energies

MDPI

Review

A Comprehensive Review on Distributed MPPT for Grid-Tied PV System: Sub-Module Level

Yousef Alharbi [1], Ahmed Darwish [1*] and Xiandong Ma[1]

[1] Lancaster University, School of Engineering, Lancaster, United Kingdom.
* Correspondence: a.badawy@lancaster.ac.uk

Abstract: The energy crises and the growth of the energy demand have increased the interest in utilizing unconventional power sources. Thus, renewable energy sources have become a topic of interest to mitigate the arising energy concerns and cope with the increased electricity demand. With its remarkable merits including cleanness and abundance, photovoltaic (PV) solar energy systems are a key player for solving these issues. The employed inverters should effectively utilize the maximum available power from the PV solar system and transfer this power to the utility grid without posing any further limitations. However, the unequal power generation of the different PV systems caused by Partial Shading (PS) and other PV panel degradation factors leads to reducing the power system generation. One of the relatively new solutions to mitigate the mismatch concerns between the PV modules and sub-modules is to extract the maximum power of each sub-module individually. The main objective of this paper is to present a comprehensive review of such PV grid-connected inverters topologies associated with sub-module connections and control. It will classify the PV grid-tied inverters in accordance with the level where the maximum power point tracking (MPPT) system is implemented. A special focus has been placed on sub-module microinverters (MI) in terms of circuit topologies, conversion efficiency, and controller design. This paper provides a comprehensive analysis of employing the Distributed MPPT (DMPPT) approach to maximize the power generation of PV systems and mitigate the mismatch issues between PV SM. The circuit topology, PV system configuration, and MPPT algorithms used for applying DMPPT solution at PV SM are intensely discussed in this study.

Keywords: Photovoltaic (PV); Grid-connected Inverter; Power Electronic Converter; Grid-connected systems; grid integration; MPPT technique.

Citation: To be added by editorial staff during production.

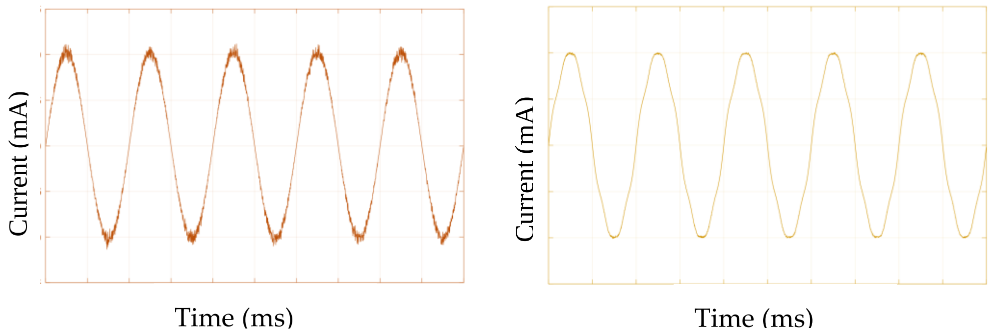
Academic Editor: Firstname Lastname

Received: date
Revised: date
Accepted: date
Published: date

1. Introduction

Nowadays, the electrical grid has evolved to become a mixture of several power-generating resources where photovoltaic (PV) generators are an important key player in this integrated system [1,2]. Extracting the maximum power from the PV system and studying the possible limitations of injecting the electrical energy into the grid is the key design goal of grid-connected PV systems [3]. Thus, tracking the maximum power from the PV systems during different irradiation levels, shading conditions, and low conversion efficiency is one of the main design concerns [3,4]. Other several standards are in place by different organizations to prevent overhead complications on the utility grid [5-7]. For example, the power quality, reactive power control, and islanding operation are of the main problems that pose severe issues for the distribution network. Therefore, the employed PV inverter should be designed so it is able to operate at a unity power factor, improve the power quality, and have a fast dynamic response. Operating at a unity power factor is important in order to reduce the total current through the cables and improve the reactive power content in the grid [8].

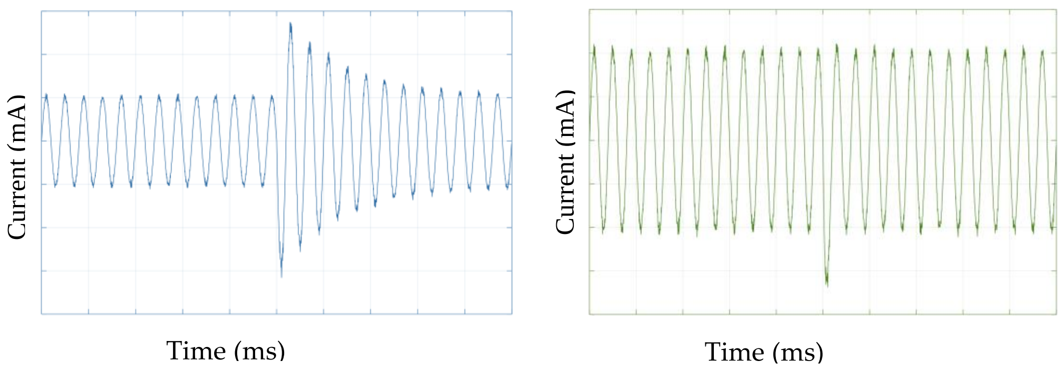
From the power quality perspective, the major grid codes state that the total harmonic distortion (THD) of the output current must not exceed the 5% limit [9]. The THD is subject to increase by either the low or the high order current harmonics [10]. To reduce the high order current harmonics, the employed inverter needs to operate at a high switching frequency or to have big filtering elements in terms of inductors and capacitors. Increasing the switching frequency puts more burden on the switching elements and may increase the switching losses while making the filter bigger will increase the size and volume of the system [11]. On the other hand, the low order harmonics can be eliminated by the suitable control loops acting as harmonic compensators [12]. Figure 1 shows experimental results for inverters producing outputs with high and low-order harmonic currents.



(a) (b)

Figure 1. Experimental results for inverters with; (a) high-order harmonic current and (b) low-order harmonic current (10 ms/div – 5A/div)

The fast dynamic response of the employed inverter will enable the system to recover from faults swiftly, increasing the reliability against faults [13]. In addition, the design must consider the islanding situation to protect both the users and equipment. The conventional islanding method often monitors the grid parameters and takes prevention actions accordingly [14]. Figure 2 shows another experimental test for an inverter experiencing faults when its controllers have slow and fast dynamic responses.



(a) (b)

Figure 2. Experimental results for inverters during faults with (a) slow dynamic response and (b) fast dynamic response (10 ms/div – 5A/div)

Categorizing the PV systems can be a helpful method for understanding the different PV system architectures and the purpose of each design [14]. This might help researchers in this field to comprehend the state of the art of grid-tied PV systems. The inverters and MI are designed to convert the Direct Current (DC) to Alternating Current (AC) in both large-scale PV plants and small PV applications, and it plays a crucial role in enhancing the PV system reliability and improving overall efficiency [14]. Therefore, PV-interfaced systems research is focused on optimizing the existing PV systems' topologies to reduce PV system costs and achieve better system performance [15-20]. The PV system's design usually comes in one of four common topologies according to the PV module arrangements and PV system requirements. Namely, these topologies are centralized inverter PV plants, string inverters, multi-string inverter PV, and PV module MI PV systems [21].

