Modeling and Evaluation of MPPT Methods for a Three-Port Converter Used in PV Applications

EFFAT UNIVERSITY
COLLEGE OF ENGINEERING
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING (ECE)

Modeling and Evaluation of MPPT Methods for a Three-Port Converter Used in PV Applications

A thesis submitted in partial fulfillment for the degree of Master's in Science in Energy Engineering (MSEE) per the requirements of Effat University

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I. APPROVAL PAGE

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This thesis, written by **Amani Saad Alzahrani** under the direction of her thesis supervisor and approved by her thesis committee, has been presented to and accepted by the Dean of Graduate Studies and Research on May 22, 2022, in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Energy Engineering.

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I hereby declare that this thesis titled **" Modeling and Evaluation of MPPT Methods for a Three-Port Converter Used in PV Applications"** is based on my original work, except for quotations and citations being duly acknowledged. I also declare that the proposed dissertation has not been previously or concurrently submitted for the award of any degree at Effat University or any other university or institution.

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Abstract

Worldwide energy demand is growing fast because of the population explosion. Technological advancement paved the way toward utilizing renewable energy sources instead of fossil fuels as they cause harmful effects on the environment. Among all renewable sources, solar energy is a promising source. Solar energy is captured by photovoltaic (PV) arrays that convert the sunlight into electricity that powers the load. Since sunlight is not always available, a battery is utilized to power the load as a backup power source. Both PV and battery are interfaced with the load using a power converter. A Three-Port Converter (TPC) has recently gained interest in the literature. The TPC interfaces the PV and the battery with the load. It is less expensive and more efficient than using two separate power converters for the PV and the battery. However, a system with TPC connecting a PV array and a battery to a load could be further enhanced by applying Maximum Power Point Tracking (MPPT) techniques to the TPC. By applying MPPT, the PV arrays are guaranteed to operate at the maximum power they can deliver. This thesis aims to simulate a system with a TPC and apply different MPPT techniques (Perturb and Observe P&O and Incremental Conductance (IC) to the TPC. Based on the resultant simulation, these techniques are compared based on their response to the environmental changes (radiation and temperature) to identify the most suitable MPPT technique for a TPC. The topological structure of the TPC is identified based on a comparison with the available TPC topologies. The comparison is based on topology complexity, efficiency, and control complexity. To achieve this aim, three steps are followed. The first step is simulating a case study of an existing PV system is considered to illustrate the importance of applying MPPT to PV systems. Namely, the PV system installed at Effat library rooftop is simulated using MATLAB/SIMULINK with and without the MPPT. The simulation shows that applying MPPT increases the system efficiency up to 99%. The second step compares the PV power of a system of the two-port converters and a system of TPC when the solar irradiance changes. In the last step, TPC is simulated in MATLAB/SIMULINK, and MPPT methods (P&O and IC) are applied. Based on the simulation, both MPPT methods exhibit similar results when the radiation and temperature change. However, the IC method performs slightly better than P&O. Hence, IC has a better response to environmental changes than P&O. The significance of this work relies on enhancing TPC used in PV applications by applying MPPT. This field has not been much investigated in the literature.

Keywords—Three-Port Converter, PV/Battery Systems, Maximum Power Point Tracking (MPPT), MATLAB/SIMULINK

الرسالة ملخص

ليتم المتجددة الطاقة مصادر أمام الطريق مهد التكنولوجي التقدم .المتزايد السكاني بالنمو متأثرًا تزايد حالة يشهد الطاقة على العالمي الطلب الطاقة مصادر تتعدد .البيئة على الملحوظة أضرارها لها المواد هذه أن حيث الأحفورية المواد من المستخصلة للطاقة كبديل استخدامها طاقة إلى الشمسية الطاقة تحول والتي الشمسية الخلايا طريق عن الشمسية الطاقة من الاستفادة يتم .الشمسية الطاقة أهمها من ولعل المتجددة، .الشمسية الطاقة توفر عدم عند احتياطي طاقة ككمصدر البطاريات استخدام يتم كله، اليوم خلال متوفرا ليس الشمسي الشعاع أن بما .كهربائية بحيث المنافذ ثلاثي طاقة محول اقتراح تم مؤخرا، .منهما لكل طاقة محول باستخدام الحِمل مع توصيلهم يتم والبطارية الشمسية الخلية من كلا الشمسية الخلية من لكلا اعتياديين طاقة محولين استخدام عن عوضا والحمل البطارية، الشمسية، الخلية من كل لتوصيل استخدامه يتم من بالرغم .والبطارية الشمسية الخلية من لكل منفصلين محولين استخدام من كفاءة وأكثر تكلفة أقل يعد المنافذ الثلاثي المحول .والبطارية يمكن التقنيات، هذه باستخدام .قدرة أقصى تتبع تقنيات استخدام طريق عن المنافذ الثلاثي المحول على المحتوي النظام تحسين يمكن ذلك، واستخدام المنافذ ثلاثي محول على يحتوي نظام محاكاة إلى تهدف الرسالة هذه .القدرة من يمكن ما أعلى تنتج الشمسية الخلية أن من التأكد ، المناخية للتغيرات الاستجابة على بناء التقنيات هذه بين المقارنة عملية تتم المحاكاة نتائج على وبناء .قدرة أقصى تتبع من مختلفة تقنيات شكل اختيار تم البداية في .المنافذ الثلاثي المحول مع استخدامها ليتم الأنسب التقنية تحديد يمكن ثم ومن .الشمسي والشعاع الحرارة تحديدا هدف لتحقيق .التحكم وتعقيد الكفائة، الشكل، تعقيد حسب تمت المقارنة .المقترحة الأشكال من عدد بين مقارنة عمل بعد المنافذ الثلاثي للمحول شمسية خلايا نظامي بين المقارنة طريق عن قدرة أقصى تتبع تقنيات أهمية من التحقق هي الأولى الخطوة .خطوات ثلاث اتباع تم الرسالة، أظهرت .سيمولينك/ماتلاب برنامج في المحاكاة إجراء وتم كنموذجا عفت جامعة مكتبة في الموجود النظام اختيار تم .التقنيات هذه وبدون مع باستخدام شمسية خلايا نظامين أداء بين المقارنة هي الثانية الخطوة .قدرة أقصى تتبع تقنيات تطبيق بعد كفاءة أعلى يحقق النظام أن النتائج من مختلفتين تقنيتين بين المقارنة هي والأخيرة الثالثة والخطوة .أخرى مرة المنافذ الثلاثي المحول وباستخدام مرة عاديين كهربائيين محولين التقنية لصالح طفيف فارق مع الشمسي الشعاع تغيير عند متقاربة نتائج إلى أدتا التقنيتين فإن المحاكاة نتائج على وبناء قدرة أقصى تتبع تقنيات تتم لم الأهمية وهذه .قدرة أقصى تتبع تقنيات باستخدام المنافذ الثلاثي المحول على المعتمدة الأنظمة تحسين في تكمن الرسالة هذه أهمية .الثانية المنشورة الأبحاث في باستفاضة دراستها

سيمولينك/ماتلاب قدرة، أقصى تتبع تقنيات البطارية، مع الشمسية الخلية أنظمة المنافذ، الثلاثي المحول **:المفتاحية الكلمات**

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF TERMS

FOCV: Fractional Open-Circuit Voltage
IC: Incremental Conductance
MPP: Maximum Power Point
MPPT: Maximum Power Point Tracking
P&O: Perturb and Observation
PV: Photovolatic
STC: Standard Test Condition
TPC: Three-Port Converter
SISO: Single-Input, Single-Output
SIDO: Single-Input, Double-Output
DISO: Double-Input, Single-Output

CHAPTER 1: INTRODUCTION

A. *Overview*

1) *General Overview*

The world is shifting toward renewable energy sources instead of fossil fuels which contributes significantly to the carbon dioxide CO_2 emission [1]. The shift toward renewables is strengthened by international policies and agreements such as the 26^{th} U.N. Climate Change Conference of the Parties (COP26) in late 2021. One primary goal of COP26 is to reduce worldwide emissions to reach zero by the middle of the century. Hence, renewable energy is a vital key player in achieving this critical goal [2]. According to the International Energy Agency (IEA), almost 290 gigawatts G.W. of power will be generated from renewable sources in 2021, where solar Photovoltaic (PV) accounts for half of the expansion of renewable energy [1]. Figure 1.1 shows installed solar energy capacity from 1996 to 2020 [3].

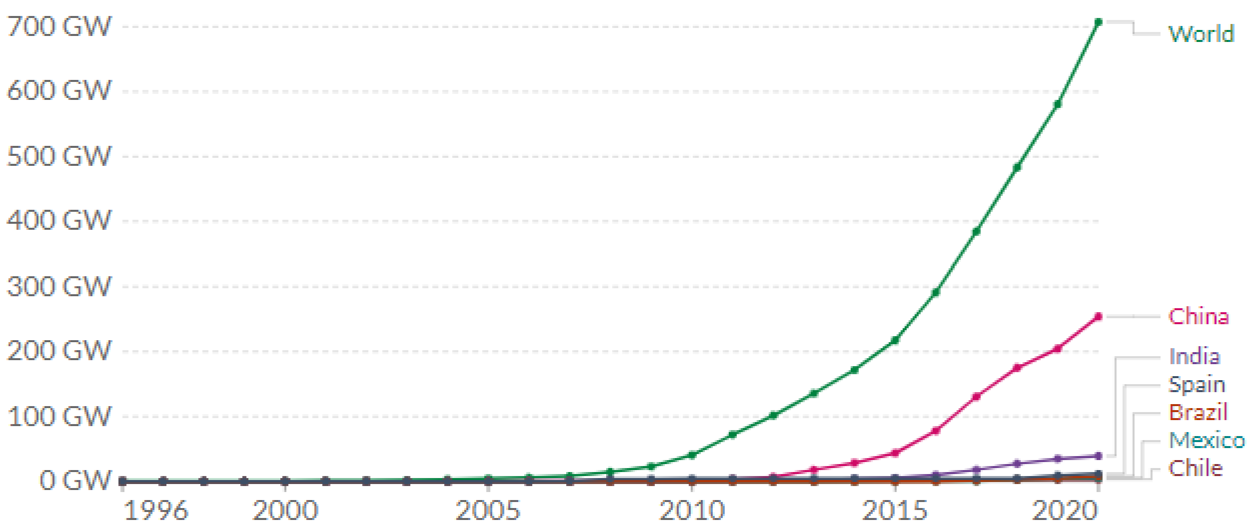

Figure1.1 Solar PV Generation Growth 2000-2030 [3]

In 2022, solar photovoltaic (PV) is expected to increase by annual growth of 162 GW, almost 50% higher than the recorded pre-pandemic level in 2019 [4]. The most significant advantage of solar PV is zero air pollutant emission during the operation [5].

2) *Solar PV Overview*

Solar photovoltaic is one solar energy category as solar energy sources are classified as either passive or active solar systems. An example of a passive solar system is the thermosiphon hot water shown in

Figure 1.2, the lens in the solar collector concentrates the sunlight. It directs it to the water tubes, so its temperature increases. Then, the warm water is delivered to the building (such as a house) when needed. The tank is refilled again with cold water, and the process of warming the water continues [6].

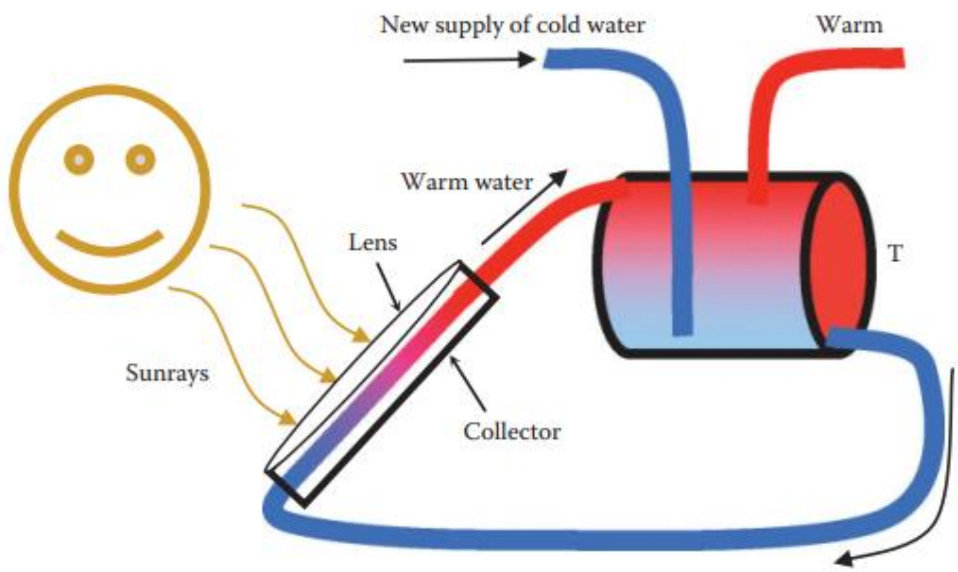

Figure 1.2. Schematic diagram of a thermosiphon hot water [6]

The main advantages of passive solar systems are the low cost and easy placement [7]. However, it requires high sunlight density to operate [6].

In active solar systems, the sunlight is utilized and transferred to another form of energy; electricity [8]. Solar PV is an active solar system that depends on the photovoltaic effect [6]. Edmond Becquerel first discovered this effect; a nineteen-year-old man working in his father's laboratory in 1839 discovered the photovoltaic effect while playing around with the voltaic cell. Becquerel reported in a French scientific journal called: '*Les Comptes Rendus de I'Academie des Sciences*' that an electric current is produced when exposing two plates to solar radiation. These plates are either platinum or gold and have been diving in acid, neutral, or alkaline solutions [9], [10], [11].

The term 'Photovoltaic' is derived from the Greek word phōs which means light, and the word volt was named after the physicist Alessandro Volta [12]. Alfred Smee first proposed this term in 1849: "Upon exposing the apparatus to intense light, the galvanometer was instantly deflected showing that the light had set in motion a voltaic current which I propose to call a photovoltaic circuit," a definition written by Smee's book titled: "*Elements of Electro-biology, Or the Voltaic Mechanism of Man of Electro-pathology, Especially of the Nervous System and of Electro-therapeut*ics" [9], [12], [13].

Charles Fritts proposed the first solar cell in 1883. The solar cell was composed of selenium and coated by a transparent gold layer [9]. This solar cell has a very low conversion efficiency (around 1%) [14].

The principle of the PV effect is based on the displacement of electrons which creates the electrical current. This displacement is caused when the photons (the light particles) excite the outermost (valence) electrons of a semiconductor material [15]. Semiconductor materials include several elements, such as silicon Si, the most common semiconductor material used in solar PV cells [16]. The octet rule states that an atomic shell is completed with eight electrons [17]. A Si atom has four electrons at the valence shell. Hence, there is a space for four other electrons to achieve the octet rule. As a result, the Si atom bonds with the other four Si atoms to achieve the octet rule by forming a crystal structure, as demonstrated in Figure 1.3 [6].

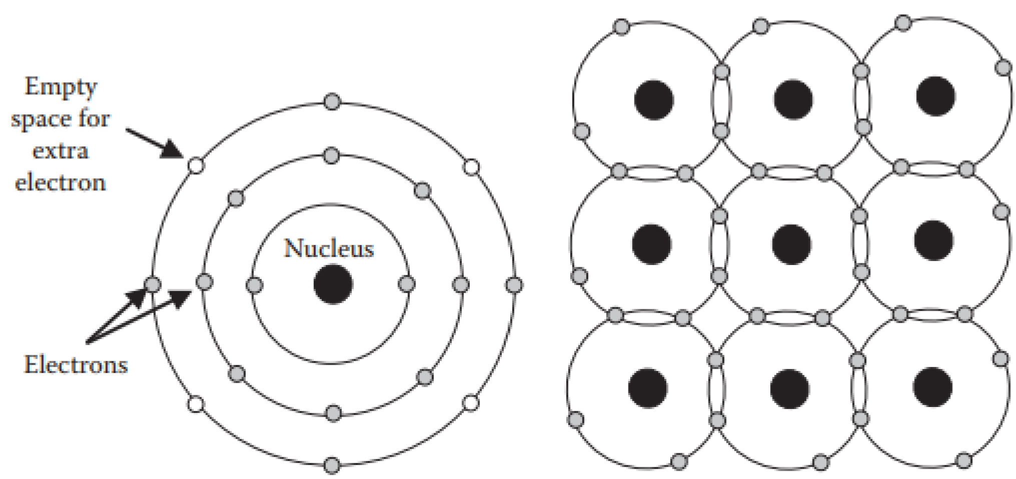

Figure 1.3. Silicon atom and silicon crystal structure [6]

The crystal structure of the silicon is a good insulator since all the electrons are used in the bonding [6]. Impurities (additives) atoms are added to Si to form a p-n junction in a process called *Doping.* These additives are elements from either the III group (such as phosphorus P) or the V group (such as boron B) [18]. The phosphorus-silicon compound is classified as an n-type since a free electron is in the structure. In contrast, the boron-silicon compound is classified as a p-type since there is a hole in the structure [19].

When the p-type and n-type structures are attached, a p-n junction or diode is created. This junction is the main component of a PV cell. An electrical current flows when the sunlight irradiates the p-n junction. The absorption of the photons generates an electron-hole pair at the p-n junction. The electrons are accelerated toward the n-doped region, and the holes are accelerated toward the p-doped region. This working principle of the solar cell is shown in Figure 1.4, where hv represents the photon energy (h is Planck's constant and v is the light frequency [19], [20].

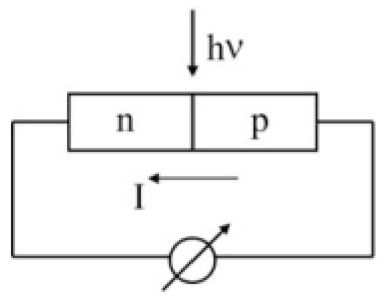

Figure 1.4. Photovoltaic effect on a p-n junction [19]

The representation of a p-n junction (diode) is demonstrated in Figure 1.5. [6]

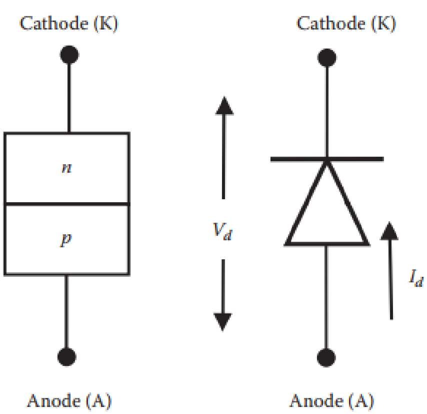

Figure 1.5. The representation of a p-n junction [6]

The IV curve demonstrates the output characteristics of PV cells, modules, strings, and arrays when all the solar cells are tested under uniform conditions. Figure 1.6 shows the IV curve [21]. The graph shows four values that represent PV output characteristics. These values are [22]:

- V_{oc}: The open-circuit voltage is measured when there is no output current due to the output terminal being open-circuited
- I_{sc}: The short-circuit current, measured when the PV generator terminal is short-circuited
- I_{MPP}: The measured current at Maximum Power Point (MPP)

V_{MPP}: The voltage at Maximum Power Point (MPP)

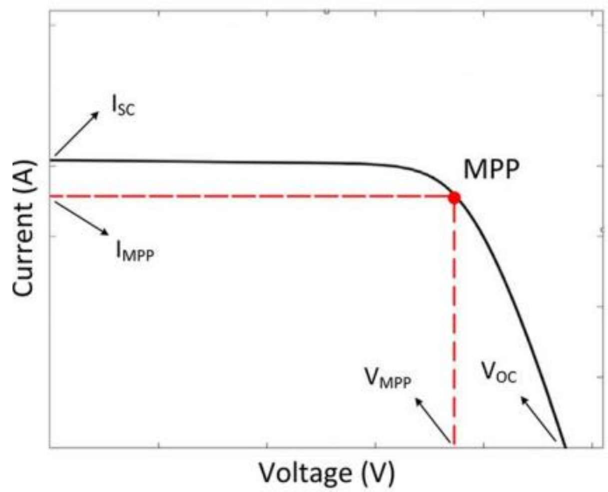

Figure 1.6. IV Curve of a solar PV [23]

As previously discussed, a solar cell could be viewed as a diode without a voltage source; instead, light photons are the energy source. The characteristic of a diode and the equivalent circuit is shown in Figure 1.7 [6].

