, which is based on a physical phenomenon known as the photovoltaic effect, which produces an electromotive force when the cell's surface is exposed to light (Singh, 2013). The voltage produced may vary depending on the material used to construct the cell. The series/parallel connection of many PV cells results in a photovoltaic generator with a non-linear current-voltage (I-V) characteristic and a point maximum power. This chapter will go through the fundamentals of solar energy, photovoltaic cell design, and operation principles. We will also look at several types of solar cells, modeling methodologies for photovoltaic systems, and major features of photovoltaic modules. We hope to provide a short and instructive review of solar energy and photovoltaic systems by focusing on these main topics.

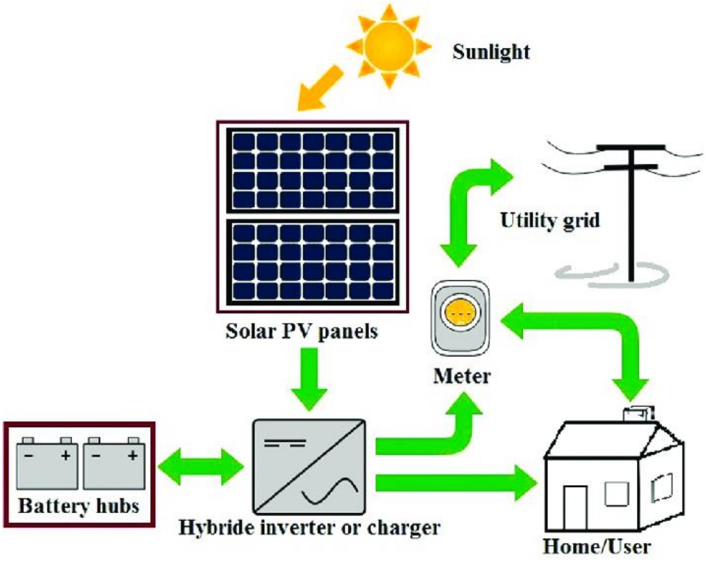


Figure 2 Schematic diagram of a typical solar PV system

B. Solar energy

The sun is an almost limitless source of energy, and it supplies enormous amounts of energy to the Earth every day. The quantity of solar energy that reaches the Earth's surface varies depending on time of day, season, latitude, and weather conditions, but on average, it is roughly 1 kilowatt per square meter. This energy can be used to generate electricity, heat water, or offer other forms of energy by utilizing solar technologies such as photovoltaic cells, solar thermal collectors, and concentrated solar power systems (Sen, 2008). Our planet's deserts receive more energy from the sun in 6 hours than humanity uses in a year. Several processes create and utilize solar energy:

- Solar thermal energy: CSP, or concentrated solar power, concentrates sunlight over a tiny area to generate heat using mirrors or lenses. This heat is subsequently converted into steam, which powers a turbine to generate energy. Solar thermal power plants can be built on a big scale, producing a significant amount of electricity (Barlev, Vidu, & Stroeve, 2011). These power facilities are often placed in bright, open locations, such as deserts. Solar thermal energy can also be used for smaller-scale applications such as domestic and commercial water heating.
- Photovoltaic solar energy: Photovoltaic (PV) solar energy is a type of renewable energy that turns sunlight directly into electricity using photovoltaic cells in solar panels (Chu & Meisen, 2011). When sunlight strikes the PV cells, it excites the electrons inside, forcing them to flow and generate an electric current. This electricity can then power houses, businesses, and other electrical devices (Rhodes, 2010). Because of its numerous advantages, PV solar energy is a fast rising sector. It is a clean and renewable energy source that creates no greenhouse gas emissions or pollution and is long-term sustainable (Shafique, Luo, & Zuo, 2020). It is highly adaptable, as it can be mounted on rooftops, on the ground, or integrated into buildings. It also promotes energy independence by minimizing dependency on traditional fossil fuels and, in the long run, can save money on energy costs.

C. Solar radiation

Despite the significant distance between the sun and the earth (150.10 Km), the terrestrial layer receives a great amount of energy (180.10 GW), which is why solar energy presents itself as an option to other sources of energy. This amount of energy will depart its surface in the form of electromagnetic radiation with wavelengths ranging from 0.22 to 10 m (Stoynov, Yarlagadda, & Yen, 2000). The energy associated with this solar radiation is roughly divided as follows:

– 9% in the ultraviolet band (< 0.4µm).

– 47% in the visible band (0.4 to 0.8µm).

– 44% in the infrared band (> at 0.8µm).

D. Different types of radiation

As it passes through the atmosphere, solar radiation is absorbed and scattered. On the ground, there are several components:

Direct radiation: Solar flux in the form of parallel rays coming from the sun disk without having been dispersed by the atmosphere.

Diffuse radiation: It is the part of the radiation coming from the sun, having undergone multiple reflections (dispersions), in the atmosphere.

Reflected radiation: It is the part of the solar illumination reflected by the ground, this radiation depends directly on the nature of the ground (cloud, sand, etc.). It is characterized bya proper coefficient of the link nature called Albédo.

Global radiation: A plane receives from the ground a global radiation which is the result of the superposition of the three compositions direct, diffuse and reflected.

E. The PV cell

Solar cells, or photovoltaic cells, are formed of semiconductor materials such as silicon. When photons (light particles) impact the cell's surface, they knock electrons loose from the semiconductor material, causing an electric current to flow.

The photovoltaic effect is the mechanism through which solar cells transform light into electricity (Ontiri & Amuhaya, 2022). Photovoltaic cells consist of:

– A thin semiconductor layer (a material with a forbidden band that acts as an energy barrier that electrons cannot cross without external excitation and whose electronic characteristics can be altered) such as silicon.

– An anti-reflective layer allowing maximum penetration of rays solar.

– A conductive grid on the top or cathode and a conductive metal on the anode.

– The most recent ones even have a new combination of reflective multi-layers just below the semiconductor, allowing light to bounce longer in this one to improve the yield.

A photovoltaic cell is based on the photovoltaic effect, which involves the generation of an electromotive force when the cell's surface is exposed to light (Nelson, 2003). A variety of factors, including the material used and how it is structured, as well as the temperature and aging of the cell, the voltage produced can range between 0.3 and 0.7 volts.

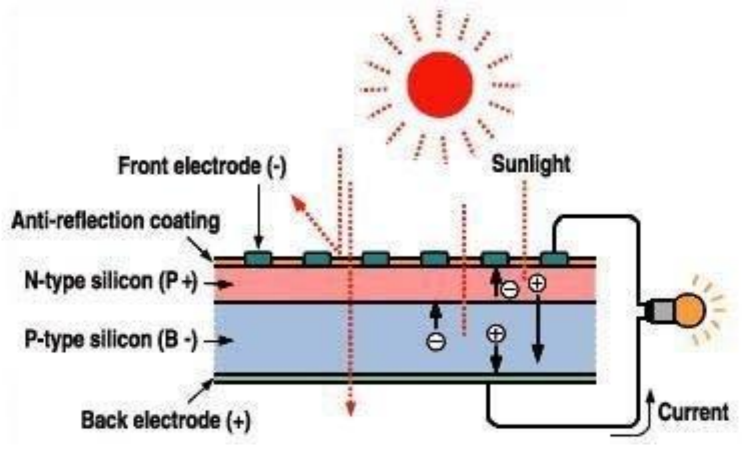


Figure 3 Schematic representation of a solar cell

A photovoltaic cell is therefore a device which makes it possible to transform solar energy into electrical energy (Mian et al., 2023). This transformation is based on the three following mechanisms:

Absorption of photons: The semiconductor material in the photovoltaic cell absorbs photons of sunlight and converts them into electrons.

Separation of charges: When the electrons absorb photons, they become excited and move from the valence band to the conduction band of the semiconductor material. This creates a separation of positive and negative charges.

Collection of charges: The separated charges are then collected by the contacts of the photovoltaic cell and transferred to an external circuit, creating an electric current.

The photovoltaic effect is a physical phenomenon that converts sunlight directly into electrical energy. It was discovered in 1839 by French physicist Alexandre-Edmond Becquerel and has since been improved and polished to become a widely utilized renewable energy generating technique (Luceño-Sánchez, Díez-Pascual, & Peña Capilla, 2019). The substance that makes up the solar cell must therefore have two energy levels and be conductive enough to allow current to flow. An electric field capable of dissociating the formed electron/hole pairs is required to collect the particles generated. A P-N junction is commonly used for this.

F. Types of PV cell

There are different types of photovoltaic cells (Bagher, Vahid, & Mohsen, 2015). Each type of cell is characterized by a yield and a cost which are peculiar to it.

1. Amorphous silicon cell

The silicon is not crystallized; rather, it is placed on a glass sheet. The cell is a very dark gray color. It is the solar cell of calculators and watches. It is made up of a thin layer of molten silicon placed directly on massive stainless steel or comparable plates (Carlson & Wronski, 1976). Amorphous solar cells have an advantage over the other two in that they are not affected by shadows. This means that even if some of the solar cells of the panel are shaded, the panel will continue to charge. These solar panels are less effective than the other two types of solar panels, but they are the cheapest to produce. These are ideal for use on boats and other types of transportation.

Figure 4 Amorphous solar cell

2. Mono-crystalline silicon cell

When the molten silicon cools, it is designed to consolidate into a single big crystal. We cut the crystal into small slices to create the cells. These cells are generally a uniform blue color. They are made up of a big silicon crystal. These solar cells are the most effective at absorbing and converting sunlight into power (Chander, Purohit, Sharma, Nehra, & Dhaka, 2015). They are, however, the most expensive. In low light settings, they perform marginally better than other solar cells. Furthermore, its efficiency ranges between 15% and 18%.

Figure 5 Mono-crystalline solar cell

3. Polycrystalline silicon cell

Several crystals form as the silicon cools. This type of cell is also blue, but the pattern generated by the different crystals is distinct. They are currently the most prevalent form of solar panel on the market. They appear to be shattered glass. They are slightly less efficient than monocrystalline solar cells but less expensive to produce (Braga, Moreira, Zampieri, Bacchin, & Mei, 2008).