The conventional classification of PV systems is mainly based on the power capacity of the PV applications and projects [21]. Thus, the three main categories of a grid-connected PV system are large-scale PV plants, medium-scale PV projects, and small-scale PV applications. The small-scale application starts from a few kW to up to 50 kW, while medium-scale project capacity can reach up to 1 MW. The PV system with a power capacity of more than 1 MW can be considered a large-scale project [14,22].

Classifying the grid-tied PV systems based on the voltage level at the point of common coupling (PCC) is another approach to categorizing grid-connected PV systems. Low Voltage grid-connected PV systems include both small PV applications and some medium-scale PV projects where PV systems are installed close to the end users. Large PV plants directly connected to a 20 kV voltage grid or more in high voltage grid-tied PV systems [23]. One main objective of PV power converters devices is harvesting and exporting the maximum available power from the PV system to the utility grid. Therefore, designing and optimizing the maximum power point-tracking strategies can significantly improve the PV system efficiency and enable obtaining the full available PV power [14, 25].

The PV inverters are designed and controlled to operate on their maximum power point (MPP) using the maximum power point tracking (MPPT) controller [26-32]. Operating at the MPP of the PV system is usually related to the scale of the PV system. This means that when the inverter or MI is connected to a few numbers of the PV modules, the tracking process becomes swift and more accurate which can improve the efficiency and reduce the overhead on the PV system controllers [25]. The grid-tied inverters are an essential part of renewable energy interfaced systems that link the different types of renewable resource and energy storage systems to the utility grid. Therefore, optimizing the grid-connected inverters can significantly contribute to reducing the investment and operation cost of the PV system [33].

The electrical grids need support from the connected distributed generators and their power generation security can be enhanced if the solar power plants can export the power directly to the medium or high voltage networks without limiting grid stability [9,34]. Controlling the active power of the PV system's current can increase energy yield and enhance PV system performance, which can improve grid-side performance. However, different power consumption patterns caused by changing the voltage and frequency of the utility grid can negatively affect grid stability. Overcoming this issue will be based on regulating the voltage and frequency during the design of the controllers of the grid-tied PV systems [34]. The stability of the utility grid can be improved if proper active and reactive power controllers are used, and common grid-related concerns especially voltage sags can be solved [34-35].

The grid-tied inverters can be interfaced with three-phase and single-phase power systems according to the PV project size [35]. In the three-phase power system, the step-up transformers are used to boost the output voltage and meet the grid-side voltage requirements [36-38]. Centralized inverters are usually used in three-phase power systems to link large-scale PV plants to the utility grid [39]. The centralized inverter technology is usually used in three-phase power systems and it might be the most traditional in PV systems, also it has been used for many years because of its large-scale conversion ability. On the other hand, in a single-phase power system, the small PV applications are often interfaced with the distribution network, and Distributed MPPT inverters are used [40].

The Distributed MPPT inverters have been proposed to increase the power harvesting from the PV systems. It can significantly increase power generation under low irradiation levels. Also, distributing the MPPT can improve the scalability of the PV system without introducing a significant disturbance to the utility grid. [33,40].

The unbalanced power generation of PV modules due to the different environmental conditions is one of the significant issues in centralized PV systems and it significantly reduces power generation in PV systems [41, 43]. One main cause of unbalanced power generation between PV components is partial shading due to buildings, clouds, and trees. This can lead to mismatch problems in PV power systems. The mismatch problem can negatively affect conversion efficiency since the PV system current will be limited by the PV module with the lowest output current [42].

Centralized grid-tide inverters might not be able to identify the power generated by each parallel sting under a partial shading effect and the overall power generation of the PV system will be reduced [43]. The bypass diode is commonly integrated with the PV SM to minimize the effect of partial shading; however, it can cause multiple peak power points. In such a scenario, the MPPT algorithm might be only able to track the average maximum power. However, the average output power can be lower than the sum of the maximum power of the PV modules [44].

DMPPT technique has been used to mitigate the mismatch issue between PV components and increase the energy yield of the PV system [45-47]. Although the DMPPT strategy requires a more complex controlling process, it can improve the reliability of the PV system and mitigate the mismatch problem [46].

Several reasons can lead to the different current generations of PV components, including external factors such as different PV panel orientations and partial shading. Also, interior features like manufacturing tolerance and aging might lead to unbalance power generation of PV strings [44]. Also, faulty PV components can limit the PV string's current which will reduce the current generated by other PV components in the series connection. Thus, processing the power generation of each PV component can mitigate the negative effect of the faulty PV component on others in the series connection [45].

Conventional PV systems have several severe problems that limit PV power generation and adversely affect PV system performance. Power losses due to mismatch issues, partial shading, and ground-associated faults can be the major issues. Thus, optimizing the typical PV system is usually based on tackling these concerns. One proper solution to overcome the mismatch concerns and partial shading effect is employing MPPT at a finer level. This review paper discusses the state of the art of distributing MPPT technology on grid-connected PV systems. It is focused on applying the DMPPT approach at the PV SM level [48].

One main objective of classifying the grid-connected inverter is to understand the latest trend in this technology and help researchers to choose the optimization opportunities effectively. Organizing the grid-tied inverters according to where MPPT is applied can be a proper categorization strategy. In this review paper, the grid-connected inverters are classified according to the level where the MPPT is applied. The grid-tied inverters can be grouped into two main groups according to the MPPT function, Centralized MPPT, and DMPPT. This work can be a helpful tool to understand different types of grid-connected PV systems and the purpose of each PV system topology.

Some review papers have discussed employing the DMMPT approach to effectively increase the power harvesting of PV systems [49]. Others discuss the negative effect of partial shading on a group of PV cells [50]. However, none of them have deep discussions about applying the DMPPT technique at the PV SM level. Thus, the lack of information about employing DMPPT leads to this review paper. Although studies on [51] present some issues related to DMPPT on the PV SM level, still there is an absence of discussion about MPPT techniques used at the PV SM level. This paper reviews common power converter topologies and MPPT techniques that have been used to employ the DMPPT systems at the PV SM level.

This paper is reviewing the power electronic converter topologies used for grid-tied PV systems, with a specific focus on low-voltage level modular PV applications. The paper will categorize the grid-connected PV systems according to where MPPT is employed and will explain the distributed MPPT strategy which has been used as a viable solution to overcome the unbalanced power generation under the partial shading effect. A detailed explanation of grid-tied PV inverter topologies including merits, limitations, and technical issues is provided in section 2. An important consideration of PV SM DMPPT architectures and a specific review of different MPPT algorithms is presented in section 3.

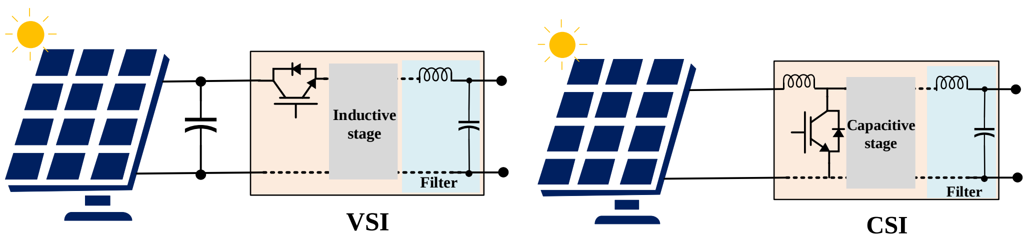
Detailed discussion about the finding of this review and proposed recommendations are considered in section 4. Section 5 discusses the present associated challenges and gives direction for related future work. Finally, section 6 concludes the outcomes of this review study.