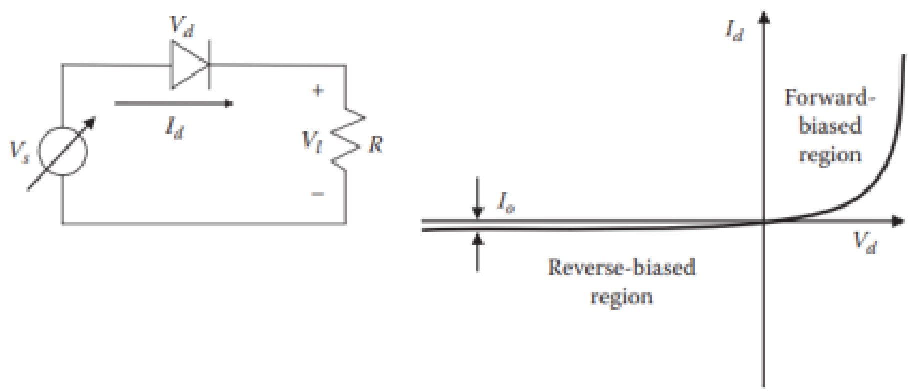

Figure 1.7. Diode characteristic [6]

The equations that describe the above graph are as shown below [6]:

$$I_d = I_o(e^{\frac{V_d}{V_T}} - 1) \quad 1.1\ [6]$$

$$V_T = \frac{kT}{q} \quad 1.2\ [6]$$

Where I_o is the reverse saturation current of the diode, V_d is the voltage across the diode, V_T is the thermal voltage, q is the charge of one electron, T is the absolute temperature, and k is Boltzmann's constant [6].

As stated earlier, a solar cell is a diode, with the sun being the energy source. This fact is illustrated in Figure 1.8 [6].

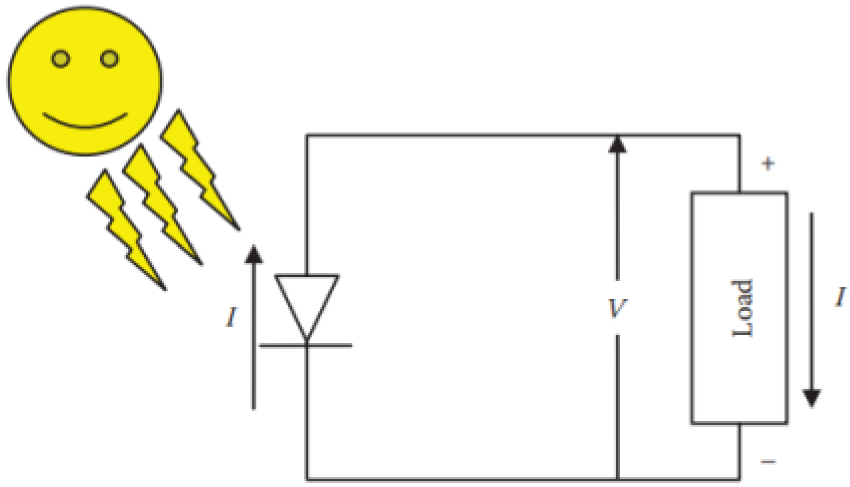

Figure 1.8. Representation of a solar cell connected to load [6]

Then, the current flows from the diode's n-junction to the p-junction into the load. This current flow creates an interesting phenomenon; it makes the upper terminal of the load positive with respect to the lower terminal. As a result, the diode now has a positive voltage on its anode with respect to the cathode. This voltage is called forward-biased voltage, which causes a forward current to flow back into the diode. Currently, there are two currents in the circuit. First: the current goes out of the diode due to the acquired energy by the sun. Second: the current going into the diode due to the positive polarity across the load. This confusion is resolved by creating a model where the two current sources are separated. This model represents the PV's acquired energy by an electric current source whose magnitude depends on the solar power density (irradiance), as shown in Figure 1.9 [6].

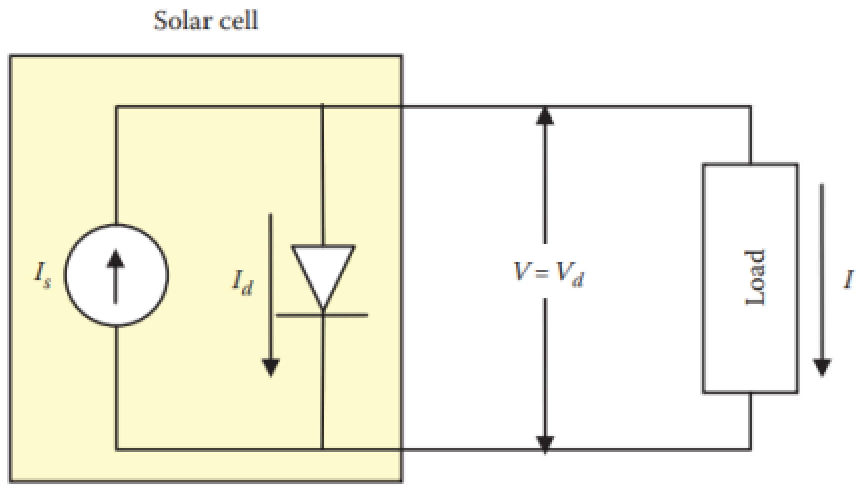

Figure 1.9. Modeling of ideal cell with a current source [6]

The current that goes through the diode can now be expressed by the previously mentioned equation. The load current is the remaining current which could be calculated as:

$$I = I_s - I_d \quad 1.3\ [6]$$

Where I_s is the solar current, I_d is the current through the diode, and I is the load current (output current). The load voltage V is equal to the forward voltage across the diode V_d [6].

$$V = V_d \quad 1.4\ [6]$$

Assuming solar current and load voltage are independent, the current-voltage (I–V) characteristics could be drawn as shown in Figure 2.10 [6].

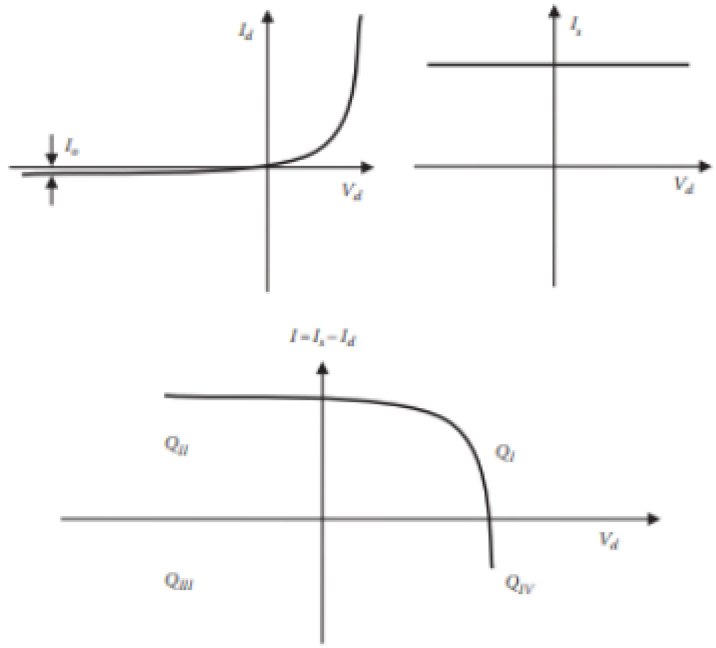

Figure 1.10. Current–volt characteristics of the PV cell [6]

The PV cell operates in the first quadrant Q_I. Q_{II} and Q_{IV} are not considered realistic operational regions because the load would be sending power to the solar cell in these quadrants. Since the solar cell can be viewed as a diode, the I-V characteristics are described by equations II.1, II.4, and II.3 [6]

The electrical power could be calculated by using the formula $P = IV$. Hence, solar cells' power-voltage characteristic is as follows [6]:

$$P = VI = V_d I_s - V_d I_o (e^{\frac{V_d}{V_T}} - 1) \qquad 1.5\ [6]$$

Both characteristics are shown in Figure 1.11. When the load current is zero, the PV voltage is at its maximum value, which is known as open-circuit voltage (V_{oc}). At zero voltage, the output current of the PV is called short circuit current (I_{sc}).

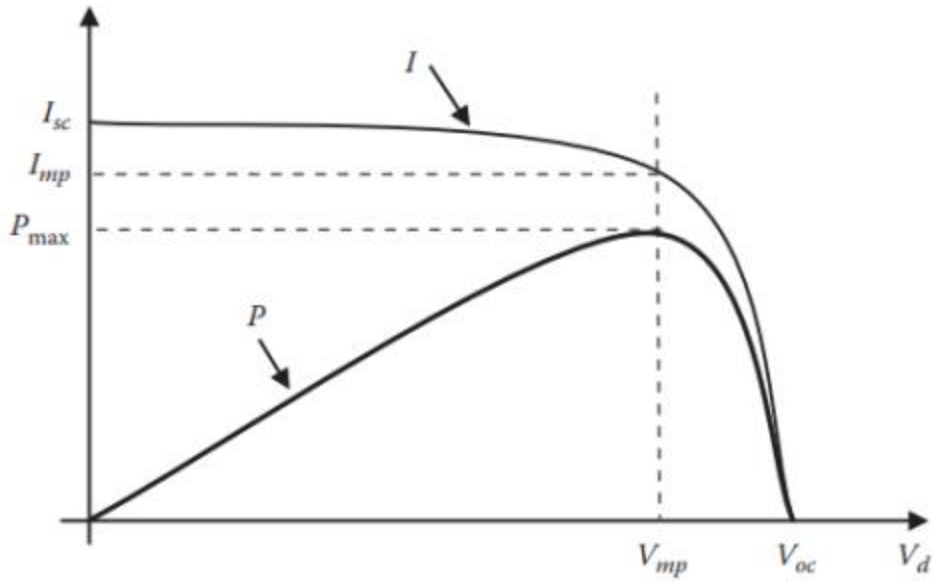

Figure 1.11. Current-voltage and power–voltage characteristics of a PV cell [6]

The above graph shows the maximum power point P_{max} which is the production of V_{MP} and I_{MP}. P_{MP} occurs when the differential power with respect to the voltage is zero, as shown in Figure 1.12 [24].

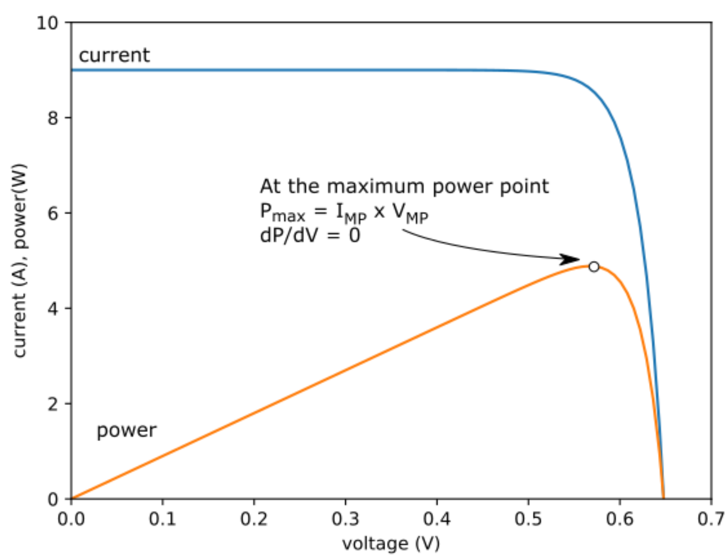

Figure 1.12. Pmax in the IV & PV Curve [24]

A single solar cell generates a small quantity of electricity. Hence, solar cells are usually grouped by connecting them in series or parallel to increase the voltage, current, and power. Figure 1.13 shows how a group of cells is called a module. A group of modules is a panel. Finally, a group of panels forms an array.[25]

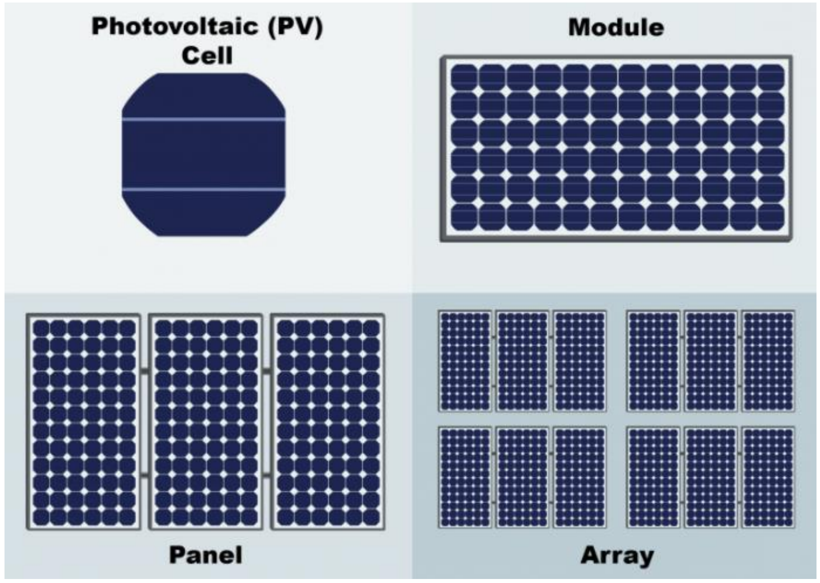

Figure 1.13. A PV cell, module, panel, and array [25]

Commercially, there are three main types of PV cells. Monocrystalline silicon, polycrystalline silicon, and amorphous silicon [14].

- **Monocrystalline silicon**: The first commercial solar cells were monocrystalline silicon cells formed by a single silicon layer. Monocrystalline silicon cells are usually referred to as silicon cells which is the most efficient technology. A typical monocrystalline silicon panel converts approximately 15%-20% solar energy to electrical energy. Unfortunately, the production of such a panel is a complicated procedure. Hence, the cost of these panels is slightly more than the other available technologies [26], [27], [28], [29].
- **Polycrystalline silicon**: This type of cell dominates the market. Around 70% of global PV production in 2015 was polycrystalline silicon cells. The recorded efficiency is in the neighborhood of 15%, a relative value to the monocrystalline PV efficiency. This type is cheaper since the construction process is more straightforward than the previous one but slightly less efficient [30], [31], [28].
- **Thin-film:** Besides crystalline PV cells, another category is thin-film PV cells. These cells are more flexible, durable, and lightweight, so thin-film cells can fit easily on different surfaces to convert sunlight into electricity [32]. However, the efficiency of this type is lower than the other two [29].

According to the International Renewable Energy Agency (IRENA), the Levelized cost of electricity (LCOE) generated from PV was reduced by 85% from 2010 to 2020, from USD 0.381/kilowatt-hour (kWh) to USD 0.057/kWh 2020. Cost reduction is driven by advancements in PV system technologies [33].

Despite these advancements, the PV industry still faces critical challenges. These challenges can be summarized in the following points:

- **PV module lifespan:** typically, the lifespan of an installed PV module is around 20 years if it is operating at 80% of the rated power. However, several studies have indicated the actual lifespan is reduced by 0.2% per year from the reported lifespan by the manufacturers. This reduction is primarily because the rapid weather conditions affect the PV module voltage [14].
- **PV cell efficiency:** the output of a PV cell is varied according to surrounding conditions. These conditions include temperature and irradiance. The effect of these two conditions on the IV curve is demonstrated in Figure 1.14 [34].

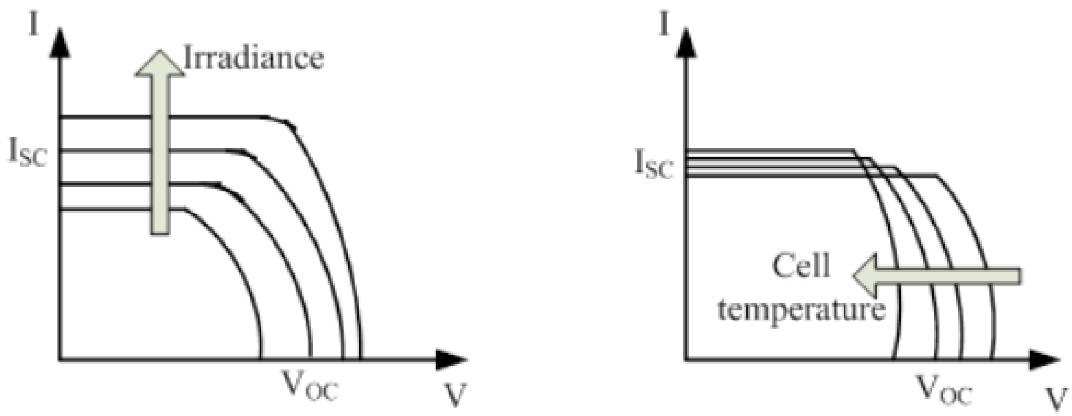

Figure 1.14. Changes in the IV curve due to changes in the temperature and irradiance [34]

As the irradiance increases, both the open-circuit voltage V_{oc} and the short-circuit current I_{sc} are increasing, resulting in a higher output power since more photons are hitting the solar cell. However, V_{oc} is decreased as the temperature increase, whereas I_{sc} is slightly increased. Hence, the overall effect is that the power is reduced as the temperature increases [34], [14]. The varied weather condition shifts the Maximum Power Point (MPP) P_{max} which is a unique point that shifts according to weather conditions [14].

3) *DC-DC Converter and Maximum Power Point Tracking (MPPT) Overview*

As mentioned in the previous section, PV efficiency is a challenging aspect of a PV project. One way to increase this efficiency is to operate at MPP by utilizing Maximum Power Point Tracking (MPPT) techniques. These techniques are applied to a DC-DC converter connected to the PV array, as shown in Figure 1.15 [35].