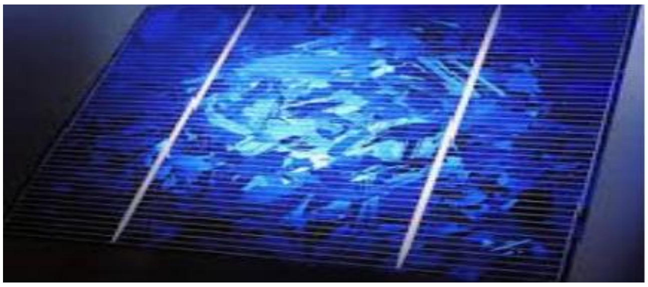


Figure 6 Polycrystalline solar cell

G. Modeling a PV system

1. Block diagram

The system studied in Figure 7 is a photovoltaic generator connected to the network via two static converters. The first is a boost chopper and the second is a voltage inverter. The chopper trigger control circuit is provided by MPPT controlled by an P&O. The commands of the gates of the inverter are ensured by an adjustment in cascade with internal loop that of the output current and external loop that of inverter input voltage. A PLL has been introduced to synchronize the generator with the grid. Below we will detail the different elements that make up the system.

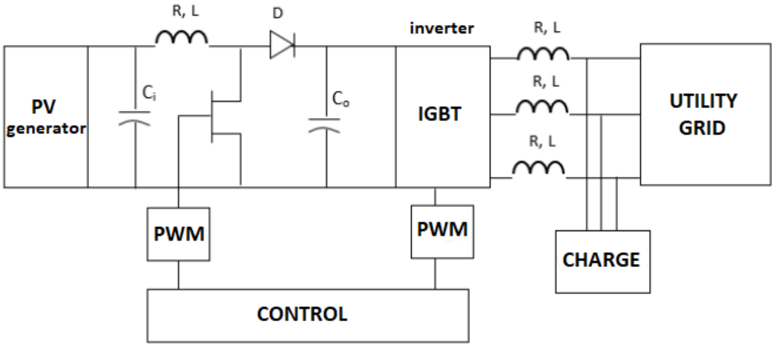


Figure 7 Presentation of the system

2. Cell model

A solar cell behaves similarly to a diode-switched current source. Figure 8 shows a series resistance caused by the junction's base and front resistances, as well as the front and back contacts, and a resistor that’s connected in parallel which is called shunt resistor (Rsh) caused by metallic contacts and leakage resistors on the cell's edges.

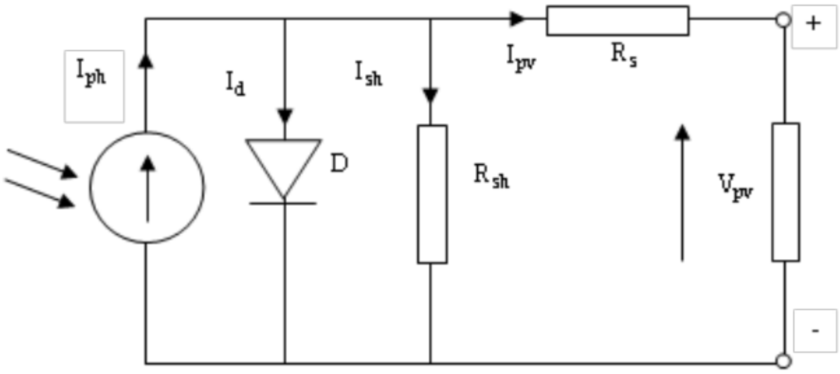


Figure 8 Electrical diagram equivalent to a PV cell

The current delivered by the cell is given by law of Kirchoff':

$$I_{pv} = I_{ph} - I_d - I_{sh} \tag{2.1}$$

The current of the parallel branch is written:

$$I_{sh} = \frac{V_d}{R_{sh}} \tag{2.2}$$

The voltage across the diode being equal to:

$$V_d = V_{pv} + R_s.I_{pv} \tag{2.3}$$

The diode current represents the internal leakage current of a cell caused by the P-N junction of the cell and is written:

$$I_d = I_s\ (e^{\left(\frac{\mathrm{Vd}}{Vt}\right)} - 1) \tag{2.4}$$

With: $V_t = \frac{a.K.T_c}{q}$

The reverse saturation current of the junction *Is*:

$$I_s = I_{sn} \left(\frac{T_c}{T_n}\right)^3 . (e^{\left(\frac{\mathrm{q.Eg}}{a.k}\left(\frac{1}{Tn} - \frac{1}{Tc}\right)\right)} \tag{2.5}$$

$$I_s = \frac{I_{scn}}{e^{\left(\frac{\mathrm{q}.V_{0c}}{a.k.T1}\right)} - 1} \tag{2.6}$$

The photocurrent Iph is directly dependent on solar radiation incident G and the temperature of the cell Tc, it is given by the following relation:

$$I_{ph} = I_{sc} = \frac{G}{G_0} \left(I_{ph} + k_i \left(T_c - T_n\right)\right) \tag{2.7}$$

$$I_s = \frac{I_{sc}(T_2) - I_{sc}(T_1)}{T_2 - T_1} \tag{2.8}$$

With: $k_i = 4.10^{-4}\,JK^{-1}$

The temperature of the cell Tc varies according to the illumination and the ambient temperature, according to the linear relation:

$$T_c = T_a + \frac{T_n - 20}{800}\,G \tag{2.9}$$

Thus the current supplied by the PV can be written:

$$I_{pv} = I_{ph} - I_s(e^{\left(\frac{\mathrm{q}}{a.k.Tc}\,(V_{pv}+R_S.I_{pv})\right)} - 1) - \frac{V_{pv}+R_S.I_{pv}}{R_{sh}} \tag{2.10}$$

Power supplied:

$$P = V_{pv}.I_{pv} = V_{pv}\,(I_{ph} - I_s(e^{\left(\frac{\mathrm{q}}{a.k.Tc}\,(V_{pv}+R_S.I_{pv})\right)} - 1) - \frac{V_{pv}+R_S.I_{pv}}{R_{sh}}) \tag{2.11}$$

3. Characteristics of PV cells

The parameters can be determined from the current-voltage curves, or from the characteristic equation (Alonso-García & Ruíz, 2006).

Short-circuit current (Isc):

It is the current whose voltage across the cell is zero. This current merges with the photocurrent Iph in the ideal situation (RS zero and Rsh infinite). In the opposite scenario, by canceling the voltage V in equation (12), we obtain:

$$I_{sc} = I_{ph} - I_s(e^{\left(\frac{\mathrm{q}}{a.k.Tc}\,(R_S.I_{sc})\right)} - 1) - \frac{R_S.I_{sc}}{R_{sh}} \tag{2.12}$$

We can ignore the term for most cells (whose series resistance is low).

$$I_s(e^{\left(\frac{\mathrm{q}}{a.k.Tc}\,(R_S.I_{sc})\right)} - 1) \tag{2.13}$$

Before we calculate the photocurrent (Iph). The closed expression of the short-circuit current is then:

$$I_{sc} \cong \frac{I_{ph}}{1+\frac{R_S}{R_{sh}}} \qquad (2.14)$$

It has the highest quantitative value of the cell's current (practically, Isc=Iph)

Open circuit voltage (Voc):

It’s the voltage which determined when the current flowing in to the cell is zero.

$$0 = I_{ph} - I_s(e^{\left(\frac{\mathrm{q}}{a.k.Tc}\ (V_{oc})\right)} - 1) - \frac{V_{oc}}{R_{sh}} \qquad (2.15)$$

In the ideal case, its value is slightly less than:

$$V_{oc} = V_t \ln \left(\frac{I_{ph}}{I_s+1}\right) \qquad (2.16)$$

The series resistance is calculated as follows:

$$I_{pv} = I_{sh} - I_0(e^{\left(\frac{\mathrm{q}}{a.k.Tc}\ (V_{pv}R_S.I_{pv})\right)} - 1) \qquad (2.17)$$

Energy efficiency:

It is the proportion of the incident solar power to the maximum electrical power supplied by the cell Pmax(Iopt,Vopt). It is given by:

$$\eta = \frac{P_{max}}{P_{inc}} = \frac{I_{opt}.V_{opt}}{I_{inc}} \qquad (2.18)$$

Pinc is equal to the multiplication of the illumination that coming from the sun and total surface area of solar cells. This metric represents the efficiency with which solar energy is converted into electrical energy.

Form factor (FF):

It’s the ratio of the maximum power produced by multiplication of the output current and voltage to the product of the short-circuit current Isc and the open-circuit voltage Vco.

$$\mathrm{FF} = \frac{P_{max}}{P_{inc}} = \frac{I_{opt}.V_{opt}}{I_{inc}} \qquad (2.19)$$

H. PV module

When compared to the needs of most home or industrial applications, the basic solar cell is a fairly modest power generator. A few tens of square centimeters elementary cell produces a few watts at a voltage of less than one volt (PN junction voltage) (PE, 2007). To generate more power, numerous cells must be connected to form a photovoltaic module or panel. Indeed, PV modules are made up of a number of cells that perform the actual conversion of sunlight into electricity. They are connected in series and parallel to generate a photovoltaic field of peak power defined by specific lighting, temperature, and solar spectrum parameters. Most of the modules on the market consist of two to four arrays of crystalline silicon cells connected in series (Vidyanandan, 2017).

Figure 9 PV module

Photovoltaic modules perform the following functions:

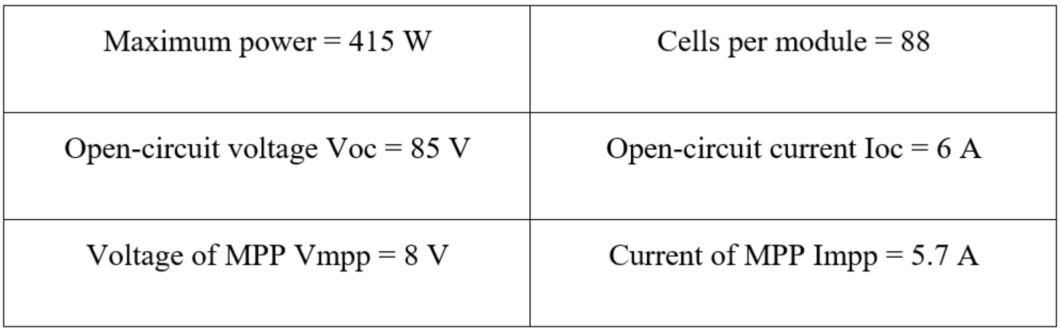
- Protection of cells against atmospheric agents
- Mechanical protection and support.
- Electrical connection between cells and with the outside.

1. PV module simulation

In our research, we used a SunPower solar module, namely the SPR-415E-WHT-D model. Table 2 shows the parameters of a PV system with 6 modules and 88 in parallel operating under typical conditions (1000 W/m2 irradiation, cell temperature of 25°C). We chose MATLAB as the tool of choice for testing and simulation.

MATLAB provides a comprehensive platform for conducting precise and reliable photovoltaic simulations, allowing us to examine the performance and behavior of the selected PV module under various operating situation.