2. Grid-Connected PV Inverter Topologies

The grid-tied DC-AC inverters have been presented to enable pumping up the generated power from PV systems into utility grid companies. To effectively send PV power to the grid, several standards should be fulfilled by the grid-tied DC-AC inverter including maintaining power quality, decoupling the arising AC current components at the input side, and consideration of the islanding situation [52]. The DC-AC inverter is an essential part of grid-connected PV systems and hence reducing the cost per inverter watt can significantly minimize the installation cost of the PV generators. Therefore, many researchers focus on innovating optimized and cost-effective inverters [53-55]. The employed inverter can operate as a voltage or current source inverter [56]. For voltage source inverters (VSIs), the input DC voltage will be chopped by input switches operating and controlled by a pulse-width-modulation (PWM) scheme, converted to the output side by the output switches and then filtered by inductors.

The main issue with the VSIs is that their input currents are discontinuous which requires large capacitors at the input side to smooth the PV module current [57]. Installing large capacitors at the input side (output of the PV modules) is not favored as it can affect the system's reliability negatively. The current source inverters (CSIs) can generate continuous currents at the input side first, then chop the currents using the set of PWM switches, and then filter this current using a capacitor [58]. The CSIs do not need large filtering capacitors at the input side and therefore are favorable to be employed as PV inverters.

However, their control system is usually more complicated than the VSIs and needs careful parameter tuning. This is because the CSI requires at least an additional input stage where the current is generated by the action of the input switches with the inductors. This means that the output current and voltage are not generated directly from the input side which appears as a right-hand plane (RHP) zero in the frequency domain analysis of the inverter. Figure 3 shows the basic structures of VSI and CSI.



(a) (b)

Figure 3. Generic configurations for dc/ac inverters: (a) VSI (b) CSI

The connection of the PV modules or panels to the inverters is important in selecting the suitable inverter system. As shown in Figure 4, there are different possible connection technologies and they will be presented briefly in the next subsections.

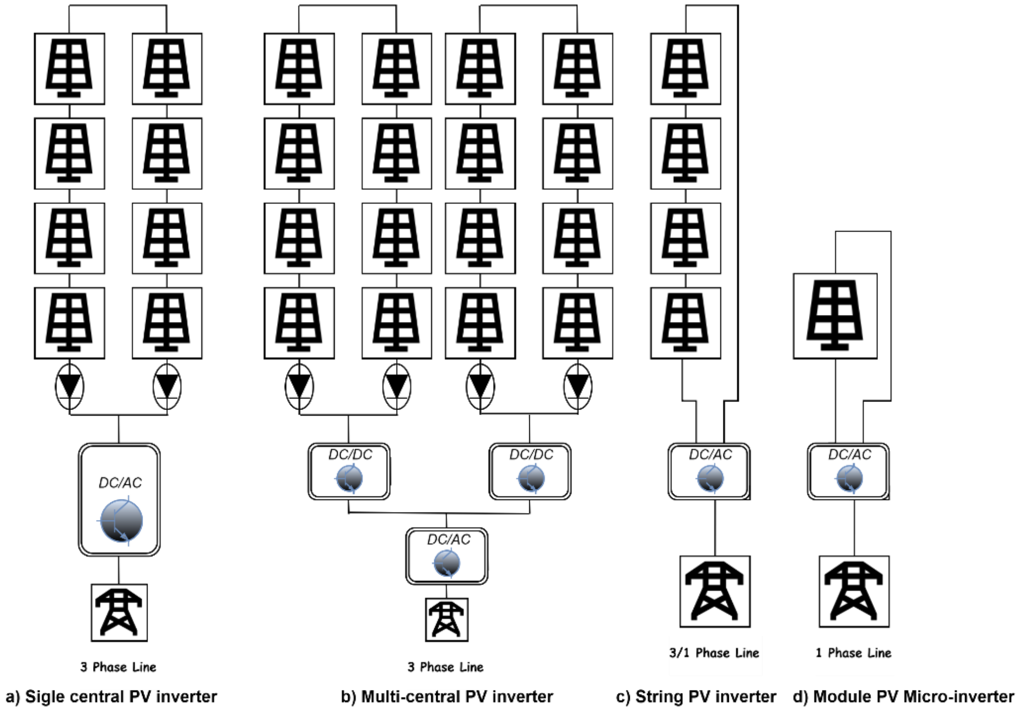


Figure 4. The grid-connected PV system classification according to DMPPT level (a) Single central PV inverter (b) Multi-central PV inverter (c) String PV inverter (d) PV module MI.

2.1. Grid-Tied Central Inverter

The grid-connected central inverts might be the oldest technology used for both grid-tied and standalone PV systems. The essential objective of the central inverters is to link the high-power PV plants with the utility grid. The central inverter technology is a combination of series and parallel connections of PV modules [59]. The series connection is called a string and, it is used to generate sufficient output voltages according to the utility grid needs. Thus, the central inverter does not necessarily require further voltage amplification during the circuit design stage. Each PV string of the central inverter is connected in parallel via string diodes to prevent the reverse current to flow from other strings in the PV array. The parallel connection in central inverters is often used to obtain the PV projects' high power requirements [60,61]. One common concern about the centralized inverter is the self-partial shading of the PV system when some of the modules cause shading to others. This issue can be solved by varying the distance from the PV strings [62].

The MPPT control of the grid-tide central inverter is usually operated at the PV plant level which reduces the MPPT controllers' complexity. However, the central inverters have several severe limitations, and one of the main concerns of this technology is the mismatch losses due to the different power generation from the PV modules during the partial shading conditions [63,64]. The central inverters often use high-voltage cables to link the PV arrays with the utility grid, significantly increasing the installation cost. Also, the scalability of the PV design is limited in this technology, thus increasing the power production might not be achieved. The string diodes that are used in central inverters have an internal loss that reduces the overall efficiency of the PV plants. The central inverter malfunction might lead to the loss generated from the PV array [65].

The breakdown of the central large-scale inverter can lead to stopping the entire PV system from working, loss of PV power generation, and can pose several limitations to grid utility. This concern can be mitigated by using multicentral PV inverters [68,69]. The multicentral inverter topologies can improve the reliability of the large PV power plant and apply the MPPT at a sub-array level which might mitigate the mismatch issues. The multicentral PV inverter technology aims to group the large PV array system into subarrays where each parallel connection is linked to an individual inverter. This technology is often preferred for medium and large PV plants where power generation exceeds 0.5 MW [70]. The multicentral PV inverters are commonly connected in parallel to obtain the maximum power from the subarrays and maintain the reliability of the PV system in the case of inverter malfunction. Figure 4 (a) illustrates the single central PV inverter topology and Figure 4 (b) shows the multicentral PV inverter connection.

A basic example of central inverters is the three-phase VSI which is shown in Figure 5. Because the full power is handled through the six semiconductor switches, the failure of any switch will result in the full shutdown of the PV system. The switches can be affected by overvoltage or overcurrent from the PV modules as well as the high temperature which are expected in this application. This might increase power losses and adversely affect the efficiency of the PV system. Distributing the MPPT at a lower level can mitigate this issue and improve PV energy harvesting.