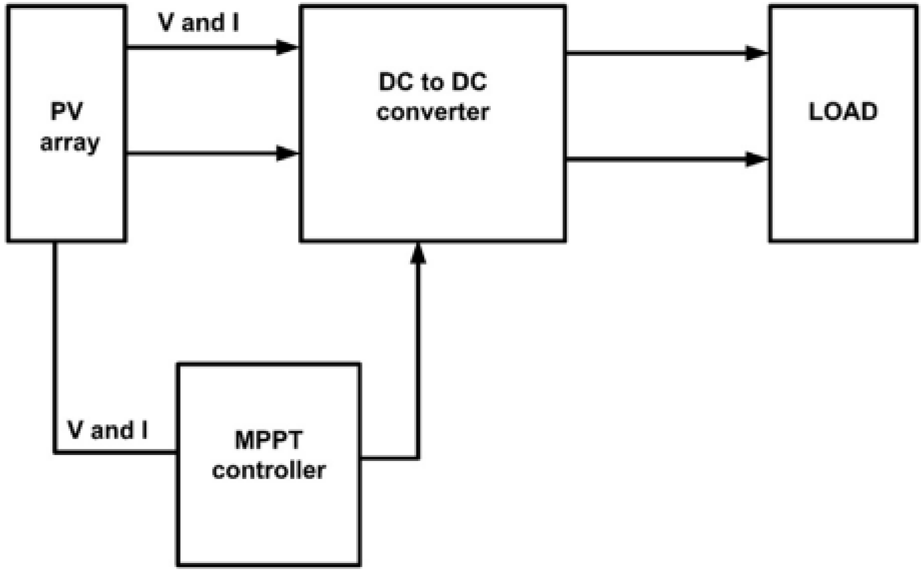

Figure 1.15. Block diagram of a DC-DC converter with an MPPT controller [35]

DC-DC converters are vital to power electronic components in solar PV projects [36], [37]. The relation between the converter's input and output determines the converter type. Converter types are summarized in Figure 1.16 [38].

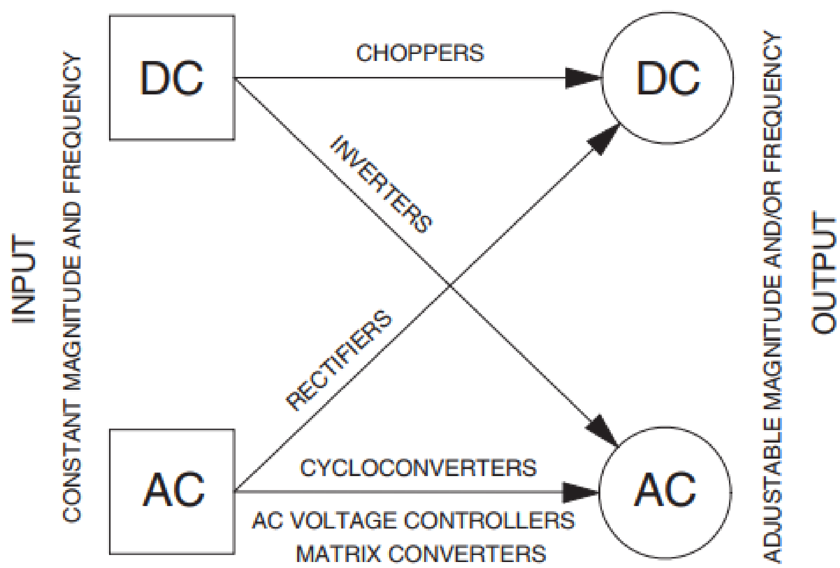

Figure 1.16. Converter types [38]

Generally, a power converter consists of switches that go ON and OFF. The converter's duty ratio is the period when the switch is ON with respect to a time interval [38], [37]. As the name suggests, a DC-DC converter converts a D.C. to D.C. and can be simply named a D.C. converter [37].

The main principle of an MPPT method is to vary the converter's duty ratio, so the ratio of the output voltage to the input voltage varies accordingly [35].

The general scheme of a PV array connected to a DC-DC converter is shown in Figure 1.17 [36].

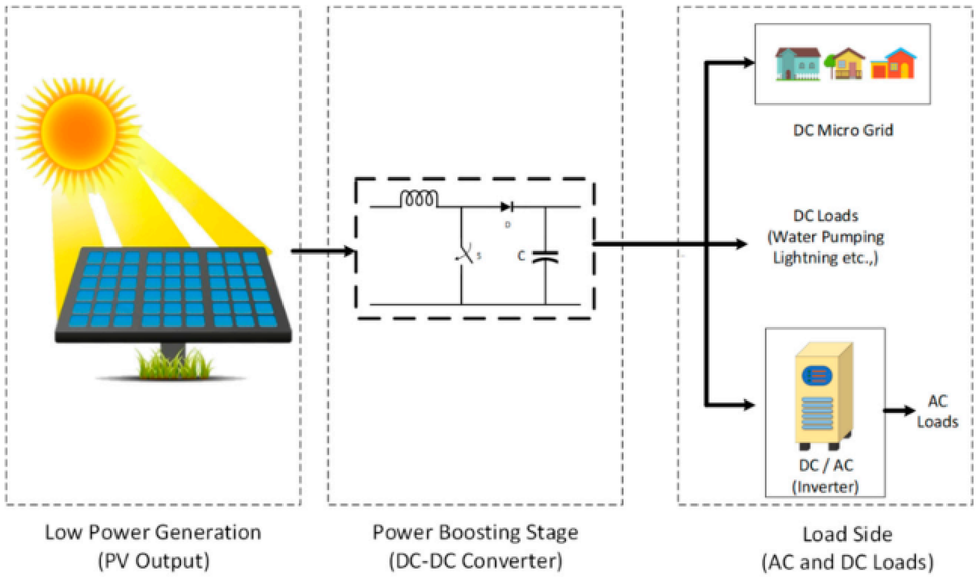

Figure 1.17. A PV array connected to a DC-DC converter [36]

There are many topologies for the DC-DC converters. These topologies could be classified into two main categories: isolated and non-isolated. The first category, a high-frequency transformer, is used as an electrical barrier between the input and output to protect sensitive loads and is generally used for high voltage applications. Whereas in the latter category, a transformer is not used. Hence, non-isolated converters are more straightforward in design and cost less. The DC-DC converter classifications are summarized in Figure 1.18 [36].

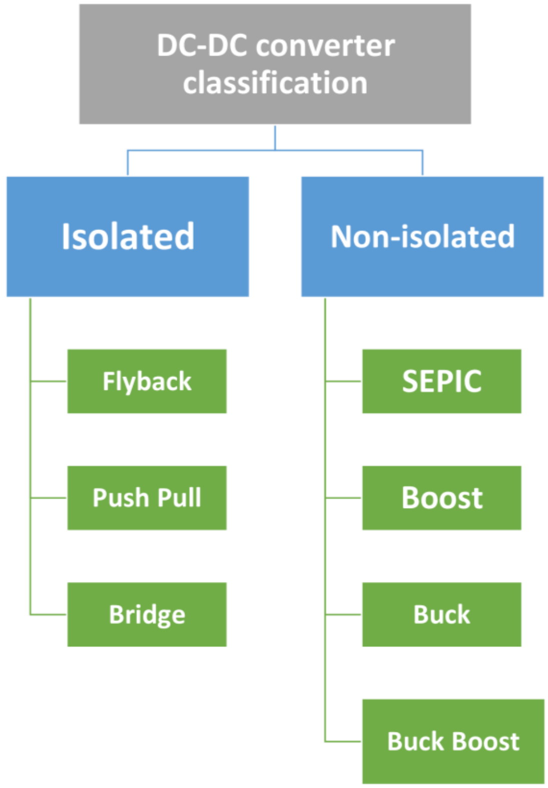

Figure 1.18. DC-DC converter classification

a) Non-isolated DC-DC Converters

BUCK CONVERTER

A buck converter has a lower voltage value than the input voltage. Hence, this type of converter is called a step-down converter [39]. Buck converters are usually used to convert the higher PV voltage to a lower load or charge a battery. The circuit diagram of the buck converter is illustrated in Figure 1.19 [36].

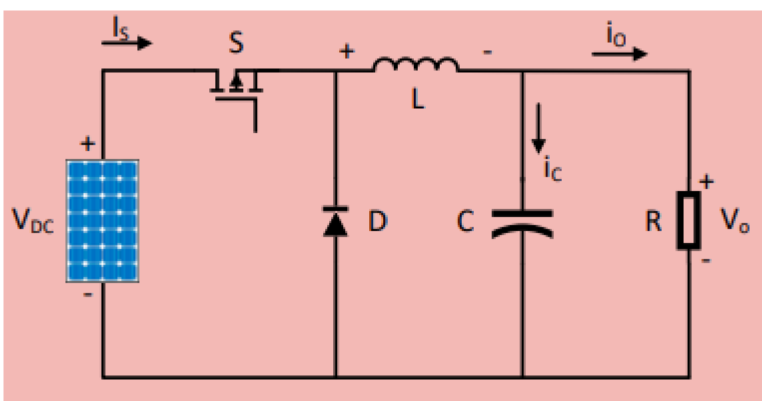

Figure 1.19. Buck converter circuit diagram [36]

BOOST CONVERTER

Usually, the load side requires more voltage than the voltage generated by the PV array. Hence, a boost converter is used in an MPPT controller [35]. A circuit diagram of a boost converter is shown in Figure 1.20 [36].

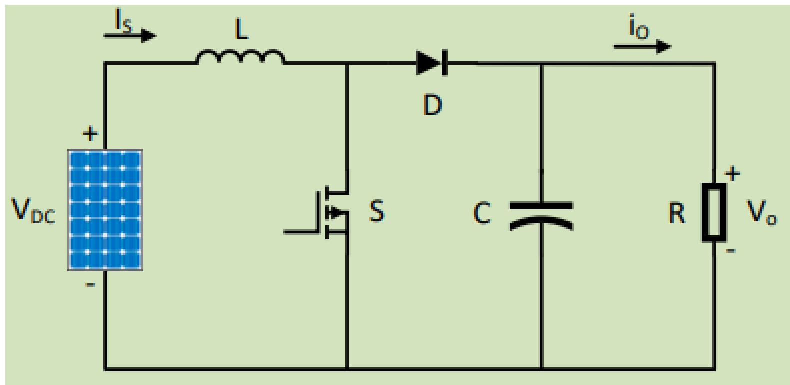

Figure 1.20. Boost converter circuit diagram [36]

BUCK-BOOST CONVERTER

This topology could be used in both stand-alone and grid-connected PV systems. Utilizing a buck-boost converter in a PV-based application is still under research to increase the voltage gain. Many topologies have been driven from the buck-boost converter. These topologies include Cuk, SEPIC, and Luo converters [36], [40]. The circuit diagram of the buck-boost converter is shown in Figure 1.21 [36].

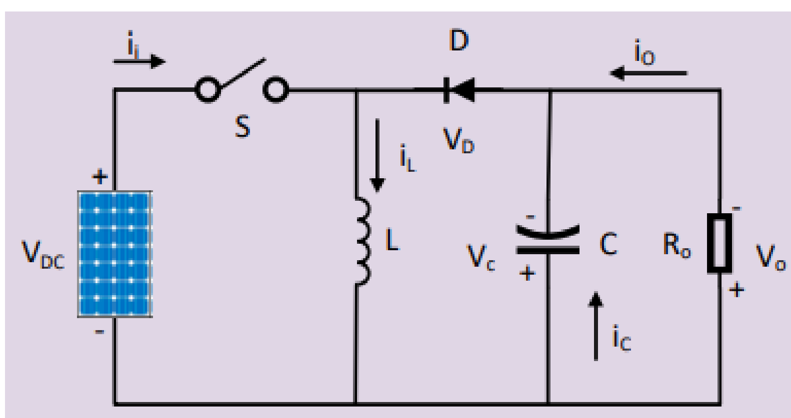

Figure 1.21. Buck-Boost converter circuit diagram [36]

Single-Ended Primary Inductance Converter (SEPIC)

This topology provides a solution to drawbacks of buck-boost converters, such as load current pulsating time [35]. Unlike the buck-boost converter, the output polarity is not inverted. This converter does not cause as much electrical stress as the other components that affect overheating the device [41]. The circuit diagram of SEPIC is demonstrated in Figure 1.22 [36].

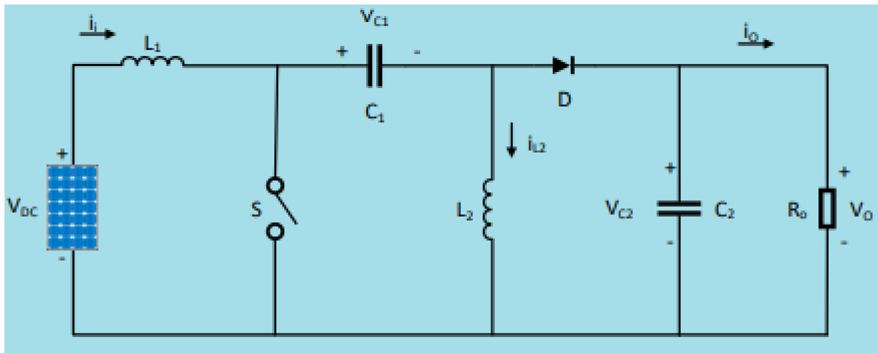

Figure 1.22. SEPIC converter circuit diagram [36]

1. Non-isolated DC-DC Converters

Flyback converter

Flyback converters are used for high load voltages. The main advantage of flyback converters is their filtered output [42]. Figure 1.23 demonstrates the circuit diagram for this type [34].

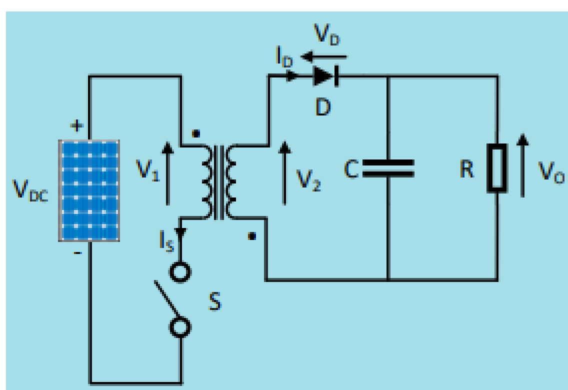

Figure 1.23. Flyback converter circuit diagram [36]

Bridge converter

Bridge converters utilize two or four active switches across a transformer. There are many types of bridge converters. One of these types is the Dual Active Bridge – Isolated Bidirectional DC-DC Converter

(DAB-IBDC). The main feature of this type is that it has a high conversion efficiency. The circuit diagram is shown in Figure 1.24 [36].

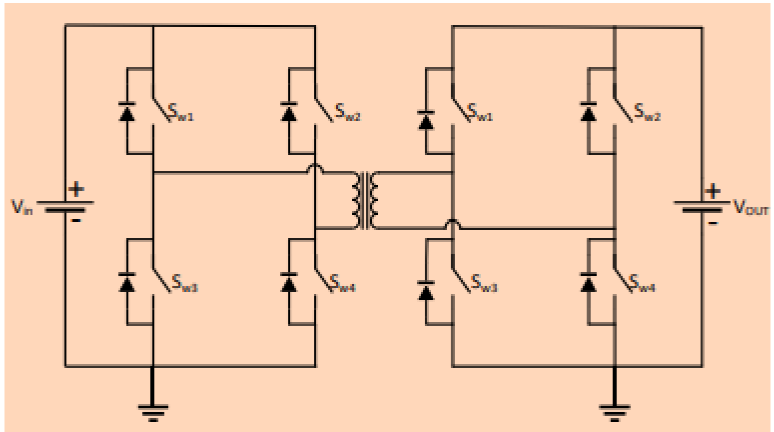

Figure 1.24. Dual active bridge converter [36]

PUSH-PULL CONVERTER

This converter is shown in Figure 1.25. The push-pull converter utilizes the transformer more effectively than the flyback converter [36]. This circuit topology reduces the output current ripples [43].

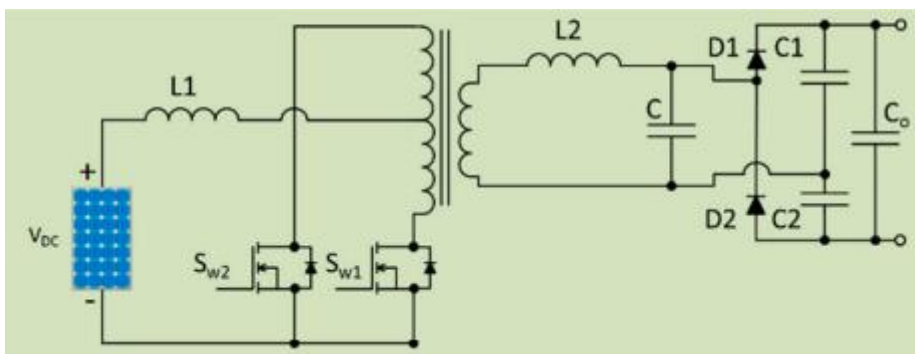

Figure 1.25. Push-pull converter circuit diagram [36]

4) *MPPT Techniques*

Many techniques are available to track the MPP, which differ in some criteria, such as efficiency, cost, and energy loss. There are two main categories for MPPT methods. The first one is the conventional method, such as Perturb and Observe (P&O), Fraction Open-Circuit Voltage (FOCV), and Incremental Conductance (IC). The other category is Artificial Intelligence (AI) based MPPT, such as fuzzy logic controller, artificial neural network, and particle swarm optimization [14]. A summary of the conventional MPPT techniques is presented in Table 1.1.

Table 1.1. Conventional MPPT methods

MPPT methods	Short description
Perturb and Observe (P&O)	- Widely used due to its simplicity and low cost [14] - Reliable and easy to implement technique [44] - It faces an issue of slow tracking speed [14]
Incremental Conductance (IC)	- It overcomes the P&O issue [14] - Depending on the slope of the PV curve [45]
Fraction Open-Circuit Voltage (FOCV)	- Based on the fact that the ratio between the array voltage to the open-circuit voltage is almost constant [46]

5) *Three-Port Converter Overview*

Since renewable energy is intermittent in energy availability, an energy storage device such as batteries is needed. Traditionally, two power converters are used. One for the PV array, and the other for the battery, as shown in Figure 1.26 (a) [47], [48].