Table 2 Characteristics of the SPR-415E-WHT-D



Maximum power = 415 W	Cells per module = 88
Open-circuit voltage Voc = 85 V	Open-circuit current Ioc = 6 A
Voltage of MPP Vmpp = 8 V	Current of MPP Impp = 5.7 A

2. I(V) and P(V) characteristics of the PV module

Figure 10 depicts the current-voltage (I-V) and power-voltage (P-V) curves of a typical solar module under standard conditions (25°C temperature and 1000 W/m2 irradiance). These curves provide useful information about the electrical properties and performance of the module. The I-V curve depicts the bond between the current of the module and the voltage across its terminals. It shows how the current output varies as the voltage supplied to the module changes. The curve is often nonlinear, with a low starting current region at low voltages followed by a rapid increase in current as the voltage rises. As the voltage rises, the current reaches a maximum and eventually saturates. The P-V curve depicts the relationship between the module's power output and voltage. It is calculated by multiplying the values of current and voltage from the I-V curve at each location. The P-V curve gives useful information about the maximum power point (MPP), which corresponds to the voltage and current combination that produces the most power from the module. The MPP is critical in photovoltaic systems because it reflects the ideal operating position for getting the most power from the module. We can determine the elements (Voc), (Isc), (Vmpp), (Impp), and (FF) of a photovoltaic module by analyzing its I-V and P-V curves under standard conditions.

These factors are critical for planning and optimizing solar systems in order to generate efficient power.

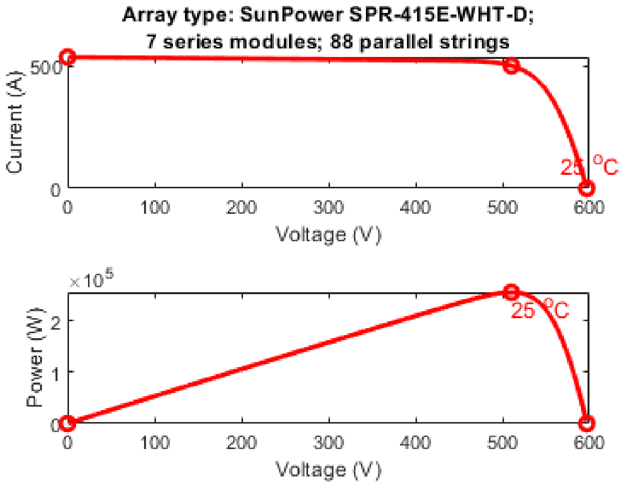


Figure 10 The current and I(V) the power and P(V) characteristics of the PV module

3. Influence of irradiance and temperature

The illuminance (solar irradiance) and temperature conditions of a photovoltaic panel determine its properties. Variations in these factors can have an impact on the performance and electrical output of the panel. The amount of sunlight intensity that reaches the surface of the photovoltaic panel is referred to as illumination, or solar irradiance (El-Shobokshy & Hussein, 1993). Higher irradiance levels cause enhanced photon absorption by the semiconductor material of the panel, resulting in higher current generation and power output. Lower irradiance levels, on the other hand, can reduce the electrical output of the panel. Temperature also has an impact on panel performance. The efficiency of solar cells decreases as the temperature rises. This is primarily because the semiconductor materials employed in the cells are temperature sensitive. Higher temperatures can cause resistance to increase and open-circuit voltage to drop, resulting in a decline in total panel performance. To maintain optimal operating conditions, it is critical to consider temperature impacts and install cooling methods in photovoltaic systems.

Influence of illumination:

Figure 11 presents an example of the curves for different radiation levels: We fixed the temperature (T = 25◦C) for different illuminations. We then observe that the no-load voltage is relatively constant, And the short circuit current increases with increasing illumination.

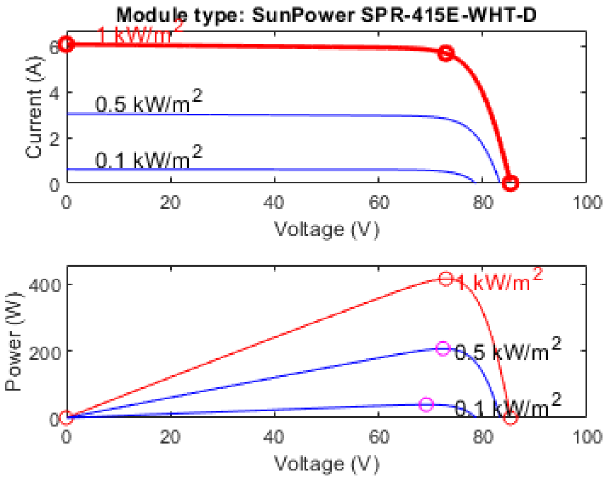


Figure 11 The characteristics P=f(V) and I=f(V) as a function of the irradiance

Temperature influence

Figures 12 presents the characteristics I − V and P – V a photovoltaic module for a radiation level (G=1000 w/m2) fixed and for different temperatures:

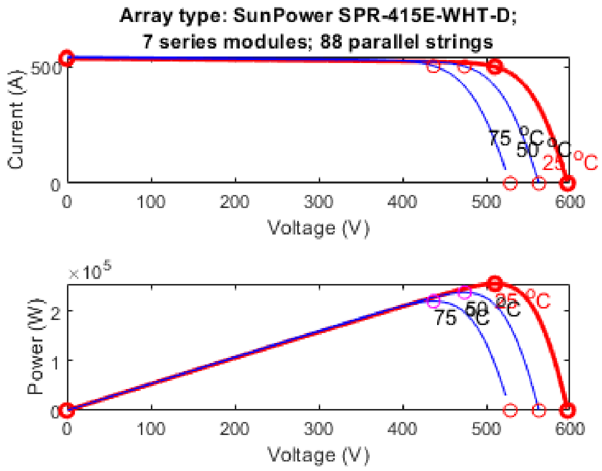


Figure 12 The characteristics of P=f(V) and I=f(V) as a function of the temperature

I. PV panel

A solar panel is made up of photovoltaic modules that are connected in series and/or parallel to generate the required power. These modules are installed on a metal frame that allows the solar field to be supported at a certain angle of inclination (Trapani & Redón Santafé, 2015).

Figure 13 PV panel

For each panel you can have as many outputs as modules, which means that you will need a junction box that groups everything, then this junction box fixed on a structure of the assembly has the role of making the connections between the modules for obtain optimum power output (Khatib, 2010).

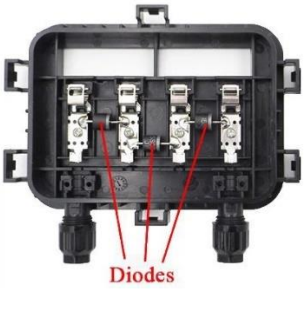


Figure 14 Junction box

The junction box is also composed of a printed circuit on which find:

- Series schotcky diodes, placed on a radiator, on each input, which it will be used to avoid the batteries from giving the current to the panels.
- Protection fuses that will avoid the batteries from giving power to the modules when there is destruction of the antiparallel diodes.
- Light diodes, in parallel on each protection fuse. These diodes to individually control each branch of modules. For example a box with 4 inputs of 24 Volts will be made up of two branches of two modules, it there will therefore be two diodes which will make it possible to observe the operation of each branch.
- Surge protection (Transil or VDR) at the outlet of the box.

The wiring of these boxes makes it possible to have a 12.24 or 48 volt output depending on the modules, they are equipped with two to twelve inputs, depending on the output voltages. The amount of electricity in all the components of the PV panels depends on:

- Electricity needs.
- The dimensions of the panel.
- The sunshine of the place of use.
- The season of use.

J. The advantages of the PV installation

– Photovoltaic systems are reliable. The installation has no moving parts, making it ideal for isolated locations (Wohlgemuth, 2008). This is why it is used aboard spacecraft. Extreme weather conditions are not a problem for the materials utilized (silicon, glass, and aluminum).

– When the building is linked to the network, the surplus production can be resold to recoup investments and produce cash.

– PV systems are available in a variety of sizes and output levels to suit a variety of applications (Shukla, Sudhakar, & Baredar, 2016). Having a light weight, which it will make it easy to transporting it also will have make the establishing of these systems simple and safe.

– A PV system can be readily extended by connecting additional panels in series to increase the voltage or in parallel to increase the current.

– Photovoltaic panels have a cheap operating cost since they require less maintenance and do not require fuel, transportation, or highly skilled employees (Song et al., 2017).

– Photovoltaic technology is environmentally friendly because the completed product is non-polluting, silent, and does not affect the environment, until massive installations occupy area.

K. Summary

To attain maximum power, the module's operating point must be matched to the load, which can be accomplished by using the property of maximum power point tracking (MPPT) algorithm. The MPPT algorithm constantly changes the module's operating point to guarantee that it is always at its maximum power point. This permits the photovoltaic system to produce the most energy possible, even in adverse weather conditions. Furthermore, new control and synchronization algorithms may increase grid-connected PV system efficiency, stability, and dependability. These algorithms can optimize the system's power output while maintaining grid stability, guaranteeing that the PV system does not disrupt the electrical grid. Overall, developments in control and synchronization algorithms, as well as the development of new technologies, have made photovoltaic energy a potential and increasingly competitive alternative to traditional energy sources.

III. THREE-PHASE PV GRID CONNECTED SYSTEM MODELING

A. Introduction

The aim of this thesis is to explore the components and interconnections of a photovoltaic (PV) system in order to produce a highly effective PV model that is connected to a grid. The PV arrays, DC-DC boost converters, inverters, linear load, and the grid are all part of the system. Each of these components is crucial to the overall performance of the PV system. The PV array is the central component of the system, responsible for converting solar energy into electrical energy. The array is made up of numerous interconnected PV modules, each of which has several PV cells. The DC-DC boost converter is a critical component for ensuring that the PV arrays function at their maximum power point (MPP). It adjusts the PV array voltage to match the inverter input voltage, maximizing the system's power production. The inverter converts the direct current (DC) electricity generated by the PV arrays into alternating current (AC) power that can be supplied into the grid or utilized to power local loads. The linear load refers to the local loads that absorb the PV system's generated power.

The grid absorbs any extra electricity generated by the PV system. Each component of the grid-connected PV system must be precisely modeled in order to produce an efficient model. Understanding the features of each component and how they interact with one another is required. The output power of a PV array, for example, is affected by various parameters such as the intensity of solar radiation, temperature, and shading effects. The efficiency of the DC-DC boost converter is affected by the input voltage and load, whereas the inverter's output power is affected by the input voltage and frequency. In conclusion, successful modeling of a grid-connected PV system necessitates a thorough understanding of each component's properties and linkages. The goal of this research is to explore these components and create an accurate model that can be used to replicate real-world circumstances, as well as to create sophisticated control and synchronization algorithms to improve the efficiency, stability and dependability of the system.