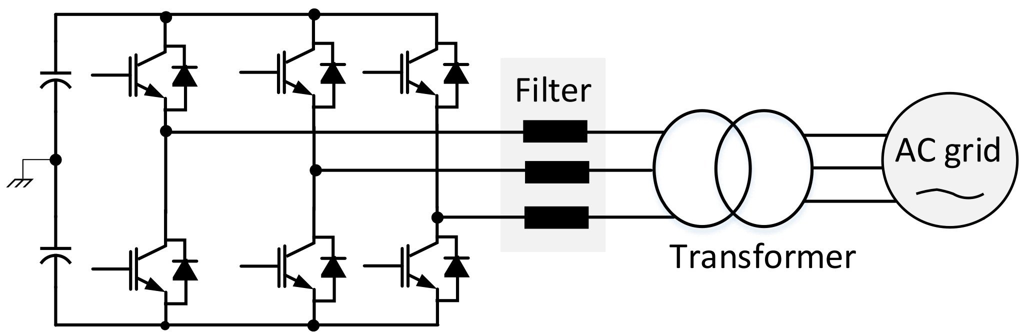


Figure 5. Three-phase VSI as an example of central inverters

The central inverter is usually a large inverter used to convert the high DC power from the PV array to AC power. The system topology might come in one of two different topologies in terms of power pressing, single-stage central inverter, and dual-stage central inverter. Three-phase converters can offer some merits compared to single-phase full-bridge converters including reducing the size of the high-frequency transformer with maintaining the switching frequency, reduction in the size of filter components, and better conversion efficiency [66]. The DC-AC central inverter is often connected to the medium and high voltage power system because this technology is designed to generate high-rated power which is more suitable to interface with a three-phase system. One of the main objectives of using three-phase grid-tide central inverters is their capability to mitigate the effect of THD and improve the transient performance, leading to higher efficiency [67]. On the other hand, single-phase inverters will be required if the scale of the PV system is lower than 10 kW which is usually the limit of residential PV systems. The main issue with single-phase systems is that they have pulsating power components at twice the grid's frequency. This pulsating power will cause the input current of the inverter, which is the output current of the PV modules, to have both dc and AC components. The AC current component will cause the output PV power to be fluctuating around the MPP and hence the maximum power will not be obtained, current-voltage and power-voltage curves are illustrated in Figure 6. Therefore, the AC component of the inverter's input current has to be eliminated using either a hardware filter or a complete control algorithm [12, 48].

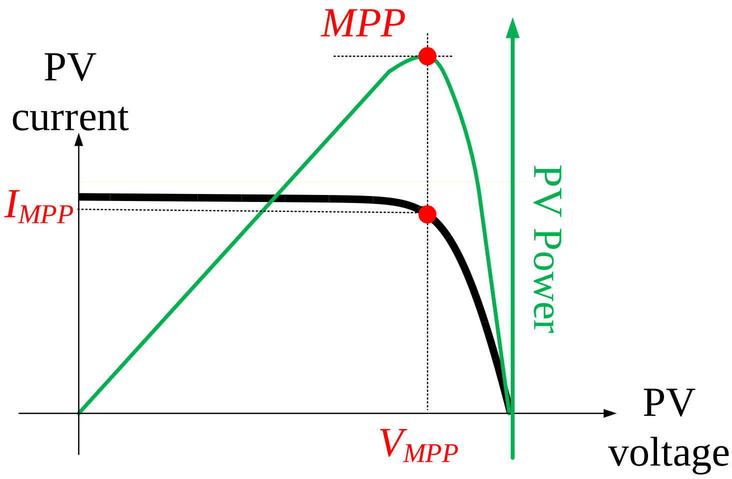


Figure 6. Generic current-voltage and power-voltage curves for a PV module

2.2. Grid-Tied Distributed Inverter

The DMPPT is a strategy used to maximize PV energy harvesting and improve PV system performance [45], [47]. The DMPPT approach can be implemented at different PV system levels starting from the PV array level to the PV cell level [46]. The maximum energy of the PV systems can be captured when the PV modules operate at their MPP as shown in Figure 6 while different tracking algorithms have been used to track and capture maximum power from PV system [29 -31]. The input voltage of the PV system should have relatively small ripples to enable the tracking algorithm to operate successfully. To maintain the tracking algorithm accuracy to become more than 98%, the voltage ripple from the PV input side should be less than 8.5% [45].

2.2.1. PV String Level Inverter

The string inverter technology in Figure 4(c) is an updated version of the conventional central inverter topology [4]. Each string is built by connecting a series of PV modules and the resultant connection is linked to the DC/AC inverter. Some string inverters can meet the voltage requirements of the grid side and hence DC-DC step-up converter will not be needed. However, some other systems will require DC-DC boost converters on the input side or boosting transformers on the output side to step up the output voltage in order to reach the voltage level of the utility grid [72]. Grid-tied string inverters can mitigate some issues presented in central inverters [25]. For example, the power losses due to using the string diode to eliminate reverse current from other strings of the parallel connection is eliminated which helps to improve the overall efficiency of the PV system. Furthermore, the mismatch issue between the PV system strings caused by different current generations is reduced, and each PV string will operate at an individual MPPT [40]. Compared with central inverters, the robustness of the PV system can be enhanced due to using string inverters because failing one string does not lead to stopping the entire PV system from working. Because the total power is shared by several inverters, the current ratings of the employed semiconductor devices can be reduced in comparison with the central inverter topology which will result in improving the efficiency and enhancing the reliability [49]. Figure 4(c) illustrates the circuit topology of the string inverters.

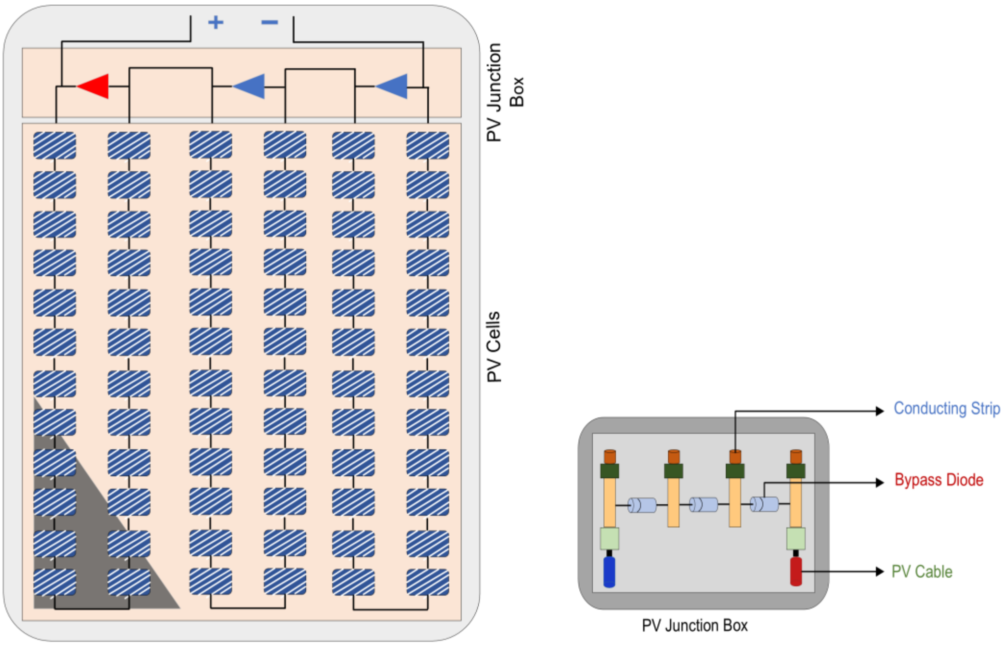
2.2.2. PV Module Level Inverter

The conventional residential PV system topology is usually based on cascading the PV panel to reach the grid-side voltage level. The maximum power can be harvested by operating each PV panel at its total MPP which will be the global point for the combined panel [73]. Nevertheless, residential PV applications are sensitive to the mismatch problem between the PV panels because it adversely reduces PV power generation [4]. One proposed solution to mitigate the mismatch problem between PV panels is to add a parallel diode with each PV panel which can reduce the negative voltage polarity of faulty PV modules caused by full or partial shading [74]. However, power generated from the affected PV panel will be lost in this case. In the PV module level inverter system, each separate PV module in the panel will have its dedicated inverter and controller to harvest the maximum energy and operate the PV modules at their local MPPs. Accordingly, each PV module will be sold with the MI which can be a single-stage or a double-stage inverter [75]. Because the MIs are designed at the module level, the employed semiconductors can have lower voltage and current ratings which will increase the total efficiency. Also, the reliability of the total system will be improved during faults in one or more MIs because the rest of the system will function normally.