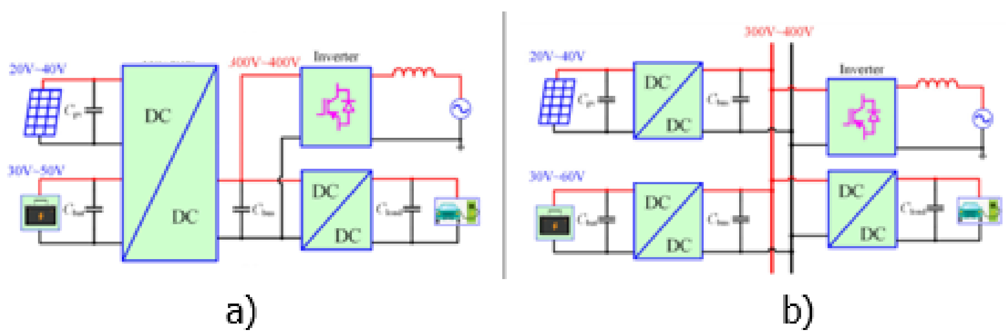

Figure 1.26. A PV panel and a battery interfaced with a load by (a) two two-port converters (b) a TPC converter [47]

The drawbacks of the two-port converter topology are shown in Figure 1.26 (a) are low efficiency caused by the increase of conversion stages, high cost due to the switches needed in each converter, and complications in control systems. These challenges paved the road toward utilizing a Three-Port Converter (TPC), as shown in Figure 1.26 (b), which does not face the mentioned drawbacks [47].

Unlike two-port converters, TPCs have different operating modes. In TPC, there are three output power, the PV cell power P_{in}, the battery power P_{bat} and the load demand power P_{out}. The power balance for a TPC is given by [49]:

$$P_{in} + P_{bat} = P_{out} \quad (1)$$

The operating modes are shown in Figure 1.27 and can be summarized in Table 2.2 [49], [50]:

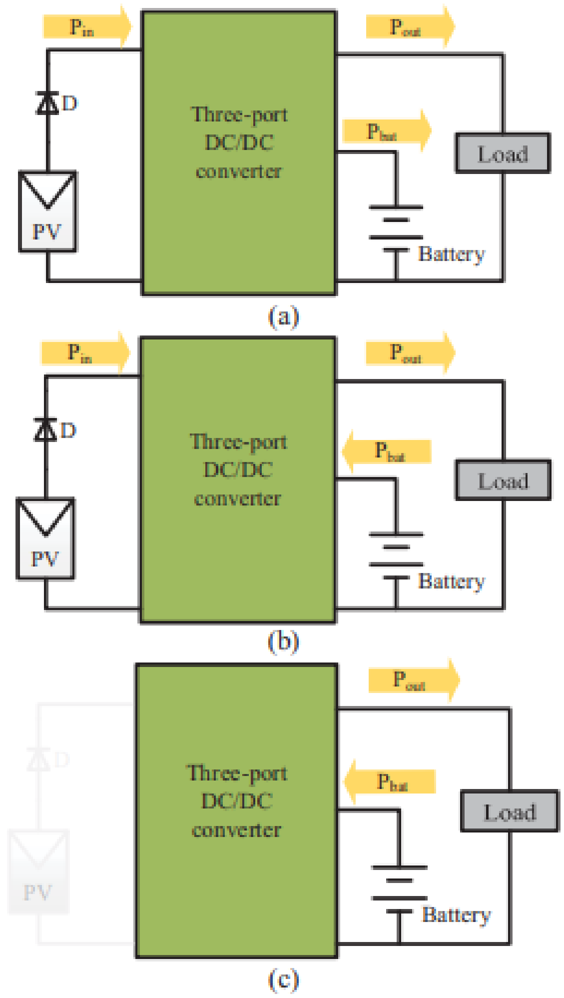

Figure 1.27. Power Flow in a) SIDO, b) DISO, and c) SISO modes [49]

Table 1.2. TPC Operating Modes

Single Input Double Output Mode (**SIDO**)	Double Input Single Output Mode (**DISO**)	Single Input Single Output Mode (**SISO**)
• When there is sufficient sunlight. • $P_{in} > P_{out}$	• When there is a weak sunlight • $P_{in} < P_{out}$	• When there is no sunlight. • $P_{in} = 0$

• PV provides power to both the battery and the load • PV continues to work at MPP	• PV and the battery provide power to the load • MPPT is achieved by controlling the duty cycle of the switches in the converter	• Only the battery provides power to the load

C. Research Aim and Objectives

Recently, utilizing TPCs in PV systems has gained interest. This thesis aims to increase the efficiency of a PV system with a TPC. This aim will be reached by accomplishing the following objectives:

- Simulating a PV system consists of a TPC, a PV panel, a battery, and a load
- Applying different MPPT algorithms applied to the TPC
- Comparing the MPPT to find the best method based on their response to environmental changes

D. Significant of the Study and Contribution

Solar PV is a crucial player in the worldwide shift to renewables as an energy source. Saudi Arabia announced an ambitious vision (Vision 2030) where renewable energy will contribute 50% to the overall energy mix by 2030. The primary renewable sources are solar and wind, as there is an impressive potential for both in Saudi Arabia [51]. Despite the advancement in this field, more efforts are needed to grow the PV market, as reported by the International Energy Agency (IEA) [52]. The significance of this study is that it touches upon a vital element of enhancing the PV system efficiency, which is operating at MPP. Recently, TPC has been introduced in PV/Battery systems connected to the load. So far, however, little attention has been paid to applying the MPPT controller methods to a TPC. This study's contribution is applying MPPT controller methods to a TPC in a PV system.

E. Outline of the Thesis

This thesis is divided into five chapters. Chapter one presented the thesis introduction. Chapter 2 presents the literature review, which investigates different TPC topologies and reviews the most common MPPT controllers used for PV applications. Chapter 3 illustrates the thesis methodology. The following chapter presents the research findings. Finally, this thesis ends with a conclusion that concludes the thesis with thesis recommendation.

A. *MPPT Techniques for PV Application: A Comparison*

1) *Perturb and Observation (P&O) Method*

As the name suggests, it is based on adding a perturbation in the PV operating voltage and current, and it observes the resultant power accordingly [53]. Then, the power value is compared with the previous value to change the direction of the P&O algorithm by changing the duty cycle [14], [54]. A considerable perturbation value leads to large fluctuations after the MPP value is reached. Conversely, a small perturbation value leads to smooth fluctuations. Hence, the perturbation value selection is vital in this method [14]. The principle of P&O on the PV curve is shown in Figure 2.1 [54]. The direction of the algorithm based on P and V values is summarized in Table 2.1 [14].

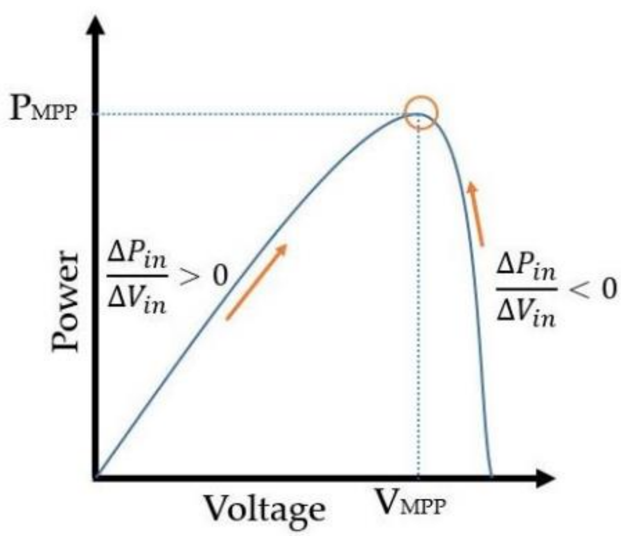

Figure 2.1. P&O principle in PV curve [54]

Table 2.1. The direction of the P&O algorithm

ΔP	ΔV	Direction of Perturbation
+	+	+
+	-	-
-	+	-
-	-	+

The P&O method has two significant drawbacks. The first is the power fluctuations around MPP. The second is divergent MPP when there are rapid changes in the environment. These drawbacks are resolved by using the Incremental conductance method [53].

2) *Incremental Conductance*

The Incremental Conductance (IC) is a widely used technique with higher efficiency than the P&O method [54]. It is based on the fact that the derivative of the power with respect to the voltage at the MPP is zero. Hence, the MPP can be expressed as [53]:

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = V\frac{dI}{dV} + I = 0 \qquad (2.1)[53]$$

Which can be re-written as:

$$-\frac{I}{V} = \frac{dI}{dV} \cong \frac{\Delta I}{\Delta V} \qquad (2.2)[53]$$

Where ΔV and ΔI represent the increments of PV voltage and current, the working principle of IC is illustrated on the PV curve shown in Figure 2.2 [53]. Despite this algorithm's features, it requires a complex control circuit [23].

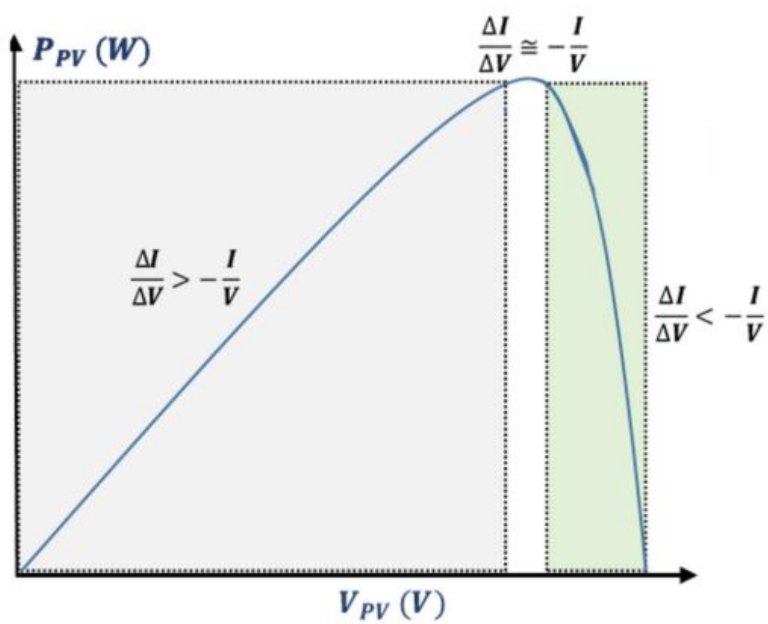

Figure 2.2. PV curve of the IC method [53]

3) Fractional Open Circuit Voltage

Fractional Open-Circuit Voltage (FOCV) is a simple technique with high-speed MPP tracking. It is based on the idea that V_{mp} is obtained by multiplying V_{oc} by a constant k_{oc}. The constant value is calculated from the datasheet. Usually, the value range is 0.7-0.85. The principle of this method is expressed graphically, as shown in Figure 3.3 [55]. The constant value k_{oc} is shown in Figure 3.3 which is near the actual maximum voltage with a minor difference.

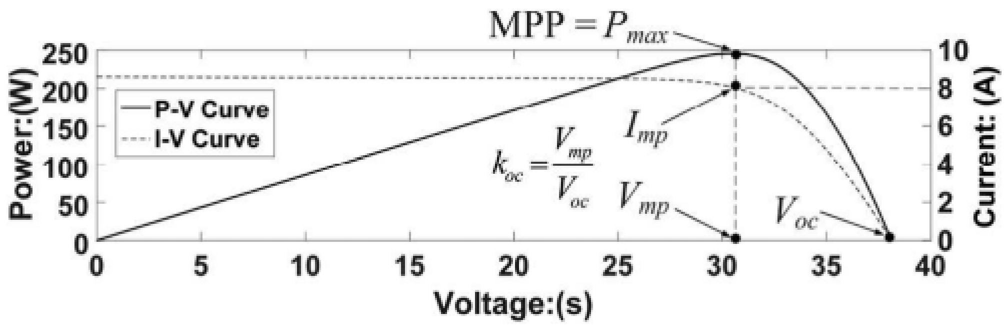

Figure 2.3. PV and IV curve of the FOCV method [55]

Even though this method is simple, it can not track the exact value of MPP since k_{oc} is varied according to the environmental conditions [55].

4) Particle Swarm Optimization

Particle Swarm Optimization (PSO) is one of the soft computing methods. techniques that are used to optimize the non-linear behavior of Photovoltaic (PV) systems [56]. It is a population-based stochastic algorithm. PSO is inspired by the movement dynamic of biological creatures like birds and fishes [57]. A bird swarm has a graceful choreography and pattern as they fly synchronously and change direction to the optimal locations. The term 'particle' represents fish, bees, birds, or any creature with swarm behavior [58]. From this simple analogy, PSO was introduced in 1995. Since then, there has been sustained research activity on applying the PSO technique [57]. The advantages of PSO are that it uses few algorithm parameters and requires low memory and low CPU speed [59], [57].

An analogy of a swarm of bees is used to visualize PSO better. The swarm goal is to determine the location in the field that has the highest density of flowers. This location is considered the optimal location. The bees start their search by spreading out randomly as they do not have previous knowledge of the field. Every bee transmits information to the rest of the swarm regarding the highest density location it has passed by so far. Over time, every bee keeps going back and forth between the highest density location it has found (personal best location) and the location reported by the swarm (global best location). The field is explored by the swarm using this method. Each bee updates the swarm by speed and direction whenever it successfully passes by a higher density location. Finally, the swarm will explore all the field locations, and the highest flower density location is identified. For MPPT, the particles have to identify the location of MPP [58].

B. Two Port DC-DC Converters

Bibliometrix, a tool programmed in R language, was used to review the literature statistically. The data were collected from the Scopus database [60]. Two thousand articles from 2011 to 2021 were extracted from Scopus and uploaded to biblometrix to visualize the annual publication's growth, shown in Figure 2.4.

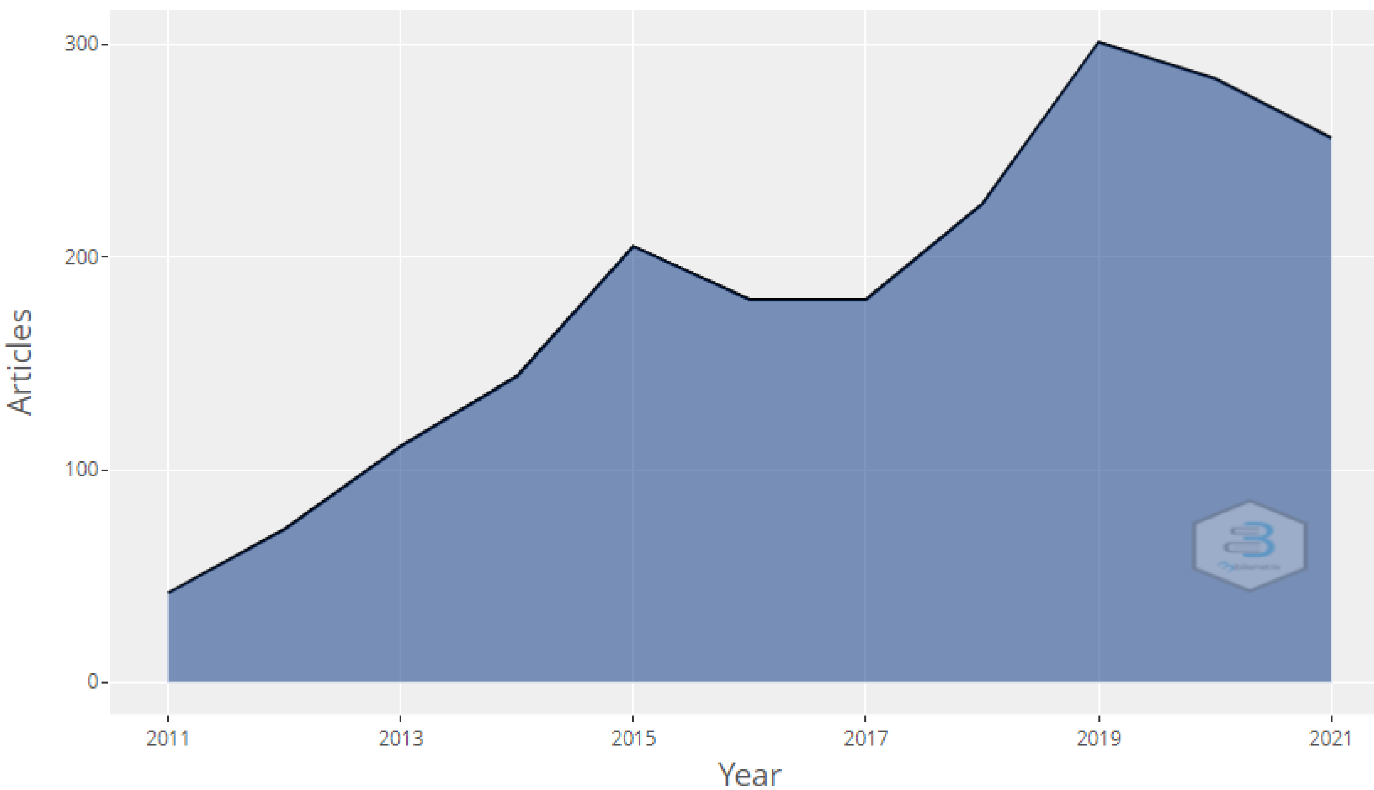

Figure 2.4. Annual article production of two-port converter 2011-2021

According to the bibliometrix tool, the annual growth rate is around 19.18%. There is an increase in the publications, with the peak publication number being in 2019.

In terms of the most used words in these publications, the articles were filtered to include 2017 to 2021. The word cloud demonstrates the most frequent words/phrases with the bigger font, as shown in Figure 2.5. As it can be noticed, the most frequent MPPT method (the one in the bigger font) is Perturb & Observation (P&O) method, followed by Particle Swarm Optimization (PSO) and Incremental Inductance (IC). The most frequent topology is the boost converter used in the converter topology. MATLAB software is the most frequent software to apply these methods.

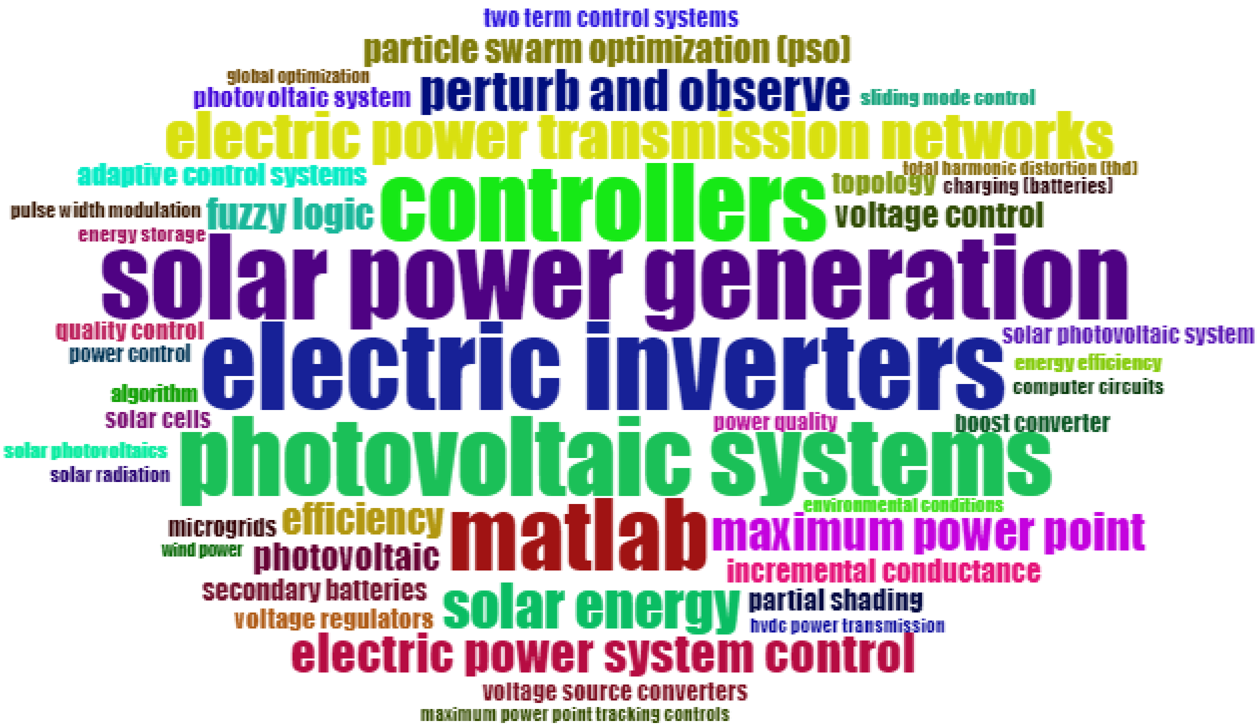

Figure 2.5. Word-cloud for two-port converter

Table 2.2 represents different MPPT techniques applied to different converter topologies for PV applications.