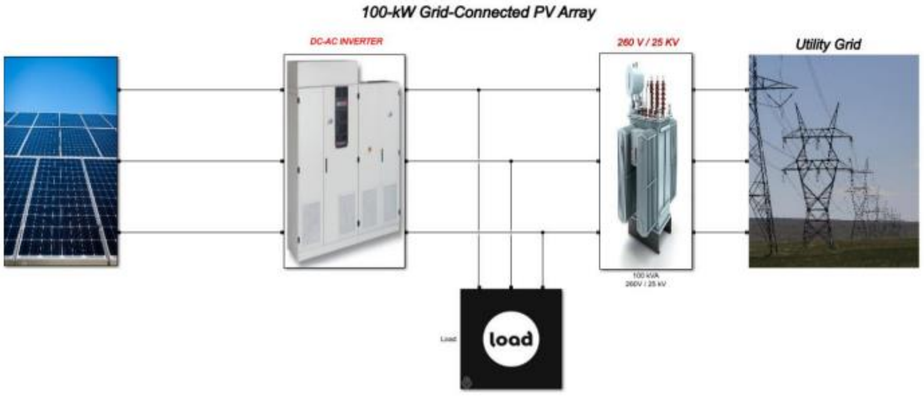


Figure 15 Block Diagram of PV Grid-Connected Model

In this study, the modeling of the grid-connected photovoltaic system includes two major stages: the DC-DC converter and the DC-AC converter. These stages work concurrently and fulfill certain functions to ensure the system's efficiency. In the first stage, a boost converter is linked to the output of the solar photovoltaic system. The boost converter serves two primary purposes. To begin, it maximizes the power output of the PV source by controlling and optimizing the voltage and current of the system. As a result, the PV system produces the most electricity feasible. Second, the boost converter raises and stabilizes the DC output voltage of the PV source, which is required for the following stage of the system.

The second stage is the DC-AC converter, which converts the DC output of the boost converter to AC before it is delivered into the electrical grid. This stage guarantees that the power generated by the PV system is compatible with the AC power grid, allowing for efficient electricity distribution. A filter is installed between the inverter and the grid to remove higher frequency harmonics from the inverter output, ensuring the quality of the power output. This filter is critical in ensuring that the power sent to the grid is of high quality and does not disturb or harm the electrical system. The modeling of the grid-connected photovoltaic system in this work incorporates a complete methodology that accounts for the many components and phases required for effective electricity production and delivery.

B. Simulink circuit model

In the simulation model, a 250 kW photovoltaic (PV) array is connected to a 10 kV grid system via a three-phase inverter. The purpose of the PV system is to send electricity from the PV array to the utility grid. The inverter uses a variety of Pulse Width Modulation (PWM) techniques to produce variable AC voltage magnitudes and frequencies. To accomplish maximum power point tracking (MPPT), the inverter control unit employs three different MPPT algorithms: Perturb & Observe (P&O), Incremental Conductance (IC), and Fuzzy Logic (FL). These algorithms are widely used in PV systems to track and optimize the maximum power point of the PV array. In the simulation model, a 250 kW photovoltaic (PV) array is connected to a 10 kV grid system via a three-phase inverter. The PV system's purpose is to send electricity from the PV array to the utility grid. The inverter uses a variety of Pulse Width Modulation (PWM) techniques to produce variable AC voltage magnitudes and frequencies.

To accomplish maximum power point tracking (MPPT), the inverter control unit employs three different MPPT algorithms: Perturb & Observe (P&O), Incremental Conductance (IC), and Fuzzy Logic (FL). These algorithms are widely used in PV systems to track and optimize the PV array's highest power point. The FL algorithm is a more complex MPPT technique that changes the operating point of the PV array based on input variables such as irradiance and temperature. Using linguistic variables and rules, the fuzzy logic controller makes decisions and optimizes power output. The simulation studies and findings for the three MPPT approaches are collected using the MATLAB/Simulink tool. The modeling system is used to compare the three MPPT algorithms under constant illumination of 1000 W/m2 and temperature of 45°.

The investigation of these MPPT algorithms is critical for PV system optimization because it can aid in increasing the system's efficiency and performance. By using advanced MPPT techniques such as the IC and FL algorithms, the PV system may track the maximum power point more accurately and effectively, resulting in higher power output and improved energy efficiency. Overall, using a three-phase inverter with modern MPPT algorithms can significantly improve PV system performance and efficiency, making them a more practical and enticing option for renewable energy generation.

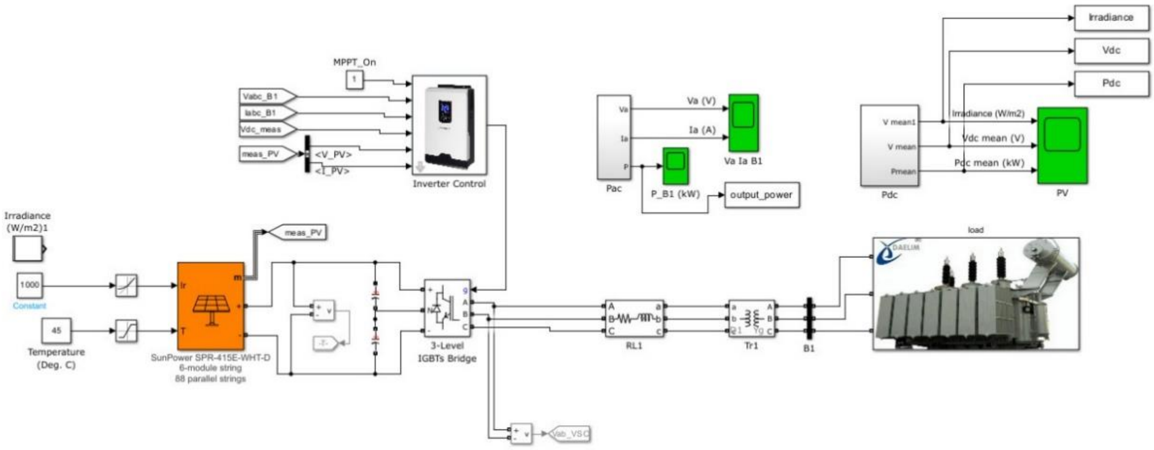


Figure 16 Simulink model of the proposed solar PV system for MPPT integration

The usage of MATLAB/Simulink as a simulation tool for this model is quite advantageous because it allows the user to assess and analyze the performance of the MPPT algorithms used. The design criteria for this model were set at a constant temperature of 45° and a constant irradiation of 1000 W/m2, which serves as a benchmark for the model's performance. As previously stated, the P&O algorithm is a popular MPPT technique that involves altering the voltage and current of the PV array to follow the maximum power point. Because of its simplicity and efficiency, the P&O algorithm is a common choice for PV systems. The Incremental Conductance (IC) algorithm, which is more complicated than the P&O algorithm, is another MPPT algorithm utilized in this model. The IC algorithm tracks the maximum power point by taking the derivative of the power curve of the PV array. As a result, the tracking is more accurate and faster than with the P&O algorithm.

The Fuzzy Logic (FL) method is the third MPPT algorithm utilized in this model, and it uses a set of rules to regulate the voltage and current of the PV array. In some circumstances, the FL method outperforms the other algorithms due to its ability to manage the nonlinear properties of the PV array. In general, the three-phase inverter and MPPT algorithms used in this model allow for a reliable and efficient power transfer from the PV array to the grid system. The implementation of simulation tools such as MATLAB/Simulink enables the analysis and optimization of system performance under varied conditions, making it a valuable tool for creating and improving PV systems.

C. Boost converter

Figure 17 displays the MPPT Boost, also known as a step-up converter. A boost converter is a power converter that produces an output voltage that is greater than the input voltage. It is made up of four fundamental parts: an inductor, a power electronic switch (such as an IGBT), a diode, and a capacitor (Masri, & Chan, 2010). The Boost converter is controlled via PWM (Pulse Width Modulation). PWM is used to operate the Boost converter by switching the switch ON or OFF at a high frequency (referred to as the switching frequency). For continuous current conduction, the following relation describes the relationship between the output voltage and the input voltage:

$$V_O = \frac{V_{PV}}{1-D} \tag{3.1}$$

Where V_O denotes the boost output voltage, V_{PV} the PV array output voltage, and D the duty cycle, which denotes the fraction of time the switch is turned on and has values ranging from 0 to 1.

$$D = \frac{T_{ON}}{T_{ON}+T_{OFF}} \tag{3.2}$$

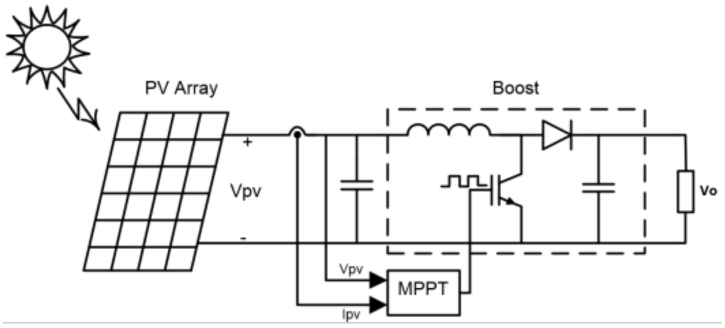


Figure 17 The Boost Converter Topology

D. Maximum power point tracking (MPPT)

Maximum Power Point Tracking, or MPPT, is a technology used in solar power systems to maximize the amount of energy harvested from solar panels. MPPT algorithms are meant to constantly monitor the output of solar panels and alter the voltage and current to harvest the maximum power from the panels at any given time. MPPT technology is employed in a variety of solar applications, including small portable solar chargers and big commercial solar installations. By lowering the number of panels necessary to obtain a given power output, MPPT can improve the efficiency of the solar system and lower the overall cost of the system (Babaa, Armstrong, & Pickert, 2014). MPPT techniques are implemented through the DC/DC converter that connects the PV array to the inverter. This can be performed by altering the input voltage of the DC/DC converter. Figure 18 shows the a block diagram for the configuration of the maximum power point tracking system the slope.