Although it can be predicted that the cost of the system will be higher than the central inverter structure, the study in [76] shows that the price can be lower on some occasions. Moreover, this system provides more degree of freedom in terms of reactive power generation and grid support in general. In this context, the DC-DC optimizer has been proposed to obtain each PV module's power and meet the end users' local demands. The DC-DC optimizer can be applied in two common topologies, series connected to DC-DC optimizer and parallel connected DC-DC optimizer [77]. The cascaded DC-DC optimizer architecture can provide better conversion efficiency compared with parallel connected optimizers [78]. Figure 4(d) illustrates Module integrated DC-AC MI.

2.2.3. PV Sub-Module Level DMPPT

This is a new approach to applying DMPPT in residential PV systems based on PV sub-panel level [23,72]. The integrated distributed power electronics enable capturing the maximum power from each sub-panel inside a single PV module. Employing this strategy not only reduces the current and voltage mismatch but also can increase the energy capturing by up to 20 % by distributing MPPT at the finer level [72]. Commercial PV panels are usually grouped into three or four groups according to the manufacturing company, also the PV panel commonly comes with a PV junction box that contains the electronic parts of the PV panel [23]. Figure 7 illustrates the typical 72 PV cell panel with its PV junction box.



a) 72 Cells PV Panel b) PV Panel junction box

Figure 7. A Standard 72 PV cells panel circuit diagram (a) The structure of the series connection of 72 solar cells PV panel (b) the Integrated junction box of the 72 cells PV panel.

The revolution of the grid-connected PV inverter is presented in Table 1. The past approach was based on conventional central inverter technology. The centralized inverter is commonly used with three phase power system. The MPPT system is implemented at the PV array level and only one MPPT is employed. The multi-string inverter technology comes after the central PV inverter. In such technology, the PV array is grouped into multi-strings. The MPPT is applied to a lower level and both three and single-phase power systems might be interfaced. In the PV string inverter DMPPT is implemented at the PV string level and a single-phase system is commonly used in this technology. The present technologies consist of a PV module and a PV SM inverter.

Employing DMPPT at this level can significantly maximize power harvesting since the MPPT system is implemented at a finer level.

Table 1. Comparison of various grid-connected inverter topologies

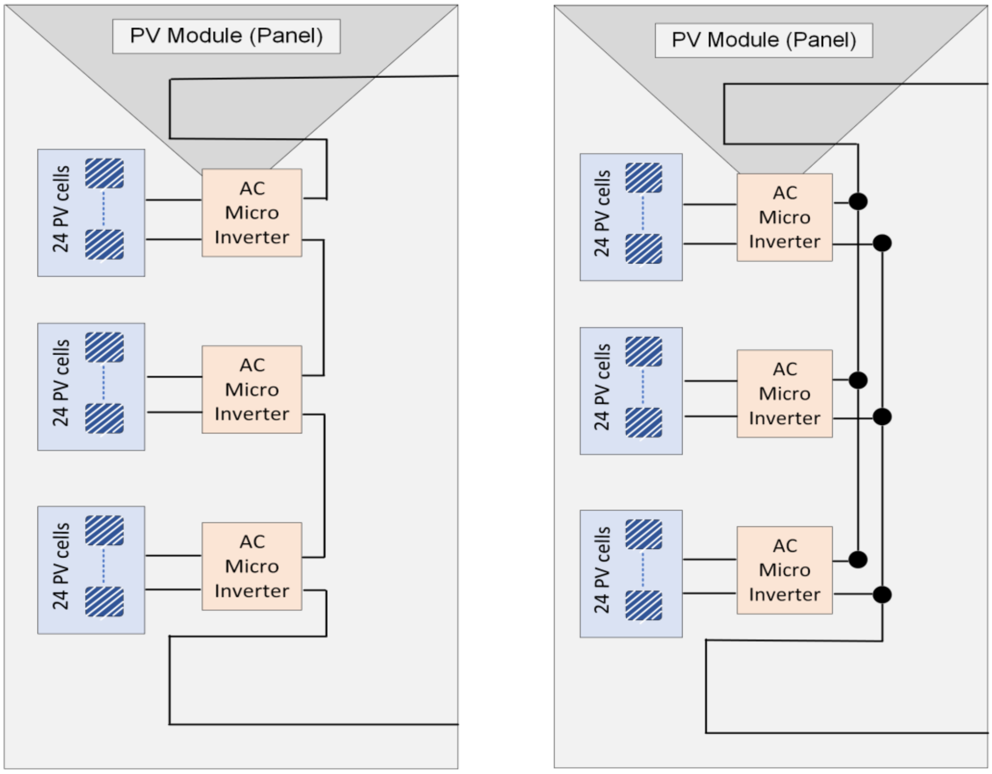
Ref.	DMPPT Level	Single/Three Phase	Voltage range (V)	Rated Power	PV interfaced Converter	Grid interfaced Inverter
[79]	Array	Three	380	20 Kw	Boost	Three Phase VIS
[80]	Multi-String	Three	180	1Kw	HFAC Link	Three Phase VIS
[81]	String	Single	110	1Kw	H-NPC	H- Bridge
[82]	Module	Single	230	1Kw	Cuk	H- Bridge
[83]	Sub-Module	Single	220	217W	Push-Pull	H- Bridge

3. PV SM DMPPT Architectures

3.1. Sub-Module MI

The harvested energy from the residential PV system can be significantly increased by applying power conditioning to the sub-panel level [47]. Appling the DMPPT at the sub-panel level can mitigate the mismatch issue between sub-panels inside the same PV module, increasing energy harvesting of the overall PV system [72]. Cascaded DC-DC optimizers have been used to reduce the sub-panel mismatch problem and optimize the residential PV system efficiency [72], [77]. However, the installation cost of this system might rise when compared with the other types and also more complex controllers will be required. Employing differential power processing (DPP) DC-DC converters is another strategy to apply power conditioning at the PV sub-panel level [78], [84].