Table 2.2. MPPT techniques applied to different converters

Converter	Authors and reference	MPPT method	Remarks
Buck	El mentally et al. [61]	Hill Climbing and FOCV	They found out the hill-climbing method is better than FOCV
	Saidi et al. [62]	IC	The authors studied IC in both direct and indirect control. Indirect control includes a Proportional Integral P.I. control loop The method with the P.I. control reduces the power oscillation
Boost	Sen et al. [63]	P&O	The authors used MATLAB/Simulink software to implement the P&O MPPT algorithm
Buck-Boost	Kumar et al. [64]	P&O	They compare P&O performance for buck and buck-boost converters. The Buck converter had a minor power loss compared to the buck-boost converter
	Blange et al. [65]	P&O Fuzzy Logic	The authors compared these two MPPT algorithms. Based on their study, Fuzzy Logic had a faster response than P&O
SEPIC	Necaibia et al. [66]	IC	The authors modified the IC algorithm to respond faster to environmental changes. They proved the efficiency of their modified version via MATLAB simulation and hardware application
	Tidke et al. [67]	P&O	The authors utilized P&O to SEPIC converter. This topology has the advantage

			of a high voltage transformation ratio (approximately 10.5 times higher output voltage than the input voltage). Combining SEPIC with P&O led to more efficient energy conversion
Flyback	Saleh et al. [68]	P&O IC	- The authors used Proteus software for modeling and simulation - The authors found that the P&O algorithm reaches the MPP faster but with higher fluctuations. Also, IC was more accurate at identifying the MPP. As a result, they concluded that IC is more efficient than P&O
Push-pull	Barros et al. [69]	IC	The authors used this method for integrating the system with the grid. This method succussed in finding the MPP
Bridge	Begum et al. [70]	IC	The authors used MATLAB/SIMULINK software as it is suitable software for such projects

C. MPPT in Three Port Converters (TPC)

Applying MPPT techniques to TPC has not been much investigated in the literature. However, some studies applied an MPPT technique to a TPC. One of which is a study accomplished in 2017 by Mahendran et al. in [71]. Their study modified the conventional P&O algorithm by including the current drift variable. As a result, the tracking time of the MPP improved by 80% using the modified P&O algorithm. The flowchart of the modified P&O is shown in Figure 2.6[71].

Figure 2.6. Modified P&O algorithm [71]

In 2018, Lagudua and his colleagues built an MPPT algorithm for a TPC [72]. The MPPT achieved the MPP with less tracking time than the conventional P&O. However, their design is complex.

D. Three Port Converter (TPC)

The topologies of TPC can be classified based on isolation. There are isolated TPCs and non-isolated TPCs. The non-isolated TPCs are smaller and have a lower cost. Thus, it is more advantageous to use non-isolated TPCs when isolation is not critically required. The isolated TPCs utilize a transformer to isolate between any two port in the circuit. This type has a higher cost and weight compared to the first one. This topology is used when high voltage regulation is required [73].

Traditionally, TPC is formed by combining two two-port converters. However, this topology has low efficiency and requires high cost. Hence, TPC is usually formed by integrating two two-port converters.

The converters' control rule states that for a TPC, three power transmission lines and two control variables are required, as shown in Figure 2.7 [50], [74].

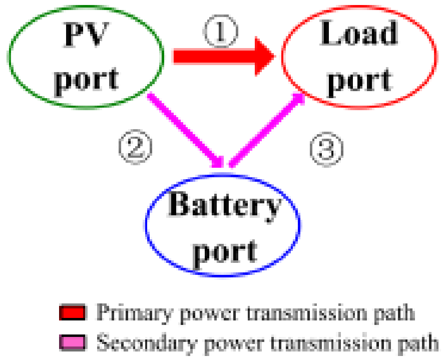

Figure 2.7. Power transmission path [50]

As shown in Figure 2.8, the primary transmission path consists of only one path, whereas the secondary path consists of two paths. Primary Single Stage, Secondary Two-Stage (P1S2) is the basic TPC topology driven based on these paths, as shown in Figure .

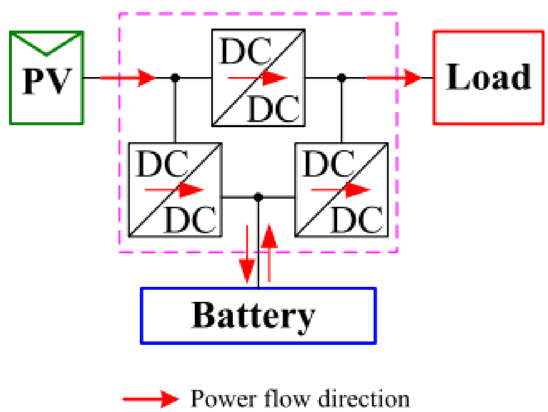

Figure 2.8. P1S2 topology [50]

Another topological structure could be extracted from another power path, as shown in Figure 2.9 [50].

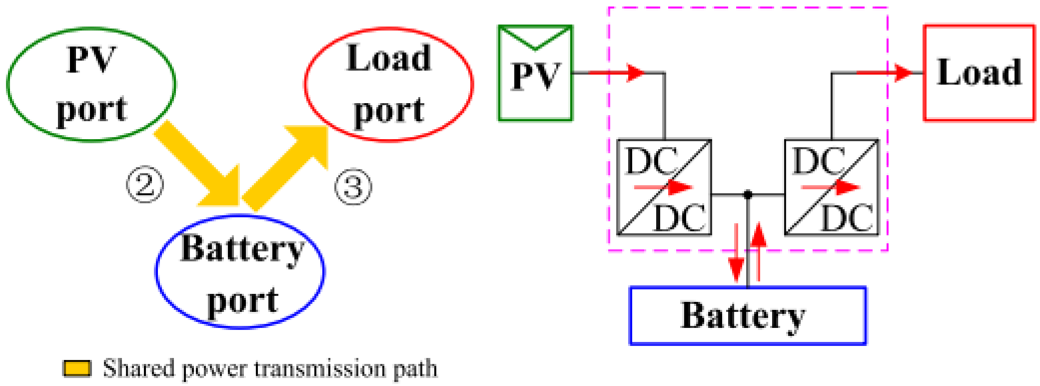

Figure 2.9. P2S2 topology [50]

Two more topological structures could be extracted as shown in Figure 2.10 and Figure 2.11 [50].

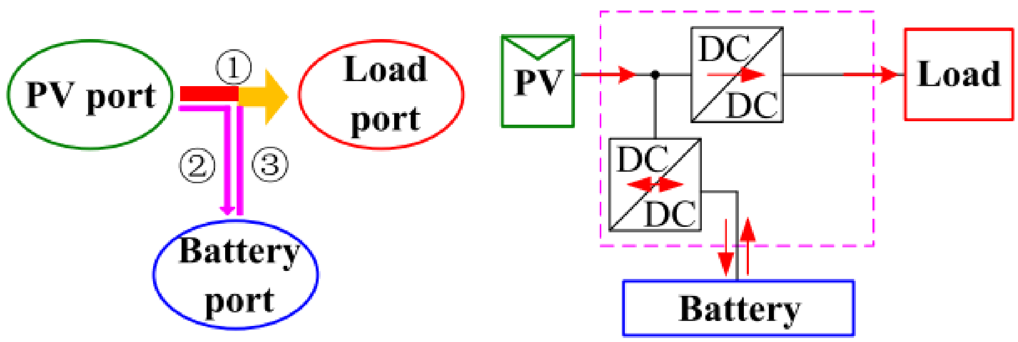

Figure 2.10. P1S3-I topology [50]

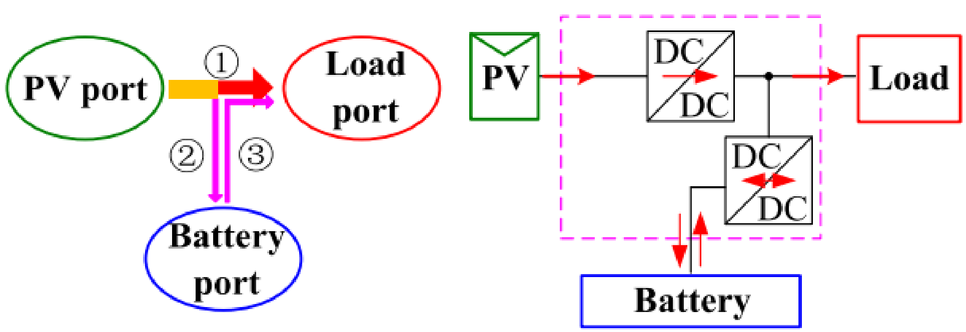

Figure 2.11. P1S3-II topology [50]

It should be noted that the converters are not separated in these topologies. Some components like inductors and capacitors are shared by component sharing [50].

Three different criteria are used to compare these topologies. These criteria are topological complexity, efficiency, and control complexity.

- **Topological Complexity:** P2S2 contains two unidirectional power paths. P1S3 contains a unidirectional path and a two-directional path. P1S2 contains three unidirectional paths. Hence, P2S2 is the simplest, followed by P1S3 and P1S2 [50].

- **Efficiency:** one main factor impacting efficiency is the number of power conversion stages. Since the load takes power primarily from the PV, the highest efficiency is P1S2. Then, P1S3-I and P1S3-II [50].
- **Control Complexity**: the more controllers needed, the higher the complexity. P1S2 is more complex than other topologies. Studies have shown that converters with P2S2 are more straightforward in control than P1S3 [50].

The comparison between the topological structure is summarized in Table 2.3 [50], [74].

Table 2.3. TPC Topology Comparison

	P1S2	P2S2	P1S3-I	P1S3-II
Topology Complexity	Low	Good	Medium	Medium
Efficiency	Low	Medium	Medium	Low
Control Complexity	Good	Low	Medium	Medium

According to Table , P1S3-I is the best topology that comprises the three criteria. Hence, the table represents a comparison of TPC circuits with P1S3-I topology.

Since a semi-isolated converter comprises the advantages of both the isolation in the isolated converters and simplicity in non-isolated converters, a semi-isolated converter with P1S3-I topology is chosen to implement MPPT methods to it and compare the resultant simulations. The chosen TPC is partially isolated where there is insolation between the load and the rest of the circuit [75].

CHAPTER 3: METHODOLOGY

The research methodology followed in this thesis is summarized in Figure 3.1.

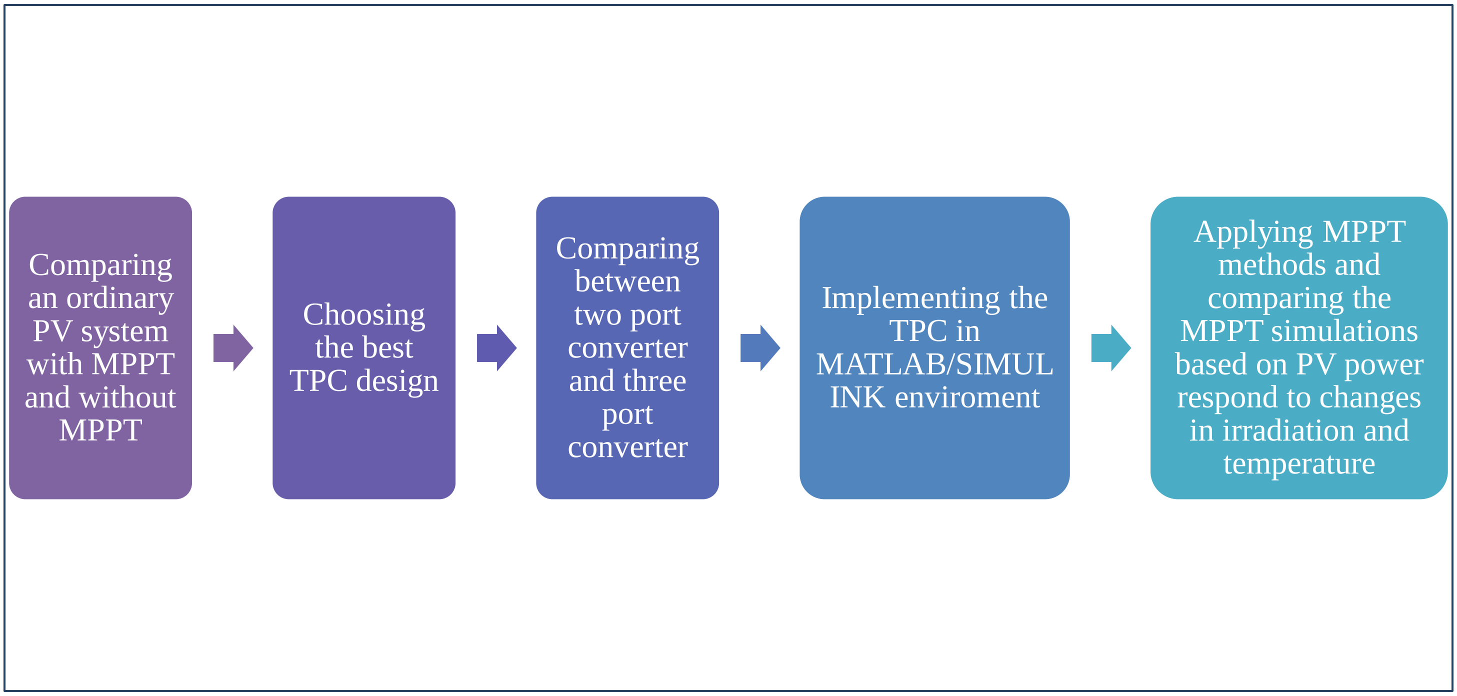

Figure 3.1. Methodology process steps

A.Comparing an ordinary PV system with MPPT and without MPPT

The PV system at Effat university library is considered a case study to illustrate the importance of MPPT in PV systems. The data was collected from this system for simulation using MATLAB/SIMULINK software. The system comprises 60 solar panels with a total area of 200 m2 with rated power. MATLAB is a standard programming software used by engineers to perform many functions, such as developing algorithms and creating models. SIMULINK is a MATLAB-based graphical environment for simulating and analyzing systems [76].

1) *Boost Converter Specifications*

The PV systems consist of a PV array, a DC-DC converter, and a resistive load. The used DC-DC converter type is a boost converter that outputs a higher voltage than the input voltage. The topology of this circuit is shown in Figure 3.2 [77]. The boost converter is designed based on the specifications shown in Table 3.1.

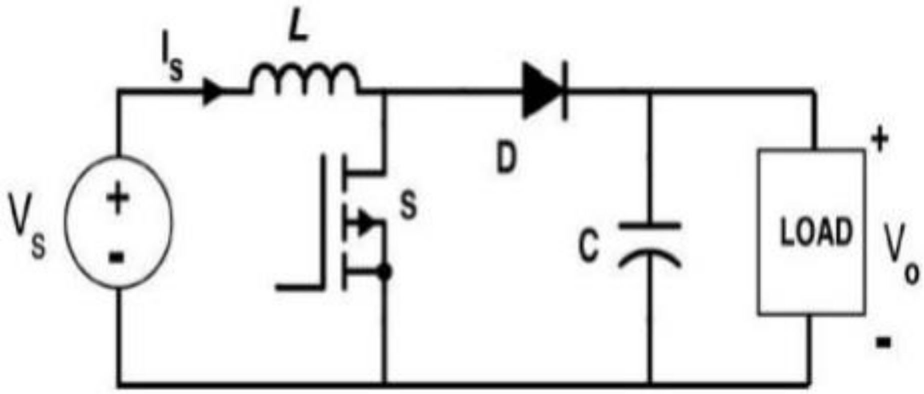

Figure 3.1. DC-DC boost converter topology [77]

Table 3.1. Boost converter

Vin	250V
Vop	652V
Rated Power	94kW
Switching frequency, f	5000 Hz
Current ripple	5%
Voltage ripple	1%

Then, the following could be calculated [78]:

$$Input\ Current = \frac{94{,}000}{250} = 376A \quad (1)$$

$$Current\ ripple = 5\%\ of\ 376 = 18.8\ A \quad (2)$$

$$Voltage\ ripple = 1\%\ of\ 652 = 6.52V \quad (3)$$

$$Output\ current = \frac{94{,}000}{652} = 144.17A \quad (4)$$

$$Inductance, L = \frac{V_{input}\ (V_{output} - V_{input})}{f * \Delta I * V_{output}} = 1.64\ mH \quad (5)$$

$$Capacitance, C = \frac{I_{output} * (V_{output} - V_{input})}{f * \Delta V * V_{output}} = 2.73\ mF \quad (6)$$

A Perturb and Observe (P&O) MPPT method was applied for the system. The output power, voltage, and current harmonic distortion were compared before and after implementing the MPPT.

B. Choosing the best TPC design

The best suitable design for a TPC is shown in Figure 3.3 based on the literature review [75].

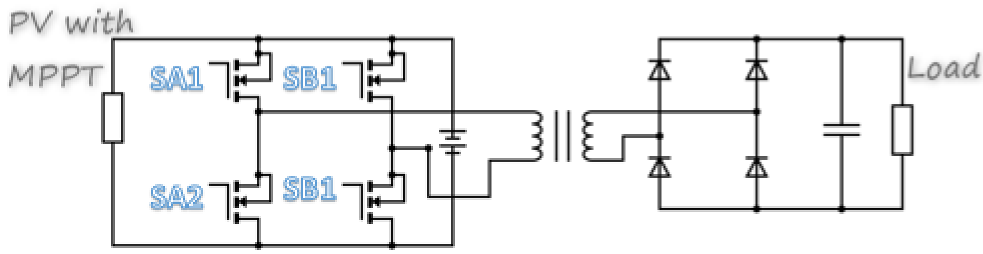

Figure 3.3. The best suitable design

The TPC selection is based on the presence of a partially isolated topology in which the load is isolated using a transformer. This topology provides a more secure operation for the load, especially if the load is sensitive [75].