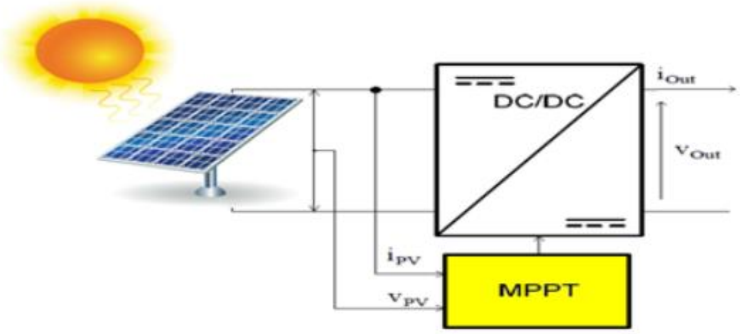


Figure 18 Block diagram of MPPT

1. Review of MPPT

A solar panel is made up of photovoltaic cells. In reaction to radiant energy absorption, photovoltaic cells detect electromagnetic radiation and create a current or voltage, or both. Irradiance (the amount of solar radiation) and temperature are the primary determinants of PV array output power. Furthermore, the output power of the

PV array is a function of its terminal voltage for a given irradiance and temperature, and there is merely one value for the final voltage at which the PV panel is utilized efficiently. Maximum power point tracking MPPT is the method of locating this voltage.

To implement the MPPT technique, several algorithms have recently been developed, such as Perturb and Observe, Incremental Conductance, Fuzzy or neural based, and so on. The insulation levels and cell temperature, on the other hand, merely specify the upper bounds of the finest available matching. The array voltage used to find the true matching. The mismatch can be remedied by using an MPPT controller to find the local maximum power point in the p-v response range of the solar panel. Solar panels are made up of several tiny cells that are linked together in series and parallel. Each cell has a maximum power point (MPP) at which it can generate the greatest amount of electricity. Temperature, irradiance, shadowing, and cell aging all have an impact on the MPP of each cell.

To keep the solar panel working at its MPP, MPPT technology employs a converter that regulates the voltage and current. MPPT technology is especially effective in cases where the solar panel's input voltage varies, such as when the panel is shaded or the temperature changes (Eltawil, Zhao, 2013). MPPT algorithms can detect the panel's MPP and alter the converter to keep it stable even under changing conditions. This can result in a significant increase in the amount of energy that can be extracted from the solar panel. Figure 18 displays the P-V characteristics of a practical PV array with MPP.

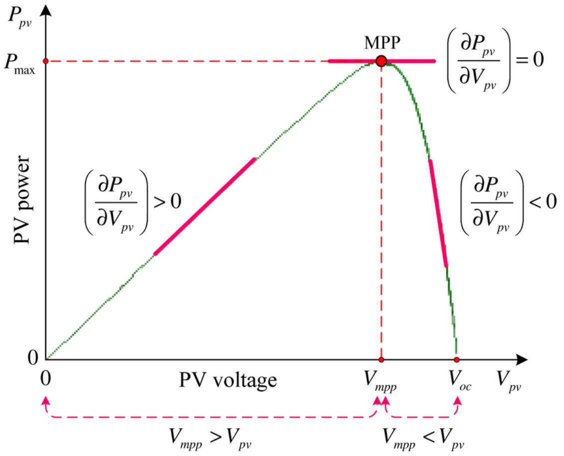


Figure 19 P-V characteristics of a practical PV array showing MPP.

2. Perturb & Observe (P&O)

A typical method is to disturb and observe. This type of MPPT algorithms widely used because of its simple response design and fewer control perimeters. The P&O approach works by perturbing or changing the operational point of the solar panel and then observing the subsequent change in power production. The algorithm adjusts the panel's operational voltage or current until the maximum power point is attained. When the maximum power point is reached, the algorithm changes the panel's operating point to maintain the MPP.

The P&O method works by measuring the solar panel's power output and comparing it to the prior power output. If the power output is raised, the algorithm keeps perturbing the operating point in the same way. If the power production falls, the algorithm alters the direction of the perturbation (Piegari, Rizzo, 2010). While the P&O system is straightforward and easy to use, it does have certain disadvantages. The algorithm may oscillate about the MPP, resulting in energy losses and a reduction in system efficiency. Furthermore, the algorithm may be slow to follow changes in solar irradiation and temperature, resulting in inefficient solar panel functioning.

To disturb the system, voltage or duty ratio are typically used. When the variation in sun irradiation is significant, this method is useless. After establishing an approximation of the maximum power point by making a search on the complete P-V curve, the slope of the P-V curve dP/dV is derived by supplying the step change in boost converter duty ratio. The next perturbation in the duty cycle is kept if the dP/dV decreases as the duty cycle increases; otherwise, the sign of the perturbation step is changed. Figure 20 shows the flow chart for maximum power point tracking based Perturb and Observe algorithm.

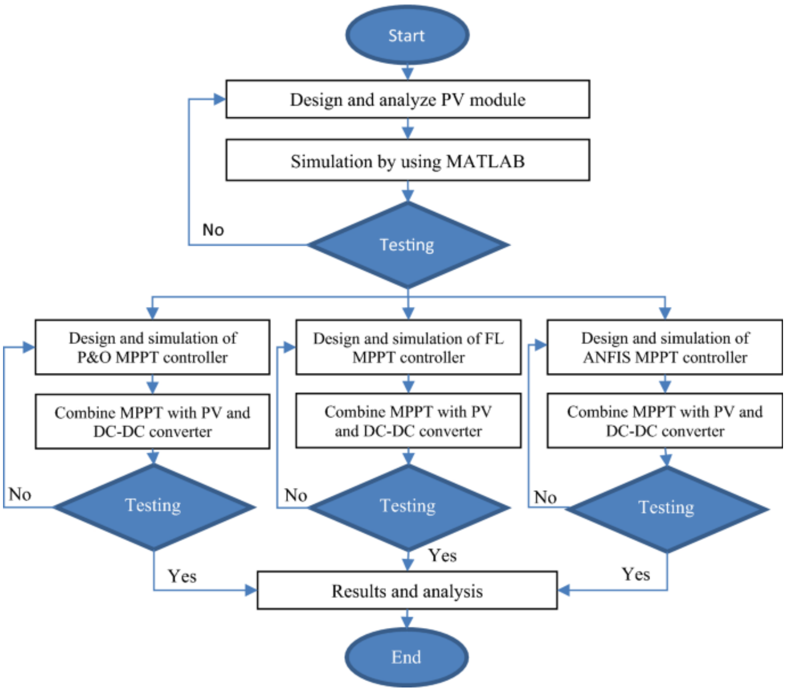


Figure 20 Flowchart of P&O Algorithm

3. Incremental Conductance (IC)

Another popular approach for maximum power point tracking (MPPT) in photovoltaic (PV) systems is the incremental conductance (IC) method. It is more efficient than the P&O approach and allows for more exact tracking of the MPP. The main concept of the IC method is to track the MPP by comparing the PV panel's incremental conductance to a reference conductance (Safari, Mekhilef, 2011). The incremental conductance is the change in the conductance of a PV panel in response to modest changes in voltage or current.

The algorithm analyzes the instantaneous incremental conductance of the PV panel to the reference conductance and modifies the panel's operating point by getting closer to the MPP. The incremental conductance is 0 when the PV panel is operating at MPP. The incremental conductance becomes nonzero when the panel's operating point travels away from the MPP. The IC algorithm then adjusts the operating point of the panel in the direction of the MPP until the incremental conductance returns to zero. The IC approach has an advantage over the P&O method in that it can properly track the MPP under rapidly changing irradiance or temperature circumstances. The IC approach, on the other hand, necessitates more processing resources than the P&O method and may find problems in the presence of numerous MPPs or partial shading of the PV panel.

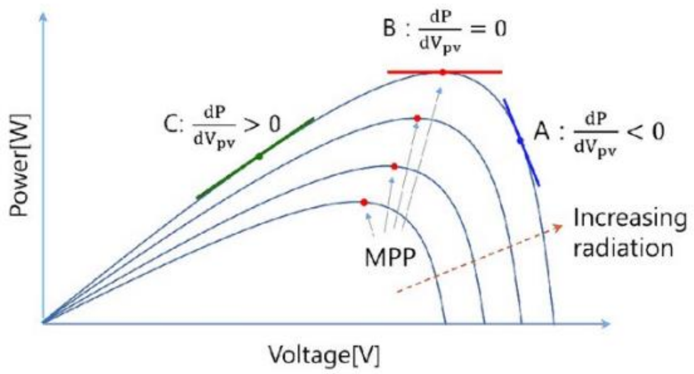


Figure 21 P-V characteristic of PV panel for IC

The incremental conductance approach assumes that the slope of the PV array power curve is zero at the MPP, positive to the left of the MPP, and negative to the right of the MPP. The PV module power is calculated as follows in (1):

$$\frac{dP}{dV} = \frac{d(I.V)}{dV} = I + V.\frac{dI}{dV} \tag{3.3}$$

If the immediate conductance derivative is on the left side of the P-V characteristic, the (dP/dV>0):

$$\frac{dP}{dV} > 0 \Rightarrow \frac{dI}{dV} > \frac{-I}{V}\text{, voltage increased } V + \triangle V \text{ and } \triangle V = +\delta \tag{3.4}$$

If the immediate conductance derivative is on the right side of the P-V characteristic, the (dP/dV<0):

$$\frac{dP}{dV} < 0 \Rightarrow \frac{dI}{dV} < \frac{-I}{V}\text{, voltage decreased } V + \triangle V \text{ and } \triangle V = -\delta \tag{3.5}$$

If the instantaneous conductance derivation is zero:

$$\frac{dP}{dV} = 0 \Rightarrow \frac{dI}{dV} + \frac{I}{V} = 0\text{ , } V + \triangle V \text{ and } \triangle V = 0 \tag{3.6}$$

4. Fuzzy Logic (FL)

In photovoltaic (PV) systems, fuzzy logic control can be utilized for maximum power point tracking (MPPT). The fuzzy logic control technique is employed in this context to adapt the PV system's operating point to follow the MPP under various environmental variables, such as variations in irradiance or temperature. There are multiple steps in the fuzzy logic control algorithm for MPPT. First, the input variables, such as PV panel voltage and current, as well as irradiance and temperature, are defined. These variables are subsequently assigned to fuzzy sets with varying degrees of membership. The fuzzy logic rules are then defined based on the input factors and the final outcome variable, which is the PV system's operating point.

The rules connect the degree of membership of the input variables to the degree of membership of the output variable, which indicates the PV system's desired power output. Given the current input conditions, the fuzzy logic controller applies these rules to calculate the necessary adjustment to the PV system's operating point. This modification is made in real-time, enabling the PV system to track the MPP as conditions change. When compared to other MPPT algorithms, fuzzy logic control has the benefit of being able to handle complicated, non-linear interactions between input and output variables, as well as quickly adapting to changes in the environment (Rai, Rahi, 2022). However, designing and precisely implementing the fuzzy logic control method can be challenging, and it requires precise adjustment of the fuzzy sets and rules to obtain optimal performance. There are three stages of fuzzy logic controller:

- <u>Fuzzification</u>

The system's inputs are turned into fuzzy sets at this stage by providing a degree of membership to each input value. The degree of membership shows how well an input value fits into a specific fuzzy set. For each input, fuzzy sets are specified by linguistic variables such as "low", "medium", and "high".