The main objective of DPP converters is to equalize the photocurrent of the PV sub-panel during the mismatch conditions. The complexity of the controlling process and the high installation cost are the main drawbacks of this optimization method. Sub-module microinverter (SMMI) can be a promising solution to effectively utilize the PV power from each sub-panel and improve the total PV system's efficiency [85]. This futuristic strategy can convert the DC current of the PV sub-panel to an AC current and link the output current to the utility grid with no need for a central DC-AC inverter. Figure 8 illustrates both series and parallel grid-connected MIs at the sub-panel level which will be presented in the next subsections.



a) Series Connected MI b) Parallel Connected MI

Figure 8. Sub-Module grid-connected Micro inverter: (a) series and (b) parallel

3.2. Sub-Module Series Converters

The PV SM DC-DC optimizer proposed in [86] aims to increase energy capture of the PV module during the unbalanced power generation of PV submodules. This study employed a synchronous buck converter topology to mitigate the PV SM mismatch issue efficiently. Low-cost devices with small sizes are used in the design stage due to increasing the switching frequency range. The synchronous buck converters are cascaded to build higher output voltage and avoid further step-up power converter circuits. The controlling process of the SM DC-DC optimizer is relatively simple since no communication is required between the SM controller during a mismatch effect. Figure 9 shows a schematic drawing of the SM DC-DC optimizer.

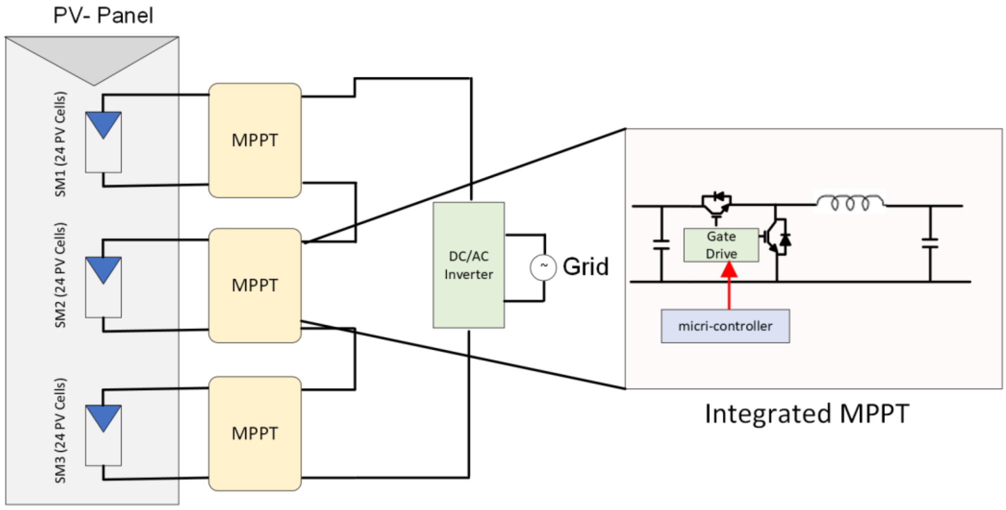
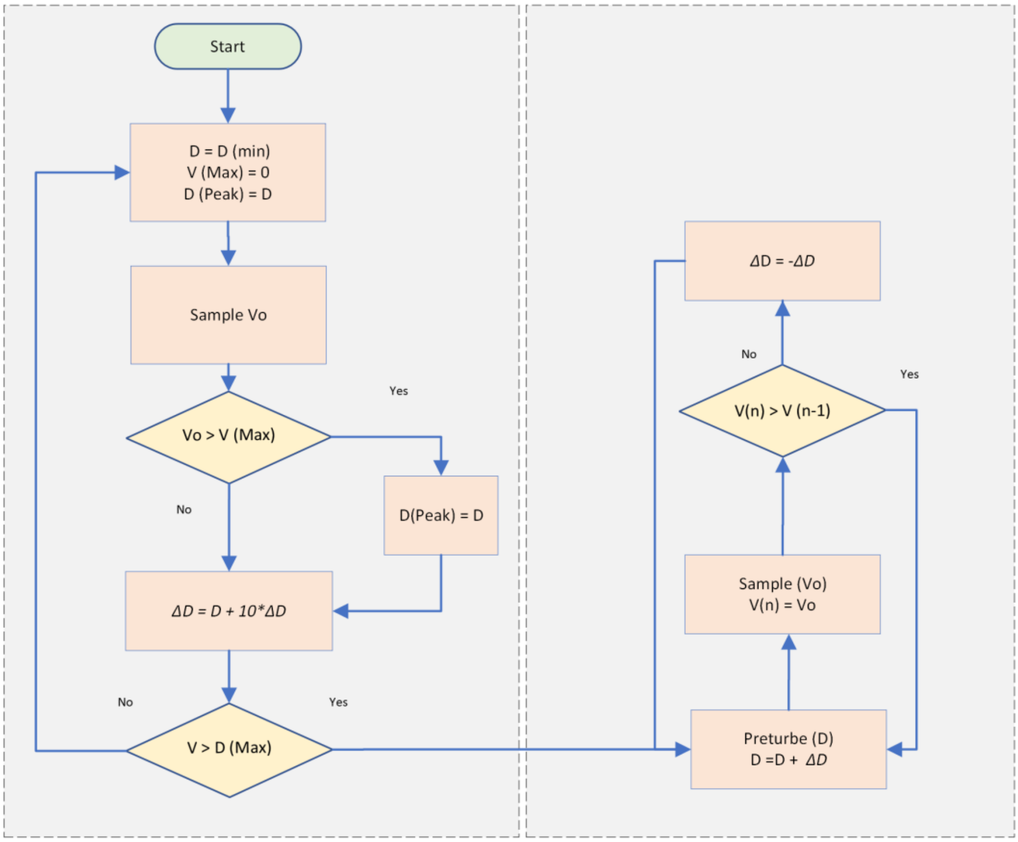


Figure 9. Drawn diagram of the PV SM integrated MPPT system

In terms of MPPT control, each PV SM power is tracked using Preturbe and Observe (P&O) algorithm. DC-DC optimizer strategy overcomes the several maximum points problem caused by bypass diode under unbalanced power generation. The string current of the three SMs can be considered a constant value since they are connected in series. Thus, the controlling parameter used to track the maximum power point is the corresponding voltage of each PV SM This becomes a direct optimization problem that aims to obtain the maximum power by varying the duty cycle of each DC-DC optimizer. The flow chart in Figure 10 illustrates the MPPT algorithm used to track the local MPP of each PV SM.

The local algorithm will start by initializing the parameters of the DC-DC converter. Then it will sample the voltage output. Comparing the output voltage with the recorded maximum voltage can determine the next step. If the duty-cycle ratio can achieve the maximum output voltage, the first algorithm will stop and the output duty ratio will become the input of the next tracking algorithm. Otherwise, the new duty ration will be calculated by perturbing the first duty ration. After the approximate MPP is found by the first algorithm, the P&O algorithm will be used to calculate the accurate MPP. The output duty-cycle ratio from the first algorithm is used as the inial value of the second algorithm. This duty ratio will be perturbed and voltage will be sampled accordingly. The direction of the next tracking cycle can be decided by comparing the voltage of the current cycle with the voltage of the previous tracking cycle.



a) Local maximum point algorithm b) Conventional P&O algorithm

Figure 10. The flowchart diagram shows the MPPT algorithms (a) the Global maximum point algorithm and (b) The typical P&O MPPT algorithm.

Zhu, et al. in [87] propose an SM single-inductor single-sensor DC-DC optimizer to reduce the converter SM MI's size and cost. With only a single inductor and a single sensor, this optimizer can make three SMs work on independent MPPs to maximize the energy harvest. The suggested buck converters are connected in series to step up higher output voltage. The MPPT algorithm used in this topology is the perturb and observe algorithm. The major drawback of such a connection is that a single MPPT system is applied for the three SMs of the PV panel. Thus, energy harvesting and PV system performance might be negatively affected. Figure 11 shows the circuit configuration of the novel topology that is based on a single inductor and single current sensor.