C. Modeling the chosen TPC

1) TPC overview

The chosen topology is based on the full-bridge converter. The load is isolated from the rest of the circuit using a transformer. Hence, this topology is considered as partially-isolated. The other two ports are the PV, where MPPT is implemented to extract maximum power and a battery as a storage system. The PV port is unidirectional, whereas the battery port is bidirectional to allow the current to flow from or to the battery (changing and discharging process). There are four switches in this circuit. SA1 and SA2 are for the PV, and SB1 and SB2 are for the battery. A rectifier of four diodes connected to the load for the A.C. to D.C. conversion [75].

There are three operation modes for this TPC, depending on the solar irradiance availability.

- **Mode 1:** the PV panel powers the load and charges the battery at the end of each pulse by turning SB1 on and SB2 off. This mode is illustrated in Figure 3.4.

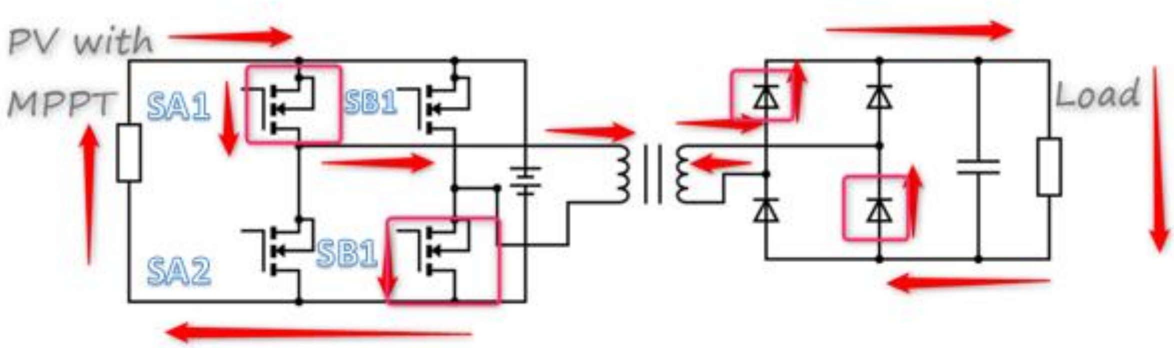

Figure 3.4. Mode 1 circuit operation

- **Mode 2:** the PV panel powers the load. When the PV power is higher than the load demand, SB1 reaches the maximum value and allows the charging of the battery. This mode is illustrated in Figure 3.5.

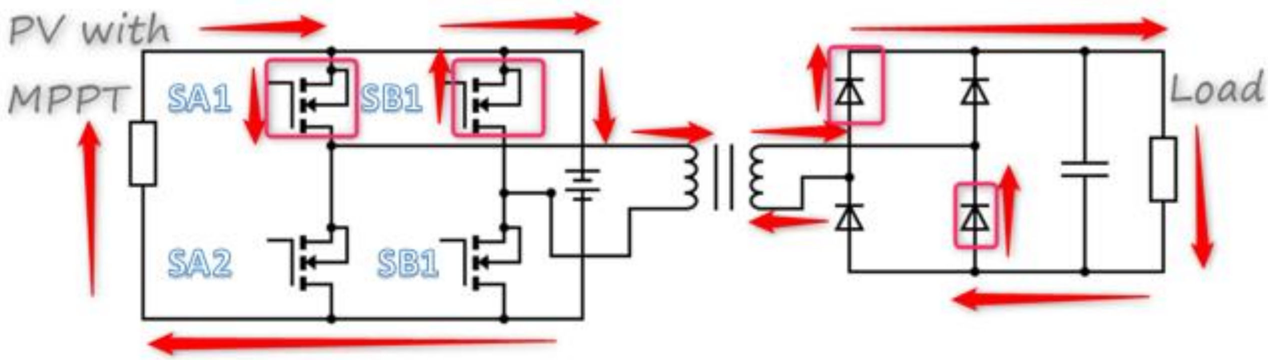

Figure 3.5. Mode 2 circuit operation

- **Mode 3:** both the PV and the battery power the load. This mode happens when there is no sufficient sunlight. If PV=0, only the battery powers the load, and SA1 reaches its maximum value. This mode is illustrated in Figure 3.6 [75].

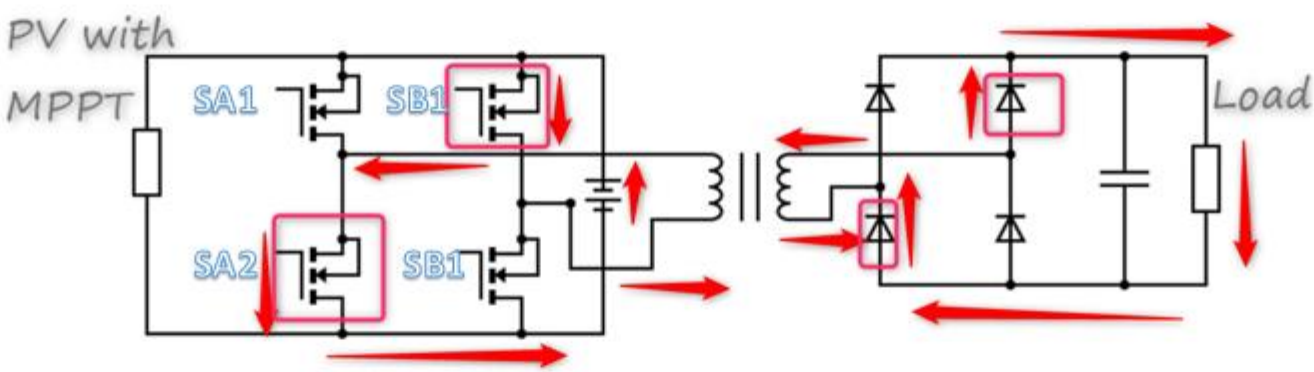

Figure 3.6. Mode 3 circuit operation

2) *Controller design*

Controlling the TPC and choosing an operation mode is accomplished by controlling the pulses generated to the four switches SA1, SA2, SB1, and SB2. In all the modes, SA1 and SA2 are compliments of each other, and SB1 and SB2 are compliments of each other. The controller is built-in MATLAB/SIMULINK along with the other circuit components. The controller inputs are the PV power and load power. The controller compares these two values to choose the operation mode and, as a result, outputs the four switch pulses. There are three cases: PV power = load power (Mode 1), PV power > load power (Mode 2), PV power < load power (Mode 3).

D. Comparing two port converters and three-port converter

This step aims to compare the two-port and three-port converters against different weather conditions using two MPPT techniques. Namely, Perturb and Observe (P&O) and Incremental Conductance (IC). All the designs and simulations were accomplished by using MATLAB/SIMULINK software

The first simulated system is the traditional system, where a boost converter interfaces the PV and the load, and a bidirectional buck-boost converter interfaces the battery and the load. The PV outputs 150W with 34V. The battery has a nominal voltage of 12V with a capacity of 10 Ah. The system was built in MATLAB/SIMULINK, as illustrated in Figure 3.7.

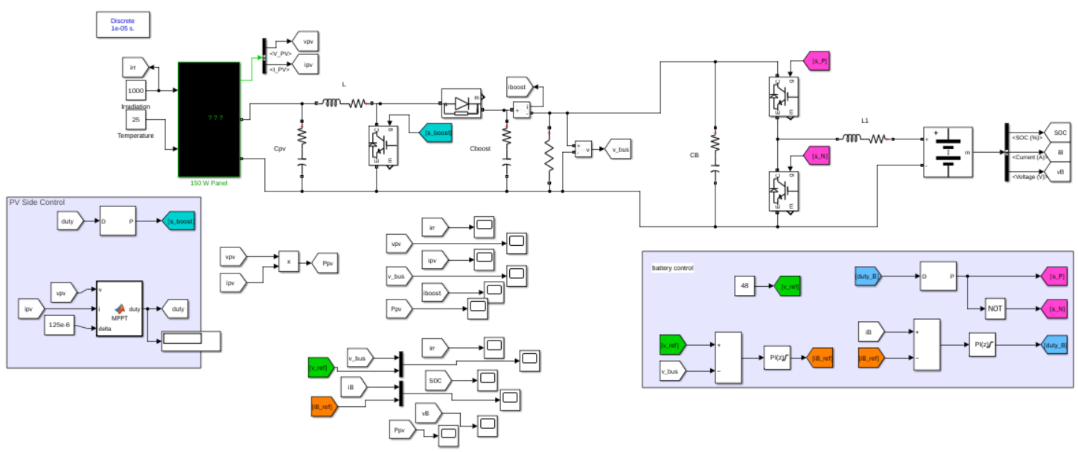

Figure 3.7. PV system with two two-port converters in MATLAB/SIMULINK

The second simulated system is the same TPC system chosen and explained in the previous step.

D. Implementing MPPT techniques using MATLAB/SIMULINK

MATLAB/SIMULINK software applies different MPPT techniques to a system consisting of a PV, TPC, and load. MATLAB is a standard programming software used by engineers to perform many functions, such as developing algorithms and creating models. SIMULINK is a MATLAB-based graphical environment for simulating and analyzing systems [79].

Perturb and Observation method (P&O) was used. This method is to be modified to be suitable for a TPC. As mentioned previously, this method is simple and does not require mathematical modeling of the system [65], [68]. The explanation of P&O on the PV curve is shown in Figure 3.8 [80].

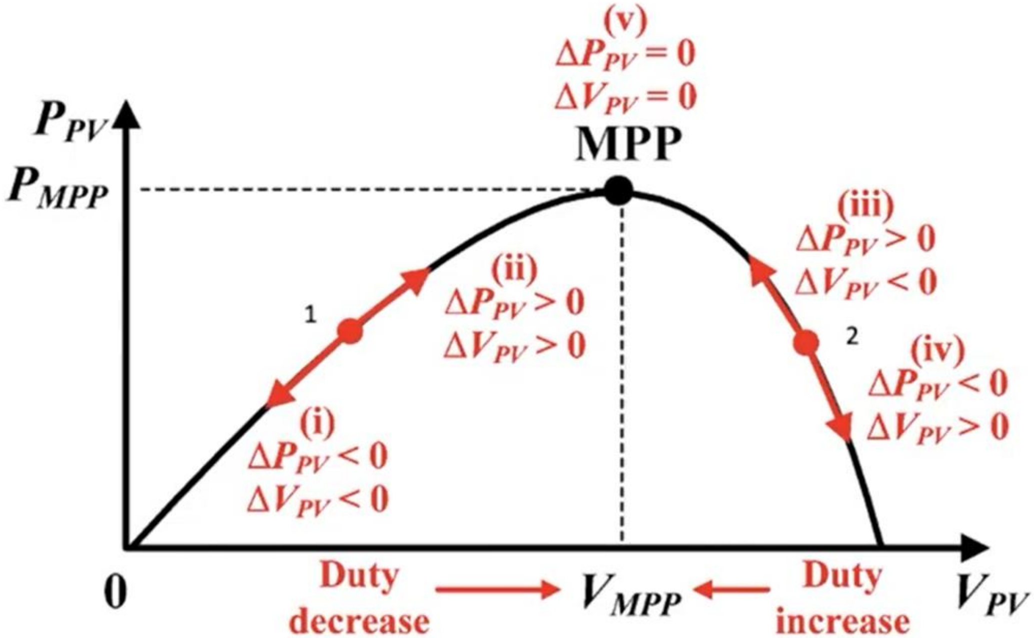

Figure 3.8. P&O in a PV curve [80]

If a PV array operates at point 1 in Figure , then, to increase the power, the voltage must increase by decreasing the duty cycle. If this PV array operates at point 2, the voltage must decrease by increasing the duty cycle [80].

The flowchart of the P&O algorithm is shown in Figure 3.9 [81].

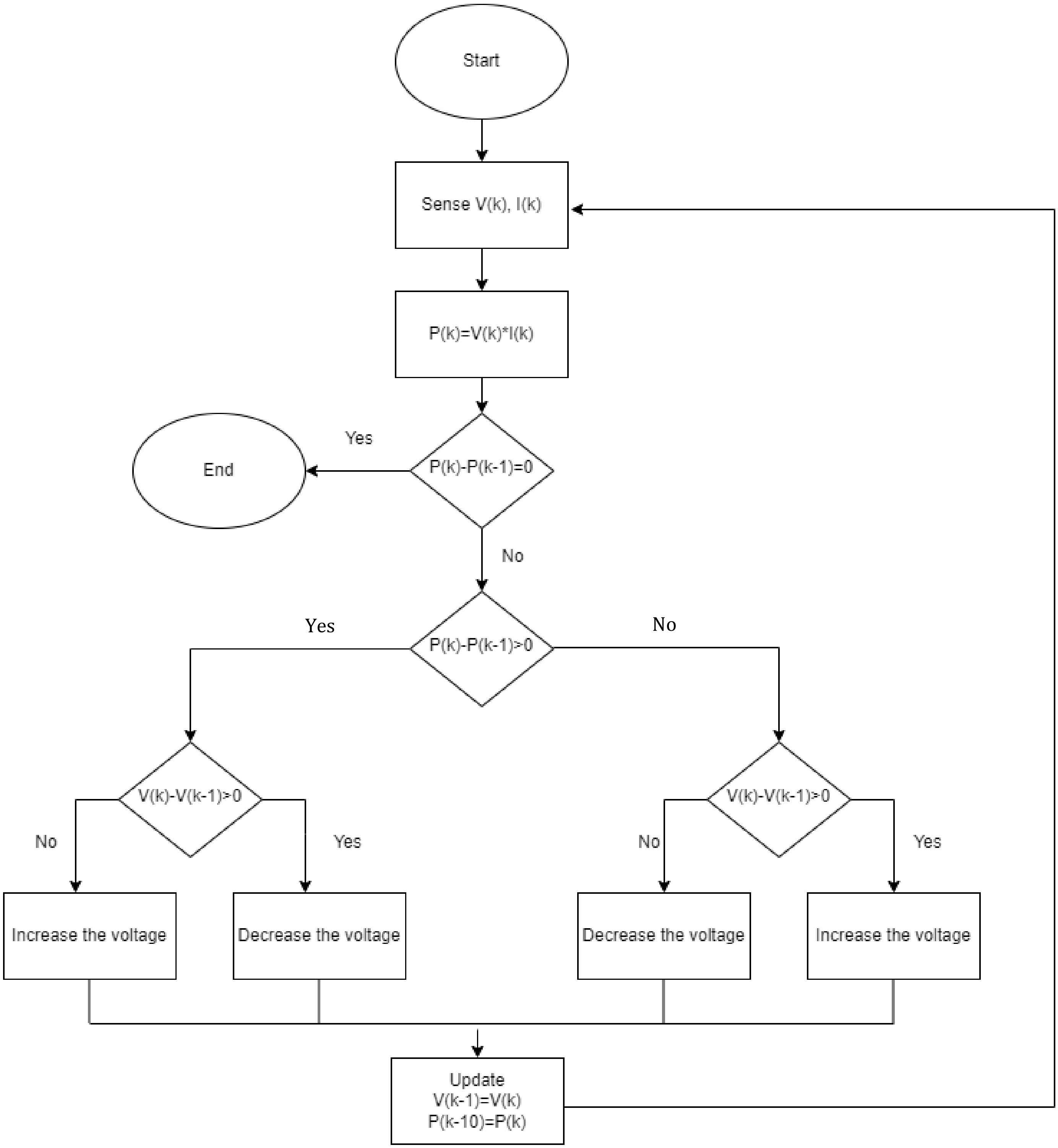

Figure 3.9. P&O algorithm flowchart

The other MPPT is Incremental Conductance (IC). In this method, the MPP is calculated using the relation between dI/dV and I/V [82].

The concept of IC is shown in Figure 3.10. The MPP is when dI/dV = -I/V [83].

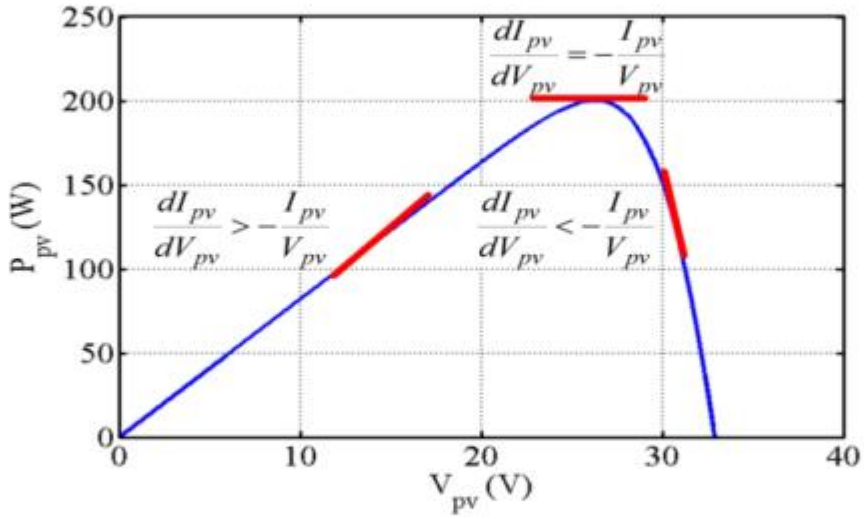

Figure 3.10. IC in a PV curve [83]

The flowchart of IC is shown in Figure 3.11 [82].