- <u>Rule Evaluation</u>

The fuzzy rules that govern the behavior of the system are evaluated at this stage based on the degree of membership of the inputs to each rule. The rules use if-then statements to specify the relationship of the input and output variables, and are typically stated as fuzzy if-then rules. If the input is "low" and the output is "high," for example, the rule might be "If the input is low, then the output is high with a level of membership of 0.8." The rules are assessed by combining the degrees of membership of the input variables using fuzzy logic processors such as AND, OR, and NOT.

- <u>Defuzzification</u>

The system's output is converted from fuzzy sets to a crisp value at this point. This is accomplished by the use of a defuzzification algorithm, which turns fuzzy sets into a single output value based on the level of inclusion of the output variables. The defuzzification approach can be as basic as a weighted average or as complex as the centroid or the max membership method. The ultimate output of the fuzzy logic control system is the resultant crisp output value, which can be utilized to regulate a physical process or make a decision depending on the input variables.

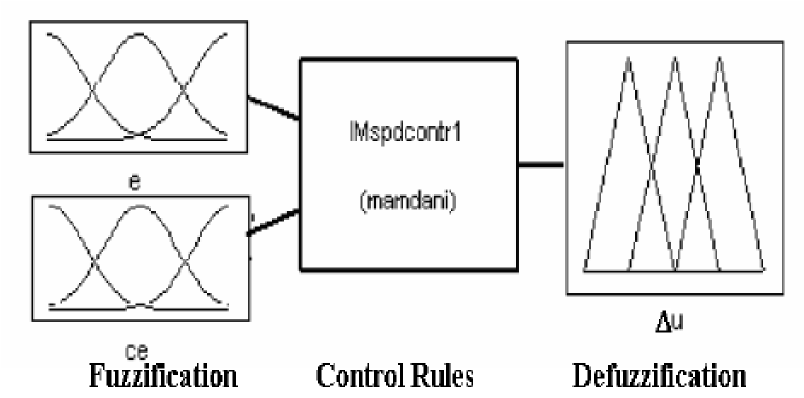


Figure 22 The three stages of fuzzy logic controller

E. Three-phase inverter

A three-phase inverter is a power electronic device that converts direct current (DC) electricity to alternating current (AC) power with three output phases. It is utilized in many different applications, such as motor drives, renewable energy systems, and grid-connected power systems. A three-phase inverter is made up of a direct current (DC) source, a collection of power switching devices, and a three-phase output filter. IGBTs (Insulated Gate Bipolar Transistors) and MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) are power switching devices that switch the DC voltage on and off at a high frequency, typically between 2 kHz and 20 kHz.

The switching pattern of the power switching devices defines the inverter's output voltage shape and frequency. The most popular switching sequence is sinusoidal pulse width modulation (SPWM), which provides a three-phase AC output voltage with adjustable frequency and magnitude by modifying the duty cycle of the switching devices. The three-phase output filter smoothes the alternating current output voltage and removes any high-frequency harmonics generated by the switching devices. It is typically made up of a series of inductors and capacitors connected to each phase of the output.

A three-phase inverter offers more power output, and an improved waveform, and is more efficient than a single-phase inverter. Because three-phase power is available in these contexts, it is also more widely used in industrial and commercial applications. Three-phase inverters are commonly used in variable speed drives for alternating current motors, energy-producing devices such as wind turbines and solar photovoltaic systems, and grid-connected power systems where they inject power into the grid.

Subsystem components of the three-phase inverter

Three-phase inverters are commonly used in grid-connected power systems, and they can be controlled using various Pulse Width Modulation (PWM) techniques to provide adjustable AC voltage magnitudes and frequencies. They can also be used for MPPT (Maximum Power Point Tracking) in renewable energy systems, such as solar PV systems, by using a control unit that employs P&O (Perturb and Observe) algorithm, DC voltage regulator, current regulator, Phase-Locked Loop (PLL) measurements, and a grid-side PWM modulator. The purpose of the PLL module is to synchronize the inverter output with the grid voltage, while the filter is used to remove any harmonic components from the output voltage to meet the grid standards.

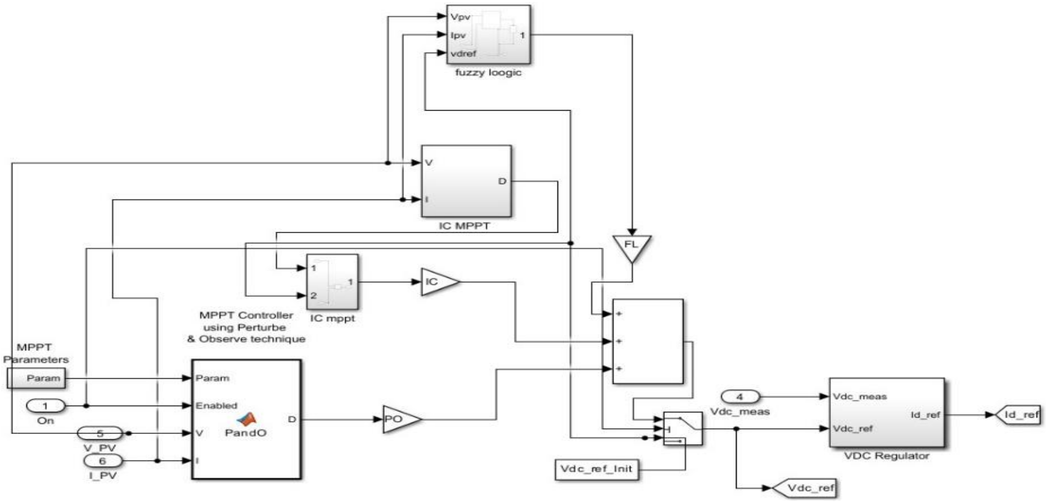


Figure 23 Simulink subsystem inverter model

1. Phase locked loop (PLL)

The phase-locked loop (PLL) is a closed-loop feedback control system that serves for synchronizing the phase and frequency of an output signal with those of a reference signal. It is widely employed in a wide range of electronic applications, such as networks of communication, frequency synthesis, and processing digital signals. A phase detector, a loop filter, a voltage-controlled oscillator (VCO), and a frequency divider are the four major components of a PLL (Dong, Wen, Boroyevich, Mattavelli, & Xue, 2014). The phase detector compares the phases of the reference and output signals and provides an error signal proportional to the phase difference between them. The loop filter filters the erroneous signal and produces a control voltage for the VCO.

The frequency of the output signal generated by the VCO is proportional to the control voltage. Finally, the frequency divider is used to separate the output signal's frequency and transmit it back to the phase sensor as a reference signal. The PLL works in a closed loop, which means that the output signal is constantly compared to the reference signal, and any phase or frequency errors are fixed by altering the control voltage applied to the VCO.

The design of loop filter influences the loop bandwidth, which influences the speed and accuracy of phase and frequency tracking. PLLs are widely utilized in a variety of applications, including clock recovery in digital systems, frequency synthesis in communication systems, and power converter synchronization in power electronics. They are also utilized in renewable energy systems for MPPT (Maximum

Power Point Tracking) control of inverters, where the PLL is used to match the inverter output with the grid voltage.

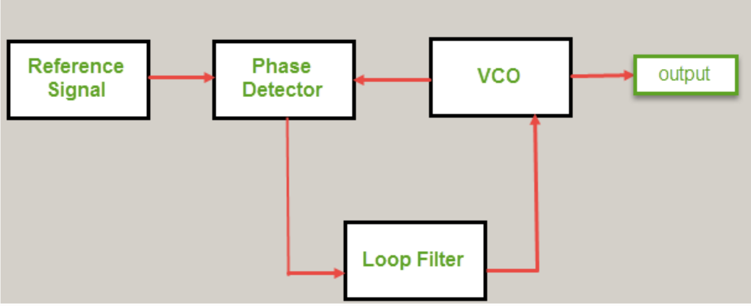


Figure 24 Block diagram of the PLL

2. Pulse width modulation (PWM)

PWM is a technique for controlling the power given to a load by adjusting the duty cycle of a square wave signal. In power electronics, PWM is widely used to manage the output voltage or current of a DC-to-DC converter, inverter, motor drive, or other power electronic devices. PWM operates by rapidly turning a power transistor on and off at a high frequency, often ranging from 1 kHz to 100 kHz. The average voltage or current given to the load is determined by the duty cycle, which is the ratio of the on-time to the whole period of the square wave signal. The output voltage or current can be changed by varying the duty cycle of the square wave. In a DC-to-DC converter, for example, the PWM signal is applied to a power transistor, which adjusts the duty cycle of the square wave to control the output voltage.

The typical voltage at the output increases as the duty cycle increases. PWM is also used to adjust the frequency and magnitude of the AC output voltage in an inverter or motor drive. PWM has several advantages, including great efficiency, precise control of output voltage or current, and reduced output ripple. In power electronics applications, PWM also enables the use of smaller, lighter, and more cost-effective components. PWM can be applied in a variety of ways, including sinusoidal, triangular, and space vector PWM. The PWM technology used is determined by application requirements such as output voltage quality, switching frequency, and control algorithm complexity (Lin, 1999).

3. DC voltage regulator

A DC voltage regulator is an electrical circuit that maintains a constant DC output voltage despite changes in input voltage or load current. Voltage regulators are often employed in power supply circuits to provide a stable and regulated DC voltage to electronic equipment. DC voltage regulators are classified into two types: linear voltage regulators and switching voltage regulators. The output voltage of a linear voltage regulator is controlled by a series pass transistor. A feedback loop is used to control the output voltage by altering the voltage drop across the series pass transistor.

The fundamental disadvantage of linear voltage regulators is their low efficiency, which is especially noticeable when the input voltage is significantly higher than the output voltage. Switching voltage regulators, often known as DC-DC converters, regulate the output voltage using pulse-width modulation (PWM) or other switching techniques. The input voltage is first transformed to a high-frequency alternating current signal, which is subsequently corrected and filtered to provide a steady direct current voltage. The duty cycle of the PWM signal is adjusted to control the output voltage.

Although switching voltage regulators are far more efficient than linear voltage regulators, they are also far more complex and loud. DC voltage regulators are utilized in a variety of applications, including electronic device power supply, battery chargers, voltage stabilizers, and voltage references. The usage prerequisites, such as input voltage range, output voltage precision, load current, efficiency, and cost, all influence the voltage regulator selection.