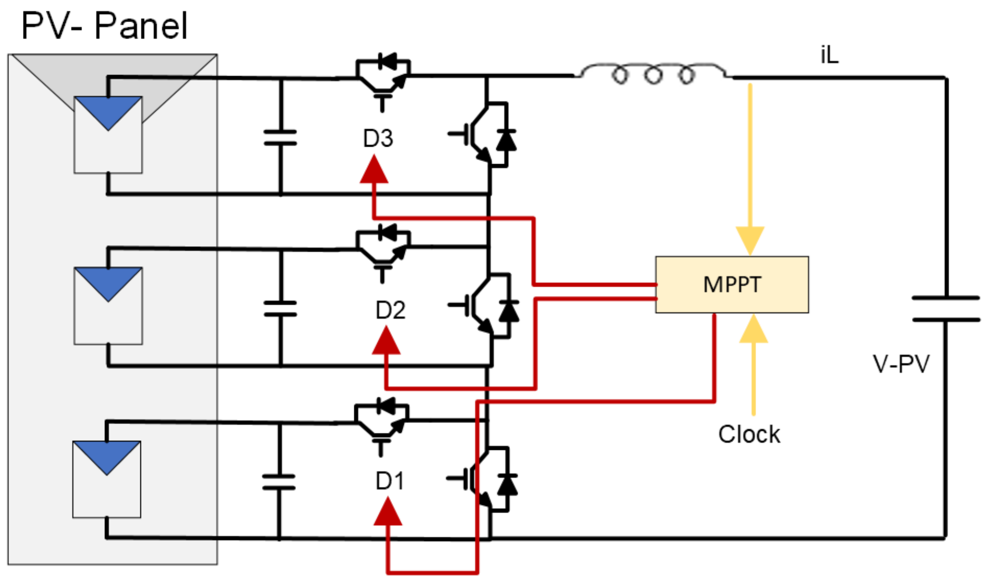


Figure 11. Configuration of the optimized buck-based MPPT system

To control the MPP of each SM, the adaptive perturb and observe (P&O) algorithm has been used to perturb the PV module current and decide the direction of the next cycle. The PV module current is sensed and compared to each SM's current which is used as the reference current of the next tracking period. The duty-cycle ratio used for operating the SM converters is calculated as the ratio between the SM current to the module current in one tracking cycle. Figure 12 shows the flow chart of the adaptive MPP algorithm used in this study where the clock parameter is a factor that decides which SM should be tracked. The algorithm will start by sampling the PV SM current iL.

The clock value is regularly increased and decided which SM should be tracked. When the value of the clock is between 0 and t the controller will track the MPP of the first SM while the seconded SM MPP can be tracked if the clock value range from t and 2t. The MPPT controller can track the third SM if the clock value is greater than 2t and less than 3t. The clock will reset after its value exceeds 3t. Once the controller decides which SM should be tracked, the corresponding current of the tracked SM is divided by the PV module current, and the result becomes the duty ratio of the SM DC-DC converter.

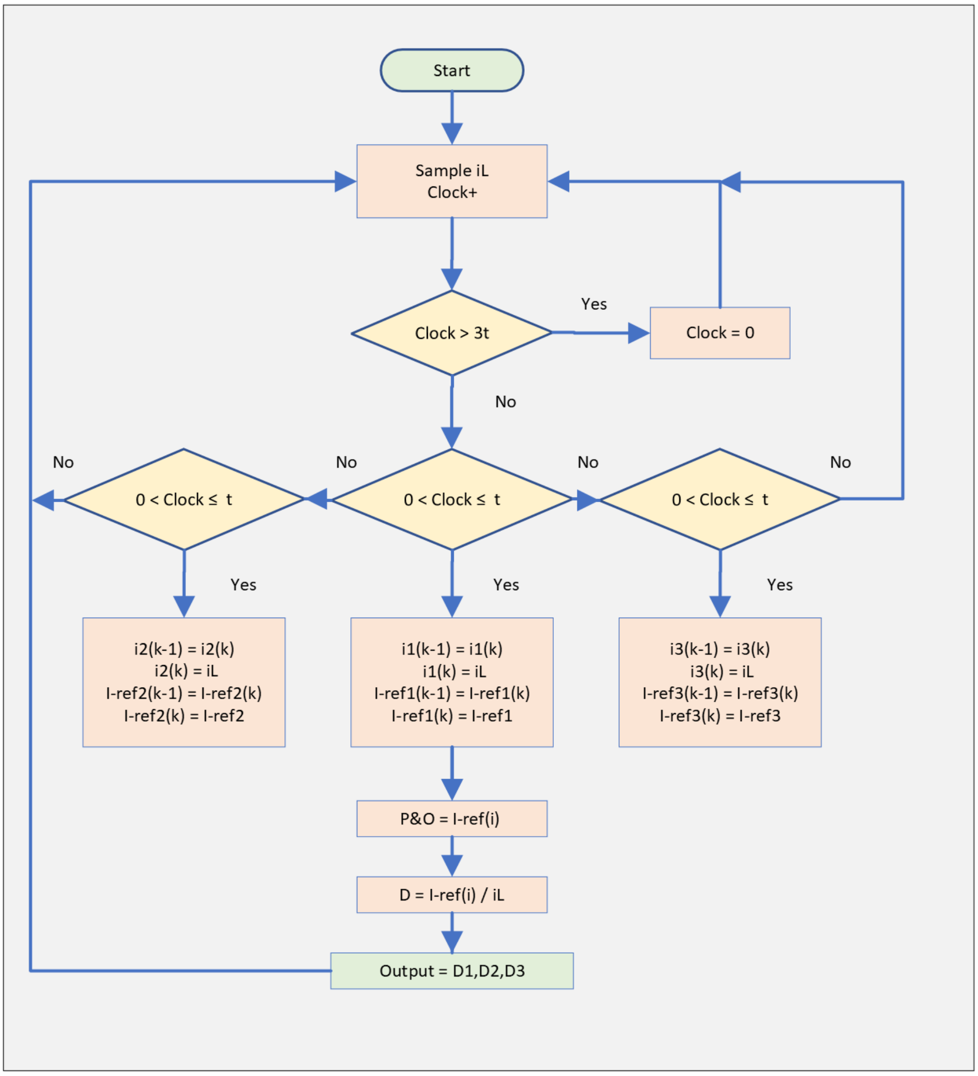


Figure 12. The flow chart illustrates the MPP algorithm according to the current of the PV SMs

3.3. Sub-Module Parallel Converters

The low voltage of solar cells makes the boost converter topologies more practical for several PV applications. The boost converters are commonly used in parallel connection to step-up the low voltage level to the grid voltage level. One of the common SM parallel converters is a synchronous boost converter [88]. This topology aims to solve the SM mismatch problem and effectively increase PV energy yield. The proposed converter is based on connecting the SM-integrated converter in parallel. The MPP of each SM can be captured individually to maximize energy harvesting and mitigate power loss. The external connection between PV modules is in series to build up sufficient output voltage. Figure 13 illustrates the circuit configuration of the SM parallel integrated converter.