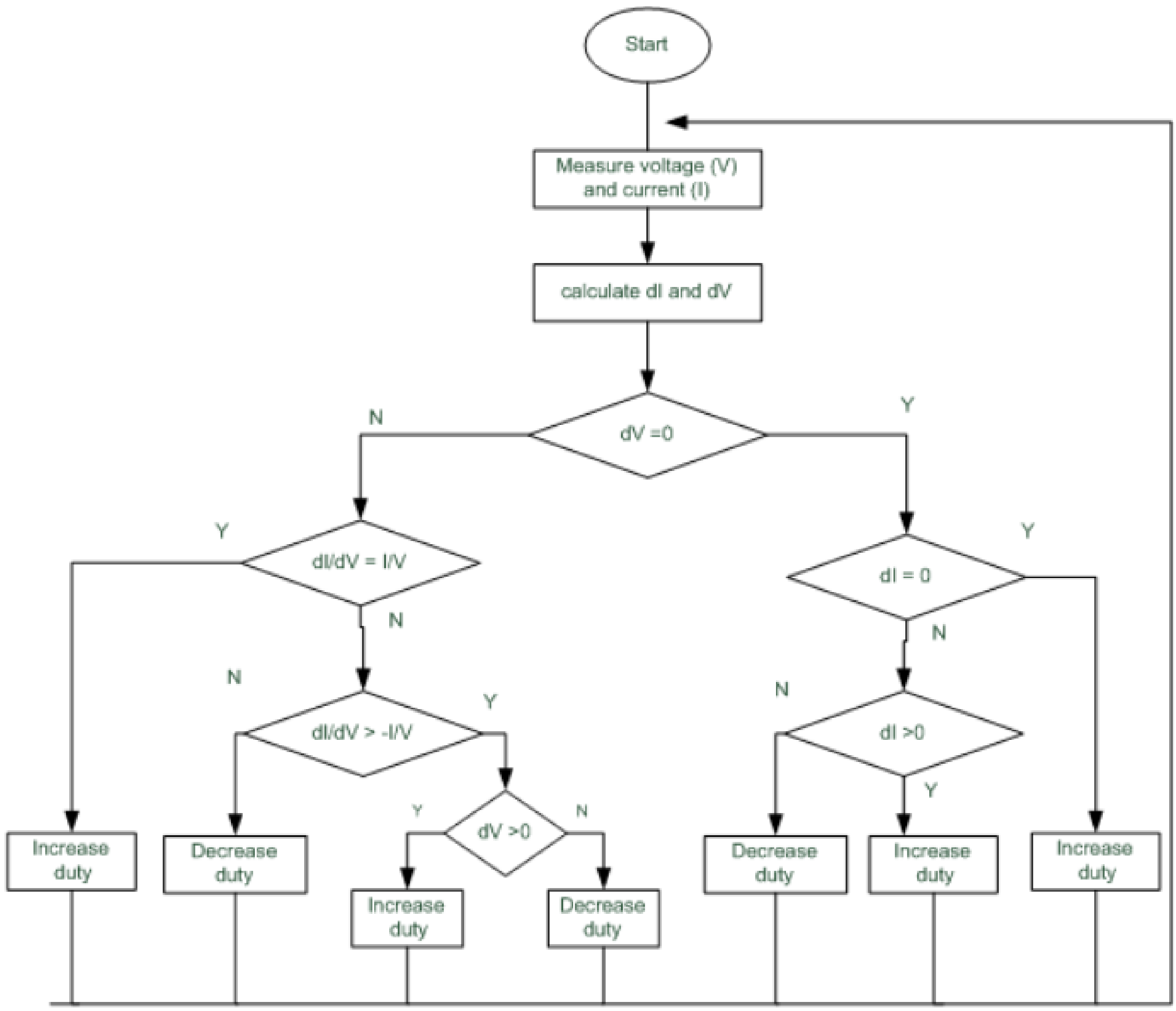

Figure 3.11. IC algorithm flowchart [82]

F. Comparing the MPPT algorithms

Both P&O and IC applied the TPC using MATLAB/SIMULINK. The output PV power is being compared based on its response to solar irradiation and temperature changes. The solar irradiation and temperature are varied to simulate real PV systems when weather conditions keep changing. The solar radiation varied with the sequence of 200,500,800,1000,800 W/m^2 with a change of 0.033,0.033,0.069,0.097s . The temperature varied with the sequence of 10,15,25,15,10 C with the same time change as the temperature. The MPP happens at the Standard Test Condition (STC). Namely, at 25C and 1000 W/m^2.

CHAPTER 4: RESULTS AND DISCUSSION

A. Comparing an ordinary PV system with MPPT and without MPPT

1) The PV system without MPPT

In the PV system without MPPT, the duty cycle of the boost converter is fixed and calculated as follows:

$$D = 1 - \frac{V_{input}}{V_{output}} = 1 - \frac{250}{652} = 0.62 \quad 4.1$$

The developed circuit is shown in Figure 4.1.

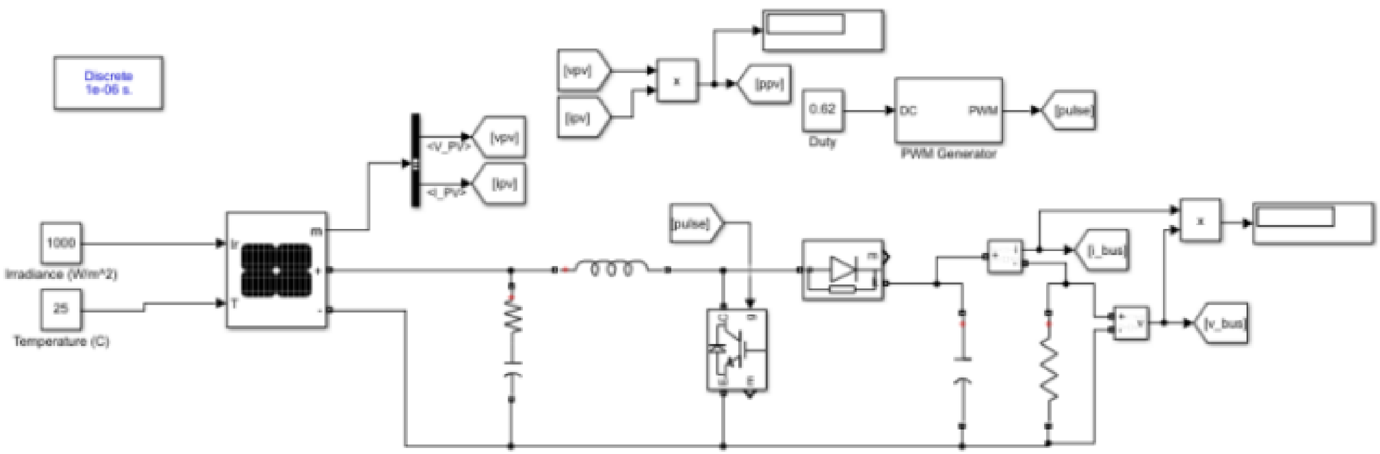

Figure 4.1. PV system without MPPT simulation

2) 2.2 The PV System with MPPT

As for the system with MPPT, the Perturb and Observe (P&O) method was used. This simple method does not require mathematical modeling [15], [16].

Both simulated systems are compared based on the output PV The comparison is illustrated in Table 4.1. According to the datasheet, the nominal (maximum) power it could deliver is 9.4×10^4 W, as shown in Figure 4.2.

Table 4.1. Comparison between a PV system with and without MPPT

Comparison	**The system without MPPT**	**The system with MPPT**
Output power	1.993×10^4 W	9.39×10^4 W
Efficiency	21.21%	99.93%

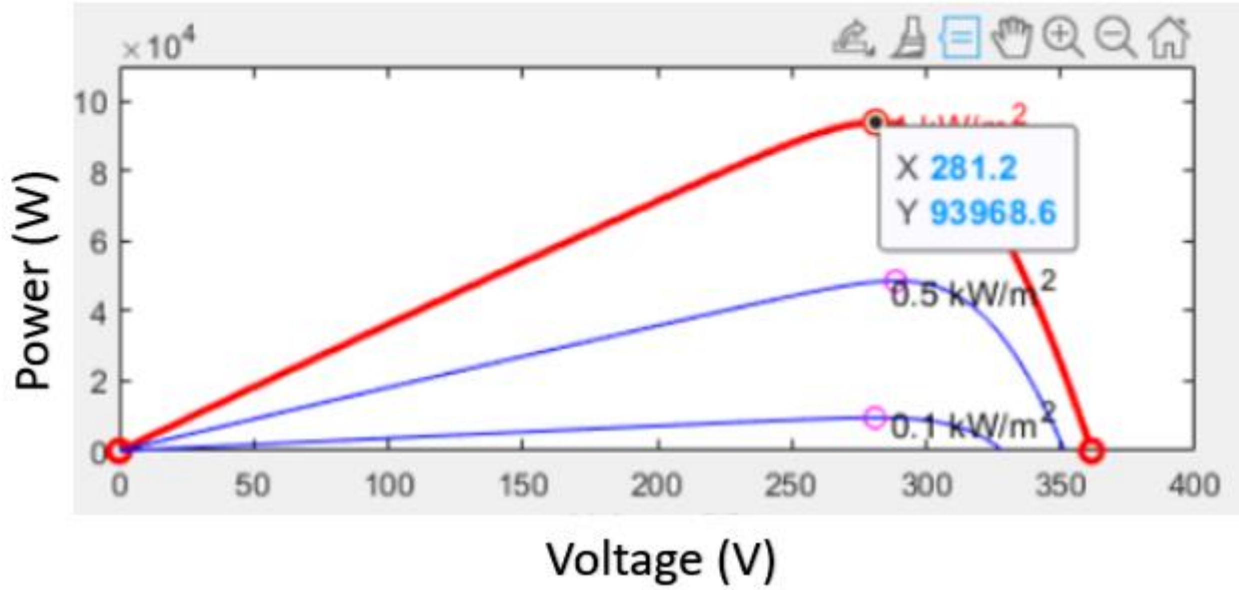

Figure 4.2. The maximum power from the PV

The PV system's PV voltage and current waveforms without MPPT are shown in Figure 4.3 and Figure 4.4.

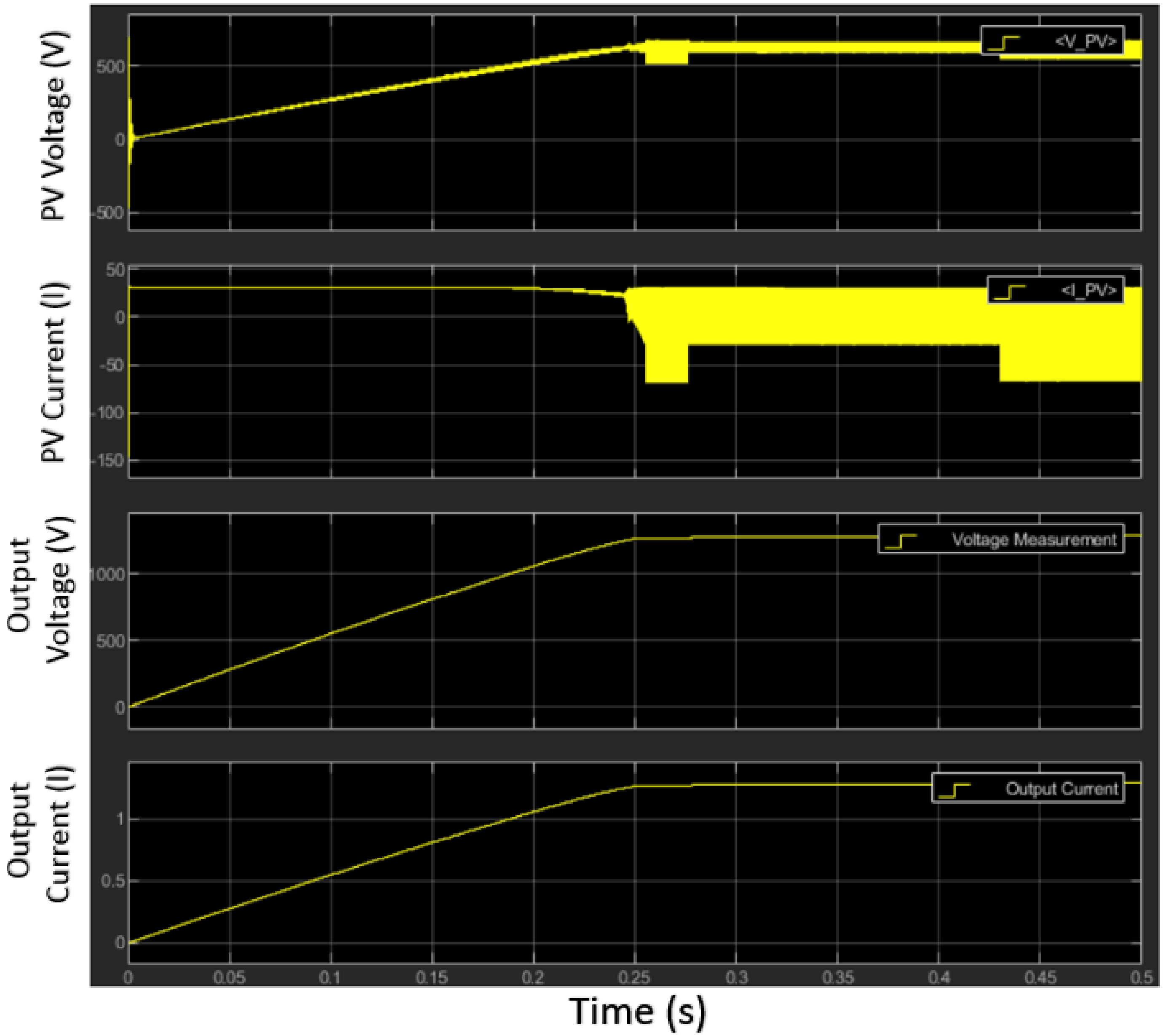

Figure 4.3. Voltage and currents waveform (the system without MPPT)

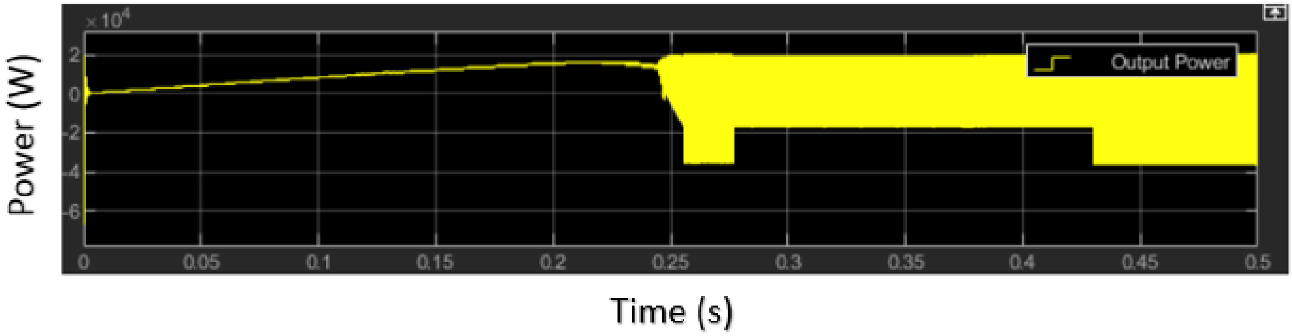

Figure 4.4. PV power waveform (the system with MPPT)

The PV system's PV voltage and current waveforms with MPPT are shown in Figures 4.5. and Figure 4.6. It is noticeable that the waveforms are smoother with fewer ripples and harmonics.

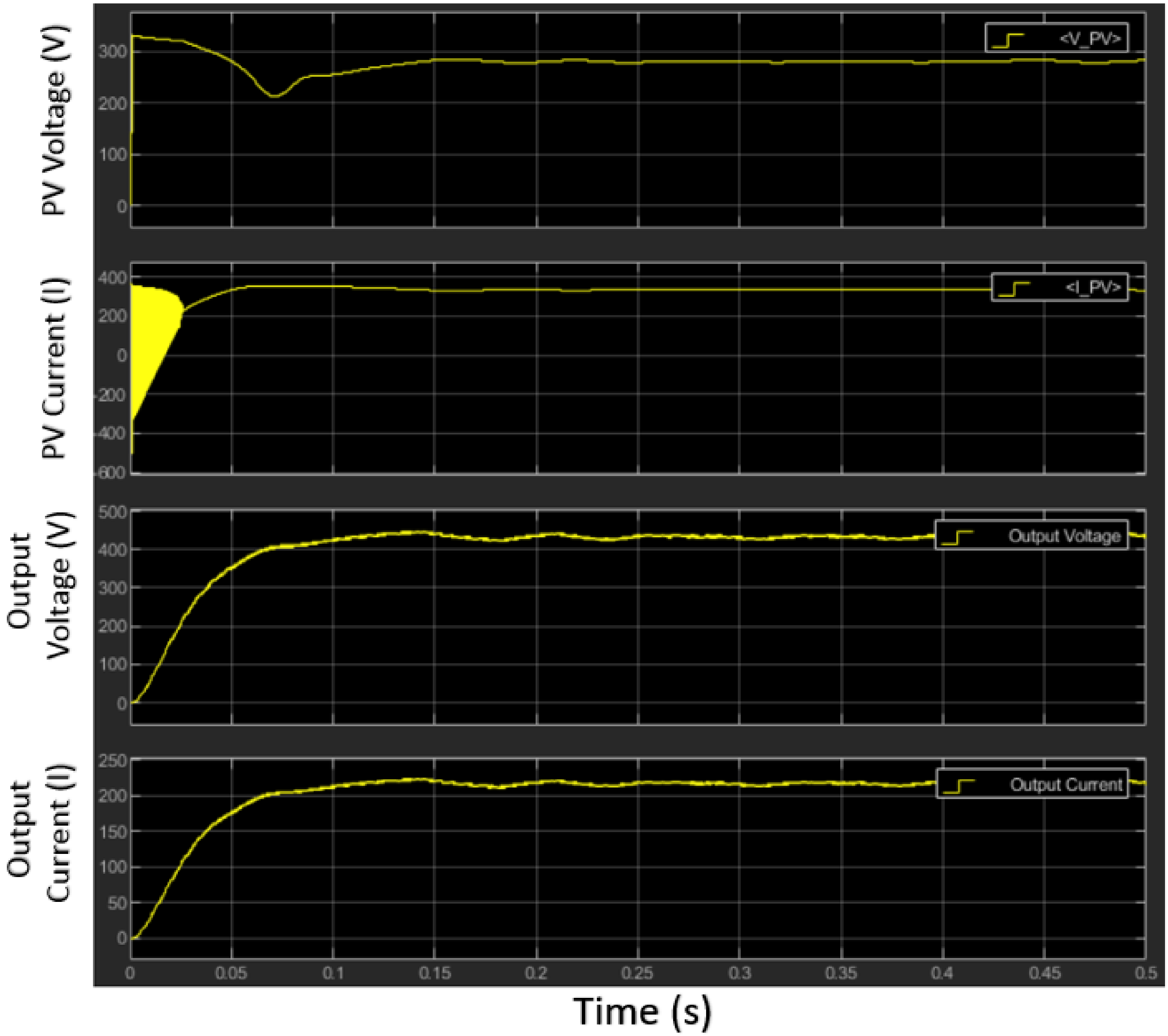

Figure 4.5. Voltage and current waveforms (the system with MPPT)

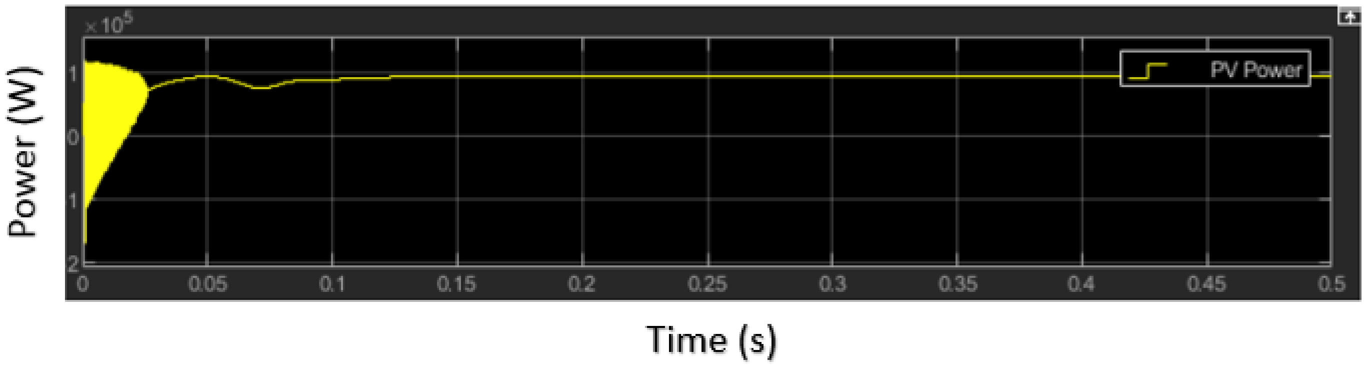

Figure 4.6. Output PV power (the system with MPPT)

The above simulations indicate that MPPT techniques affect the PV system by increasing the output power closer than the maximum power. And applying MPPT results in smoother waveforms for the voltages and current. Hence, applying MPPT to the current PV system at the Effat library rooftop is recommended.