4. Current regulator

A current regulator is a type of electrical circuit that regulates the flow of electricity to a load. Current regulation is widely utilized in power electronics applications that demand precise control of the load current. Current regulators are used in power electronics to control the output current of DC-to-DC converters, motor drives, and other energy electronic circuits. Adjusting the duty cycle of a pulse width modulation (PWM) signal or the frequency range of a switching signal controls the output current. A feedback loop in a current regulator compares the actual load current to a reference current and modifies the PWM or switching signal correspondingly.

An operational amplifier, a microcontroller, or an isolated current control IC can be used to implement the feedback loop. Current regulators are classified into three types: linear current regulators, switching current regulators, and hysteretic current regulators. The application specifications, such as output current range, precision, efficiency, and response time, influence the choice of current regulator. Many applications rely on current management, including battery charging, LED lighting, motor control, and power factor correction. The efficiency and dependability of the system can be enhanced and the load's lifespan can be extended, by adjusting the current.

5. LC filter

Power electronics, audio circuits, and radio frequency applications all make extensive use of LC filters. The basic LC filter is made up of an inductor and a capacitor that are coupled in series or parallel. The inductor has a high resistance to high-frequency impulses and a low resistance to low-frequency signals, whereas the capacitor has a low resistance to high-frequency signals and a high resistance to low-frequency signals. The LC filter may efficiently reduce undesired signals while passing useful signals by selecting the right L and C values. Depending on the application, LC filters can be built as low-pass, high-pass, band-pass, or band-stop filters. The frequency range that is passed or blocked by the filter is determined by its cutoff frequency. LC filters are extensively used in power electronics to equalize the output voltage or current of a changing power supply, reduce electromagnetic radiation, and enhance power factor.

LC filters are used in audio circuits to remove distortion and noise from the audio stream. LC filters are used in radio frequency applications to select or reject specific frequency ranges. The key benefits of LC filters are their ease of use, low cost, and high reliability. They do, however, have certain drawbacks, including a limited frequency range, susceptibility to device tolerances, and a big size for applications that require considerable power. The effectiveness and type of filter utilized influence the quantity of harmonic components muted in a grid-connected solar PV system. Among the several types of filters described above, the first-order filter with only an inductor connected in series with the mains has grown in popularity in recent years. This is because it is simple, affordable, and does not have the resonance issues that two and three filters do. Despite the fact that it requires a large filter to provide appropriate harmonic diminution, such a filter is still a viable choice.

The high-frequency changing process of a VSI system model is ideal for this filter. The LC filter in VSI applications is a second-order filter that reduces frequencies at the inverter's output voltage. The LC filter depicted here is employed in both grid-connected and off-grid PV power systems. The resonance frequency of this sort of filter fluctuates with the grid's contained values, which is a big disadvantage. As a result, it must design its export LC-filter to reduce inverter oscillations while maintaining clean power to the grid.

IV. SIMULATION RESULTS AND DISCUSSION

To test the effectiveness of the three different MPPT algorithms, a simulation model was constructed using the MATLAB/Simulink environment. The model included a 250 kW PV array connected to a three-phase inverter, which in turn was connected to a 10 kV grid system. The inverter utilized Pulse Width Modulation (PWM) techniques to provide adjustable AC voltage magnitudes and frequencies. Three MPPT algorithms were employed in the inverter control unit to track the maximum power point of the PV array and optimize power output: Perturb & Observe (P&O), Incremental Conductance (IC), and Fuzzy Logic (FL).

A simulation model was built in the MATLAB/Simulink environment to examine the performance of the three distinct MPPT algorithms. A 250 kW PV array was connected to a three-phase inverter, which was then connected to a 10 kV grid system in the model. To deliver adjustable AC voltage magnitudes and frequencies, the inverter used Pulse Width Modulation (PWM) technique. To track the highest power point of the PV array and maximize power output, three MPPT algorithms were used in the inverter control unit: Perturb & Observe (P&O), Incremental Conductance (IC), and Fuzzy Logic (FL).

The P&O method is a basic but commonly used technique that perturbs the PV array operating point and records the change in power output before modifying the operating point to follow the maximum power point. The IC method is a more sophisticated technique that computes the difference in conductance between two neighboring operating points and adjusts the operating point to track the maximum conductance. The most complex technology is the FL algorithm, which utilizes a fuzzy logic controller to modify the operating point based on input factors such as irradiation and temperature. The efficiency of each method in various circumstances and under various conditions was evaluated using simulation data. The results revealed that all three algorithms were competent at tracking the PV array's greatest power point and maximizing power output. However, the FL algorithm performed the best, especially under situations of variable sun irradiance and temperature. In addition, various tests were carried out to examine the influence of disturbances on the proposed algorithms.

The results demonstrated that all three algorithms were resilient and capable of fast recovering from disturbances such as abrupt changes in irradiation and temperature. These findings show that advanced MPPT techniques can be used in PV systems to improve power output and increase system efficiency.

A. Simulation results when the irradiance is constant

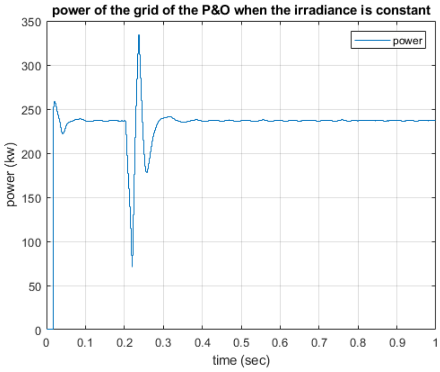


Figure 25. Power of the grid of the P&O when the irradiance is constant.

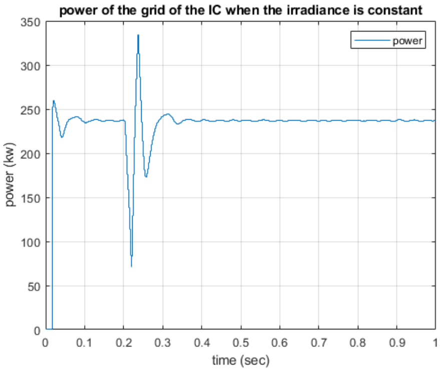


Figure 26. Power of the grid of the IC when the irradiance is constant.

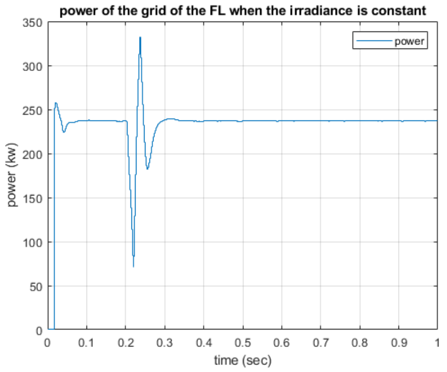


Figure 27. Power of the grid of the FL when the irradiance is constant.

B. Simulation results when the irradiance is changing

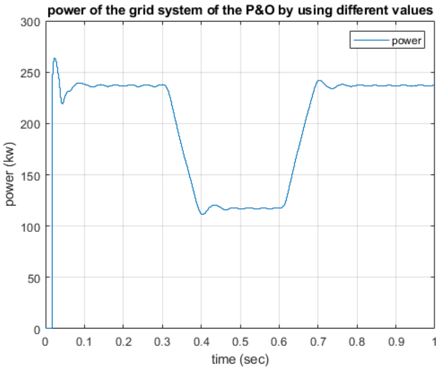


Figure 28. Power grid of the P&O by changing the irradiance from 1000 to 500 W/m² to 1000 W/m²

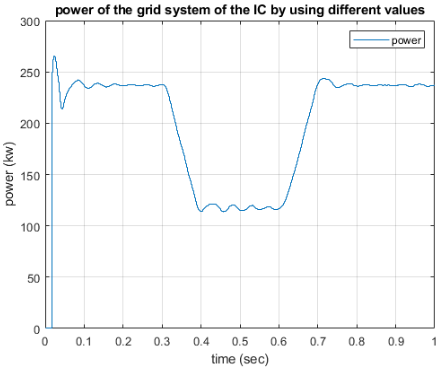


Figure 29. Power grid of the IC by changing the irradiance from 1000 to 500 W/m² to 1000 W/m² again.

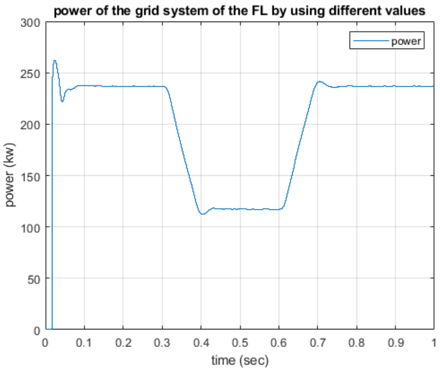


Figure 30. Power grid of the FL by changing the irradiance from 1000 to 500 W/m² to 1000 W/m² again.

C. Simulation results when the fault happen in 0.5

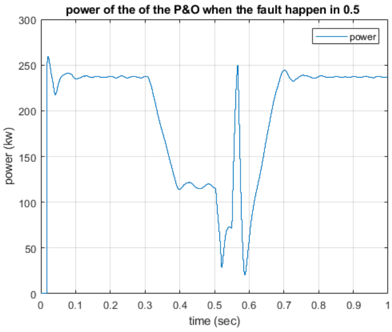


Figure 31. Power grid of the P&O when the fault happen in 0.5.

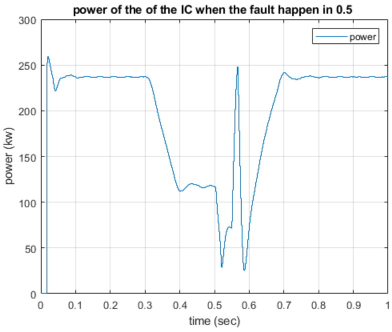


Figure 32 Power grid of the IC when the fault happen in 0.5.

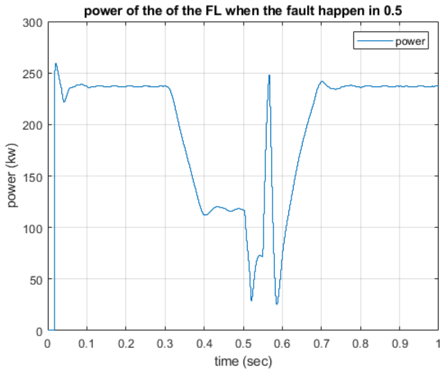


Figure 33. Power grid of the FL when the fault happen in 0.5.

D. Simulation results when the irradiance is constant at 1000 W/m²

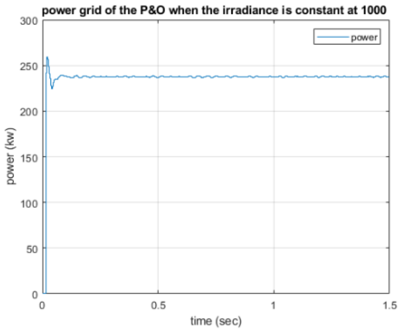


Figure 34. Power grid of the P&O when the irradiance is constant at 1000W/m².

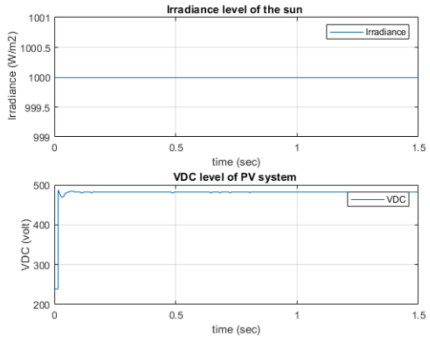


Figure 35. The irradiance and DC voltage level.

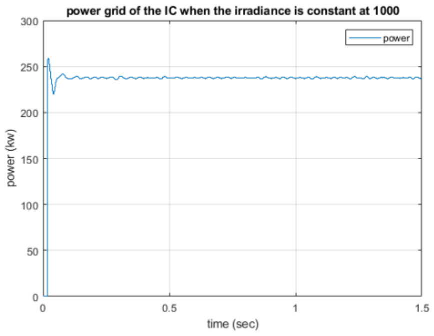


Figure 36. Power grid of the IC when the irradiance is constant at 1000W/m².

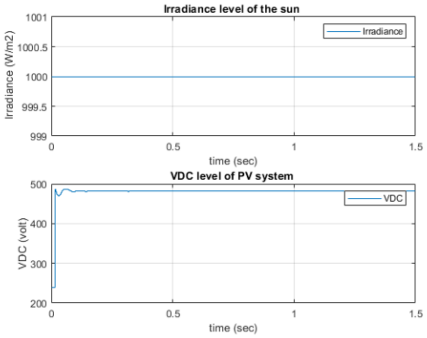


Figure 37. The irradiance and DC voltage level.

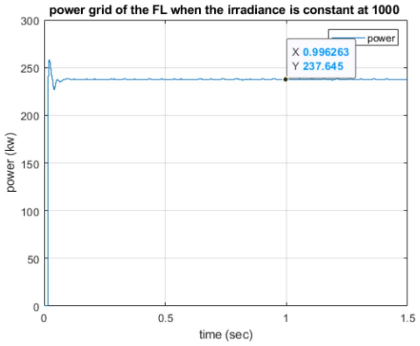


Figure 38. Power grid of the FL when the irradiance is constant at 1000W/m².

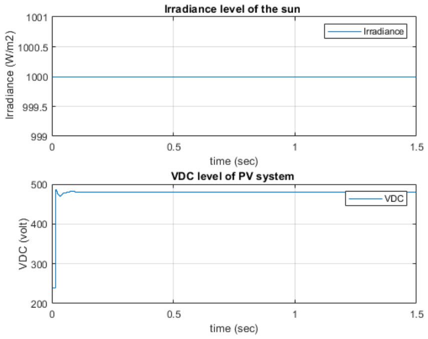


Figure 39. The irradiance and DC voltage level.

E. Simulation results when the disturbance is from 0.5s to 0.6s

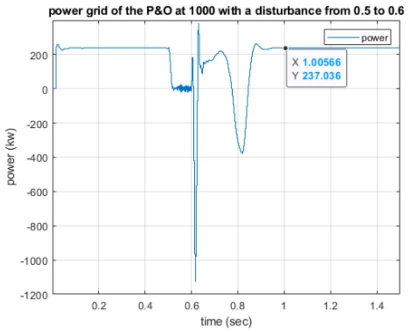


Figure 40. Power grid of the P&O when the irradiance is constant at 1000W/m² with a disturbance from 0.5 to 0.6.

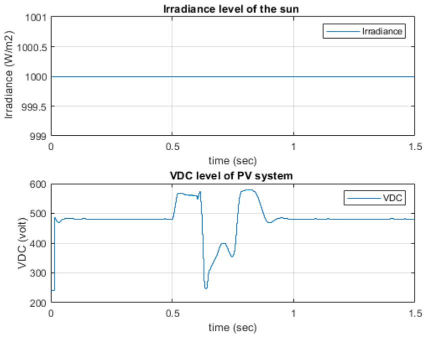


Figure 41. The irradiance and DC voltage level of the

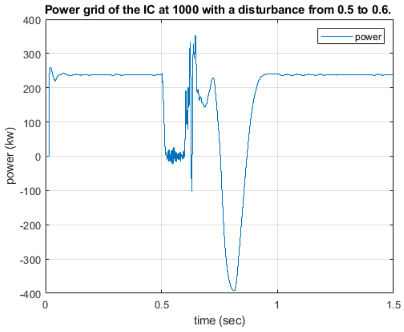


Figure 42. Power grid of the IC when the irradiance is constant at 1000W/m²

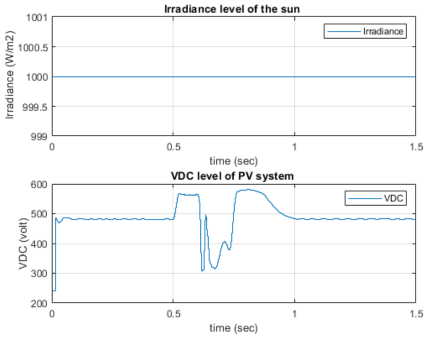


Figure 43. The irradiance and DC voltage level of the

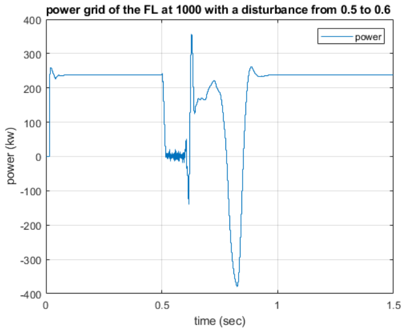


Figure 44. Power grid of the FL when the irradiance is constant at 1000W/m² with a disturbance from 0.5 to 0.6.

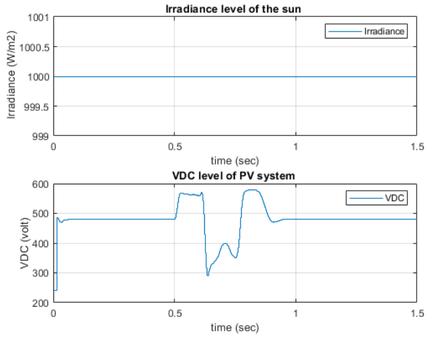


Figure 45. The irradiance and DC voltage level of the

F. Discussion

The preceding sections provide a thorough examination of the performance of various maximum power point tracking (MPPT) methods in a grid-connected solar energy system. The simulation findings reveal that the irradiance level and system disruptions influence grid power output. As seen in the first three figures, when the irradiance is constant, the three MPPT algorithms offer a stable grid power output of roughly 250 KW. When the solar energy input is consistent, the algorithms are excellent in managing the power output. However, lowering the irradiance value from 1000 W/m2 to 500 W/m2 reduces grid power production to 120 KW. This drop in power production is most likely caused by a decrease in solar energy input.

When a failure occurs in 0.5 seconds or less, the system remains steady and unperturbed by the disturbances. When the disturbance happens around 0.5 and 0.6 seconds at an irradiation level of 1000 W/m2, the system experiences power output fluctuations. The system is clearly damaged by the disturbance in this scenario, but it quickly recovers power output. The simulation findings show that the MPPT techniques incremental conductance (IC) and perturb & observe (P&O) function similarly at high and low irradiance levels. However, changes in output power are possible.

In contrast, the fuzzy logic (FL) MPPT technique provides consistent output power in both high and low irradiation conditions. A fuzzy logic controller is used in the FL technique to modify the point of operation of the PV array based on input factors such as irradiance and temperature. To make judgments and optimize power production, the controller employs linguistic variables and rules. In all, the simulation findings indicate that the fuzzy logic technique may be the most successful in providing a stable power output in a grid-connected solar energy system, particularly under variable irradiance levels. However, the choice of MPPT algorithm will be influenced by a variety of factors such as cost, complexity, and specific system needs. The study's findings are useful for designing and optimizing grid-connected solar energy systems.

V. CONCLUSİON AND PROPOSALS

A. Conclusion

A grid-connected PV system has been examined and simulated in this work using MATLAB/SIMULINK. The major goal was to track the highest power point using the suitable MPPT algorithm, which is critical for increasing the system's power output. We used a comparable model and three different strategies to do this: Perturb & Observe (P&O), Incremental Conductance (IC), and Fuzzy Logic. To develop a high-fidelity model of the system, PV panels, a boost converter, a three-phase inverter, and the power grid were experimentally modeled. The findings of the research revealed that the MPPT fuzzy logic approach beat both the P&O and IC strategies. The influence of illumination on multiple algorithms was attributed to this. The fuzzy logic strategy proved more effective than the other two strategies at adapting to variations in irradiance, resulting in enhanced performance and greater power production.

The study also assessed how the system performed under various levels of irradiance and disruptions. According to the simulation results, the IC and P&O algorithms delivered a consistent grid power output under a variety of irradiance levels, albeit with occasional swings in output power. When disturbances such as spikes in voltage and temporary faults occurred, however, the fuzzy logic algorithm surpassed the other two techniques by giving a stable output power. As a result, the fuzzy logic technique was found to be more appropriate for providing consistent power generation in grid-connected photovoltaic systems, especially when irradiance rates and disturbances vary. In conclusion, this work sheds light on the construction and maintenance of grid-connected PV systems. The high-fidelity modeling and analysis of several MPPT strategies revealed that the fuzzy logic strategy is remarkably beneficial for optimizing power production and assuring consistent power output under varying situations. These discoveries can be utilized to boost the effectiveness and reliability of future PV systems, as well as to encourage the widespread use of solar energy as a sustainable energy source.

B. Future work proposals

- Development and testing of a physical model for an MPP based on the fuzzy logic controller technique using microcontrollers. A general-purpose microprocessor or microcontroller is the most frequent technique to build a fuzzy controller.
- Investigating the digital protection mechanism required for the PV/grid network.
- Comparing alternate inverter control methods and their effect on the quality of electricity from the standpoint of the utility grid.
- Investigating the effect of power quality fluctuations on the reliability of maximum power point tracking devices.
- Using an optimization method, such as the Genetic Algorithm with Fuzzy controllers, to decrease the rules of the controller.
- Examine the effect of several inverters linked to a local grid on grid performance (power quality).
- Photovoltaic Grid-Connected Systems with Smart Grid.

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