G. Comparing between two port converter and three port converter

Figure 4.7 shows the PV power output with the irradiance being changed and by using P&O MPPT technique in the two-port converter system.

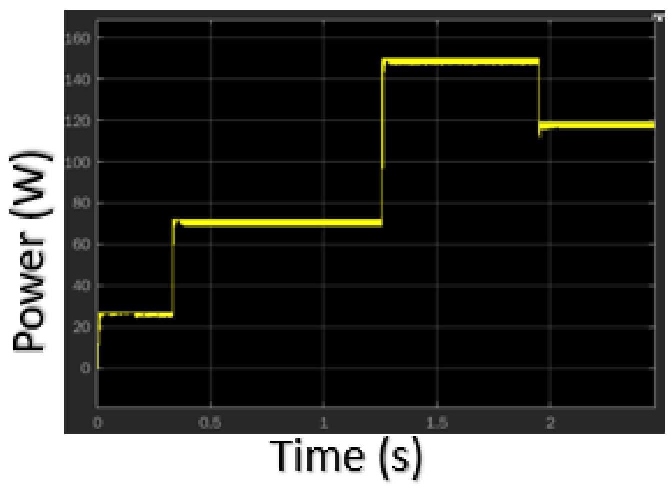

Figure 4.7. Two-port converter PV power output

Figure 4.8 shows the PV power output with the irradiance being changed using the P&O MPPT technique.

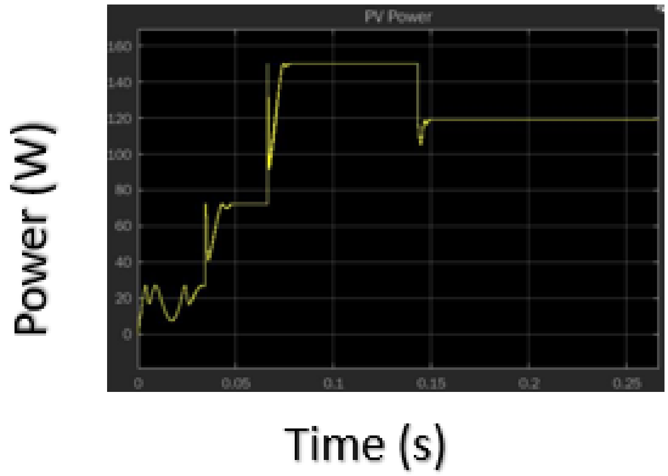

Figure 4.8. Three port converter PV power output

From the above figures. It could be concluded that the two-port converter handles the changes more effectively than the three-port converter. However, the three-port converter has a more stable response than the two-converter when the temperature is kept constant for a specific time. Hence, a two-port converter is recommended if the PV system is installed in an area where the temperature is changing fast. Otherwise, the three-port converter is recommended for its stability.

H. Implementing the TPC in MATLAB/SIMULINK environment

The chosen TPC is implemented using MATLAB/SIMULINK. The main components of this system are the PV, the battery, the full-bridge converter, the rectifier, the load, and finally, the controlling system. The developed system is shown in Figure 4.9. The section denoted by 1 is the PV array where MPPT methods (P&O and IC) are implemented. The second section is the full-bridge converter with the battery. The third section is the rectifier. The fourth signal is generated by the pulses of the four switches in the full-bridge converter.

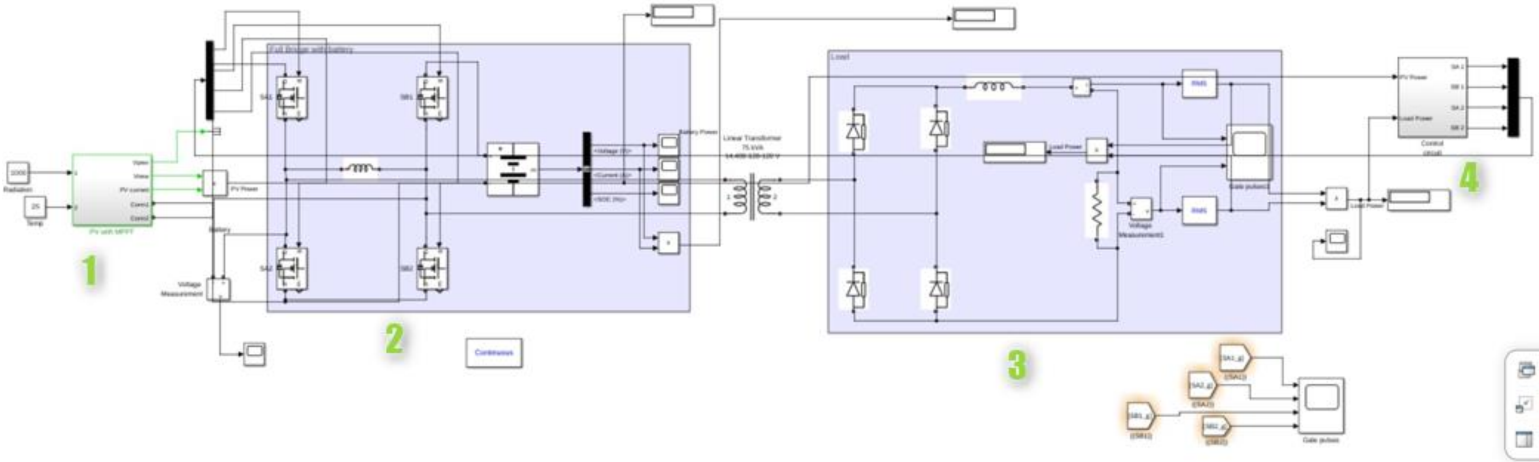

Figure 4.9. TPC modeling in MATLAB/SIMULINK

1) 3.1 Radiation change effect

The MPP of a PV is affected by the radiation; higher radiations result in higher MPP. In real-life, the radiation keeps changing, so the MPPT method needs to respond fast to these changes with higher efficiency. The system's PV power when applying the P&O method and varying the radiation is shown in Figure 4.10. The system's PV power when applying the IC method and varying the radiation is shown in Figure 4.11.

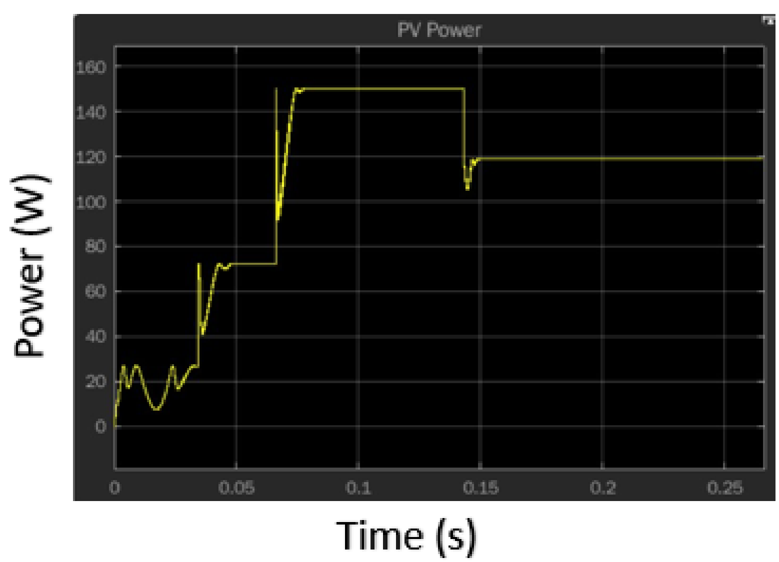

Figure 4.10. MPP changes when radiation changes (P&O)

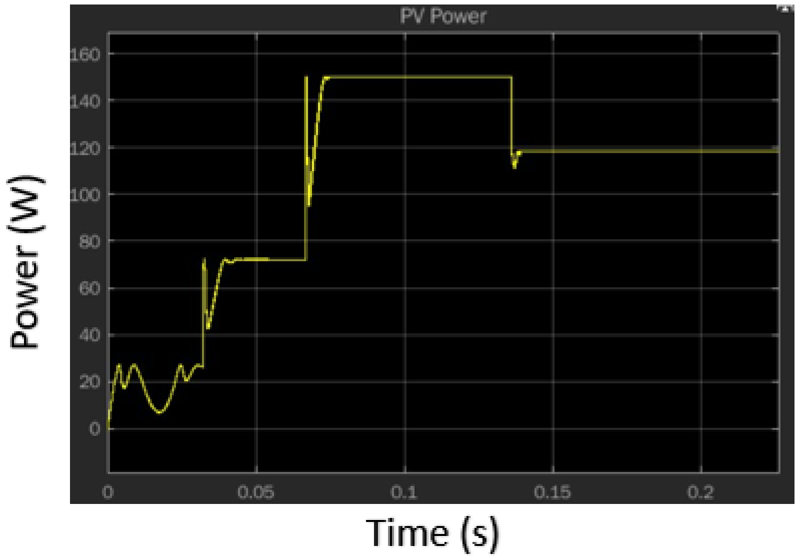

Figure 4.11. MPP changes when radiation changes (IC)

It could be observed that both MPPT methods led to MPP of 140W at the STC condition (1000 W/m^2 and 25C). However, they respond to changes in radiation different. Both methods have a very similar attitude, as seen in Figure V.VIII and Figure V.IX. There is a minor difference before 0.15s. The IC method has a faster response with less distortion than P&O. This is expected as IC was invented to handle P&O issues. However, in TPC, the difference between P&O and IC performance is less significant than the difference when these methods are applied to a standard two-port converter [84], [85], [86]. [87]. This indicates that TPC is more stable regarding environmental changes than regular two-port converters.

2) 3.2 Temperature change effect

Regarding changing the temperature, there is no difference in the MPP graph generated by both the P&O and IC method, as seen in Figures 4.12 and Figure 4.13. However, in standard converters, there is a difference between the two methods when the temperature changes [84], [85], [86]. [87].

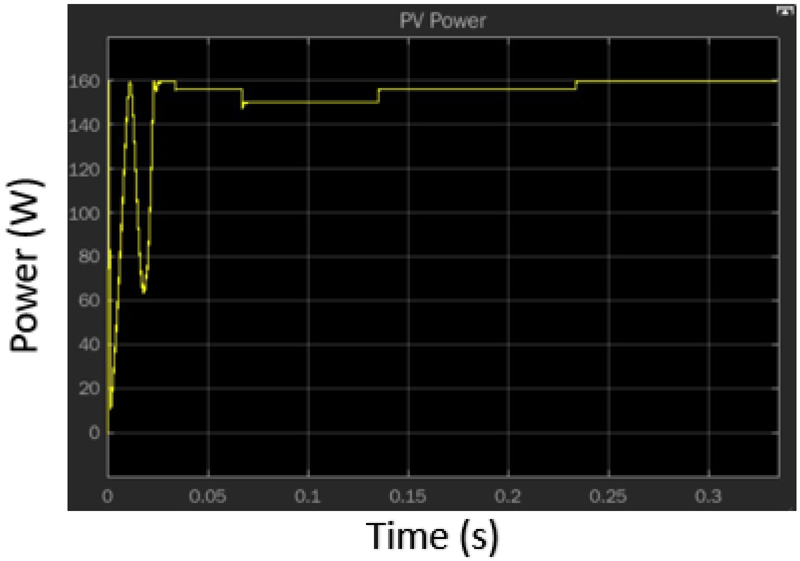

Figure 4.12. MPP changes when temperature changes (P&O)

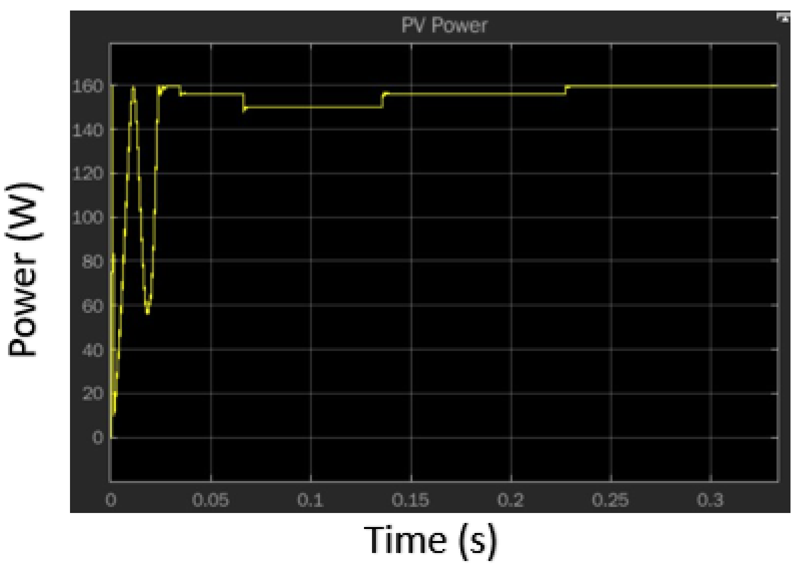

Figure 4.13. MPP changes when temperature changes (IC)

CHAPTER 5: CONCLUSION

There are worldwide procedures and initiatives taken toward more utilization of renewable energy sources as an alternative to fossil fuels which harm the environment. The sun, our planet's star, is an excellent energy source. One way to utilize this source is by using Photovoltaic (PV) arrays that convert sunlight into electricity. The PVs are interfaced with the load by employing a power converter. Since sunlight is not continuously available, the battery stores (charges) power from the PV and discharges this power to the load when there is no sufficient power provided by the PV Traditionally, two power converters are needed; the first converter interfaces the PV array to the load, and the other interfaces the battery to the load. This topology has several drawbacks, such as control complexity because of the increased number of components. Recently, Three-Port Converters (TPCs) have been studied in the literature. A TPC is a power converter with three ports: the PV, the battery, and the third for the load. TPC overcomes the limitations faced by using two separate two-port converters.

To further enhance the efficiency of a PV system with TPC, the PV array has to operate at the Maximum Power Point (MPP). As a result, the load and the battery can receive the maximum power from the PV This MPP varies with temperature and irradiance. Hence, MPP Tracking (MPPT) techniques are developed to track this point. To highlight the importance of MPPT in PV systems, The PV system at the Effat library rooftop is simulated in MATLAB/SIMULINK twice. Once with applying MPPT and once without applying MPPT. The result shows that applying MPPT is vital as it leads to an efficiency of approximately 99%. There are several MPPT techniques investigated in the literature. However, these techniques are primarily applied to traditional two-port converters. There is a need to apply these techniques to TPCs. This thesis aims to apply different MPPT techniques to a TPC used in PV applications and compare them to choose the most suitable one. Several steps are followed to achieve this aim.

- Comparing between an ordinary system with and without applying MPPT
- Choosing a TPC topology and simulating it.
- Comparing between a PV system with two-port converter and three-port converter
- Applying different MPPT techniques to the chosen TPC.
- Comparing the resultant MPPT simulation and choosing the best technique.

The chosen TPC is a semi-isolated converter where the load is isolated from the rest of the circuit. The TPC was simulated in MATLAB/SIMULINK with two MPPT methods. Perturb and Observe (P&O) and Incremental Conductance (IC). The temperature and irradiance are varied to simulate environmental changes in a real-world environment. Both MPPT methods lead to a similar result. The IC method slightly performs better than P&O. This indicates that TPC is more stable regarding environmental changes than regular two-port converters. As for the recommendation, it is recommended to apply more than two MPPT methods to expand the comparison further.

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APPENDIX A

Publications

Paper 1

Part of this thesis was accepted by the 3rd International Conference on Clean and Green Energy Engineering (CGEE 2022), which will be sent to EI Compendex, Scopus, and some major databases for indexing.

CGEE 2022

2022 3rd International Conference on
Clean and Green Energy Engineering (CGEE 2022)
August 28-30, 2022 | Istanbul, Turkey

Website: http://www.cgee.org/; **E-mail:** cgee@iacsitp.com

Acceptance Notification of Full Paper

Co-sponsored by: University of Zagreb; ORTA DOĞU TEKNİK ÜNİVERSİTESİ MIDDLE EAST TECHNICAL UNIVERSITY

Technically Supported by: KADİR HAS ÜNİVERSİTESİ

Media Partner: JOCET

Paper ID#: CEE004
Paper Title: Effect of MPPT Technique in Solar System Efficiency: a Case Study

Dear Amani Alzahrani, Aziza Hussein, Marwa Ahmed,

Congratulations! Based on the recommendations of the reviewers and the Technical Program Committees, we're pleased to inform you that your paper identified above has been accepted for both publication and oral presentation. You are cordially invited to present the paper orally at 2022 3rd International Conference on Clean and Green Energy Engineering (CGEE 2022), Istanbul, Turkey during August 28-30, 2022.

Your paper will be published in published in International Conference Proceedings, which will be sent to *EI Compendex*, *Scopus* and some major databases for indexing.

Paper 2

A paper titled: **Comparison Between Two-Port Converter and ThreePort Converter at Different Weather Condition"** is accepted in **The 5th Asia Conference on Energy and Electrical Engineering (ACEEE 2022).** This conference is co-sponsored by IEEE, IEEE PES, Singapore Institute of Electronics, and Beijing CAS Industrial Energy and Environment Technology Institute (BIEET) and supported by Universiti Teknologi MARA (UiTM), Malaysia. This paper will be included in **ACEEE Conference Proceedings**, included in **IEEE Xplore**, and submitted for **Ei Compendex and Scopus.**

2022 5th Asia Conference on Energy and Electrical Engineering
(ACEEE 2022)

Notification of Acceptance for Publication and Presentation

Kuala Lumpur, Malaysia

July 8-10, 2022

www.aceee.net

Dear Amani S. Alzahrani, Aziza I. Hussein, Marwa M. Ahmed and Mohamed A. Enany,

Paper ID: **EE1009**

Paper Title: **Comparison Between Two-Port Converter and Three Port Converter at Different Weather Conditions**

2022 5th Asia Conference on Energy and Electrical Engineering (ACEEE 2022) to be held in Kuala Lumpur, Malaysia during July 8-10, 2022. which is co-sponsored by Singapore Institute of Electronics(Singapore) and Beijing CAS Industrial Energy and Environment Technology Institute (BIEET) and supported by Universiti Teknologi MARA (UiTM), Malaysia. Based on recommendation of Technical Committees, your paper is accepted for **Publication and Oral Presentation.**

Accepted and presented papers will be published in the volume of Conference Proceedings, which will be submitted and reviewed by the **IEEE Xplore** as well as Ei Compendex and Scopus Index.