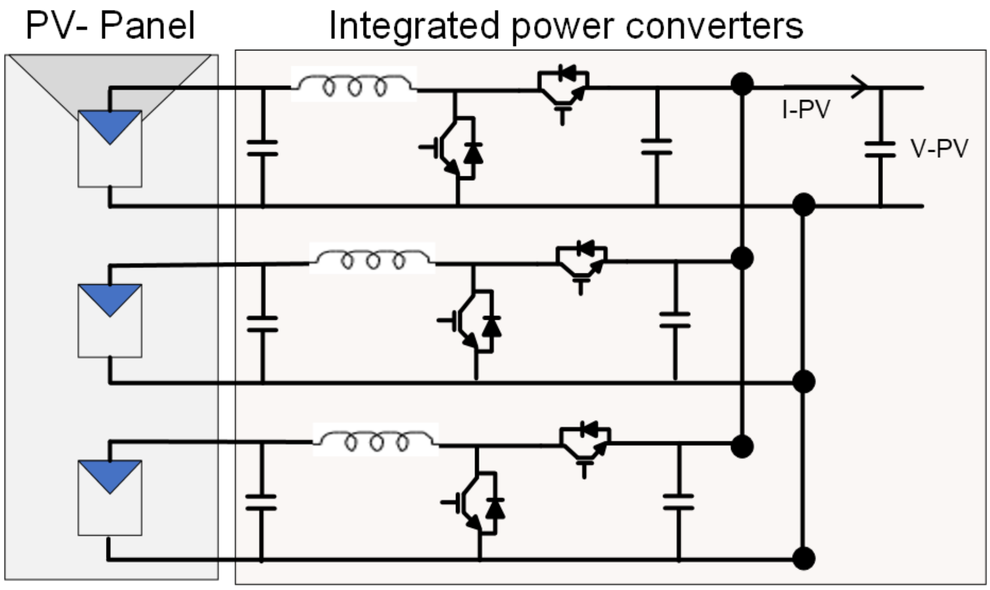


Figure 13. The connection between the PV sub-module and sub-panel micro converters of a single PV panel

One MPPT microcontroller has been used to regulate the three SM on the PV panel since the three converters are connected in parallel. Preserve and observe (P&O) tracking algorithm used to track the MPP of each SM. The PV module output voltage is used as a reference value to compare with SM voltages and then decide the direction of the next tracking cycle. In every cycle of the tracking process, the three voltages of the SMs are perturbed and compared with the output voltage. Figure 14 shows the MPPT controlling algorithm flow chart used in [88].

The first step of the MPPT algorithm is initializing the parameters of the tracking system. Then the algorithm starts to measure the output voltage and PV SM voltage of three SM voltages. The SM indices are deciding which SM voltage is controlled. The three SM voltages will be perturbed continuously and the change of the output voltage of the PV module will be recorded. The PV module will have three indices, but they are not shown in Figure 14. The change in the output voltage of the PV module index will be measured according to changes in SM voltages. The direction of the tracking cycle of each SM can be decided according to the change of output voltage based on perturbing respective SM voltage. The tracking algorithm will continue in the same direction, if a change in output voltage is positive, else the direction of the tracking process will be reversed.

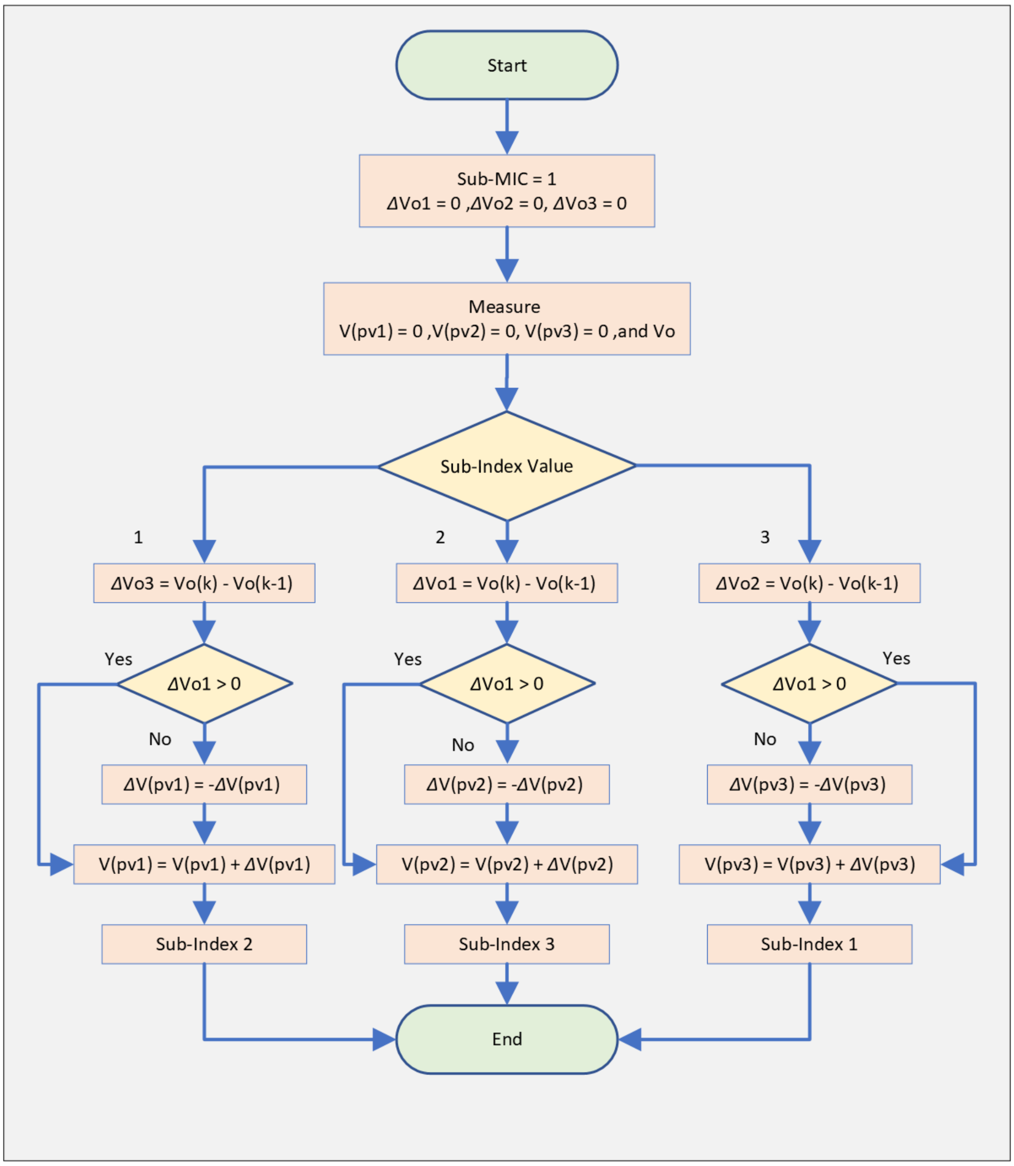


Figure 14. The flowchart shows the unified MPPT algorithm for capturing the MPP of PV sub-modules

3.4. Sub-Module Differential Power Processing Converters.

In [89], Differential power processing DPP topology for PV SM MPPT implementation has been proposed. This study employs DPP PV-PV topology with a bidirectional buck-boost converter to solve the mismatch issue between the PV SM to maximize energy harvesting and reduce power losses. The main objective of the proposed design is to efficiently balance the current between the PV SM under unequal power generation. Figure 15 illustrates the DPP PV-PV architecture that is used to mitigate mismatch issues between the PV SM.

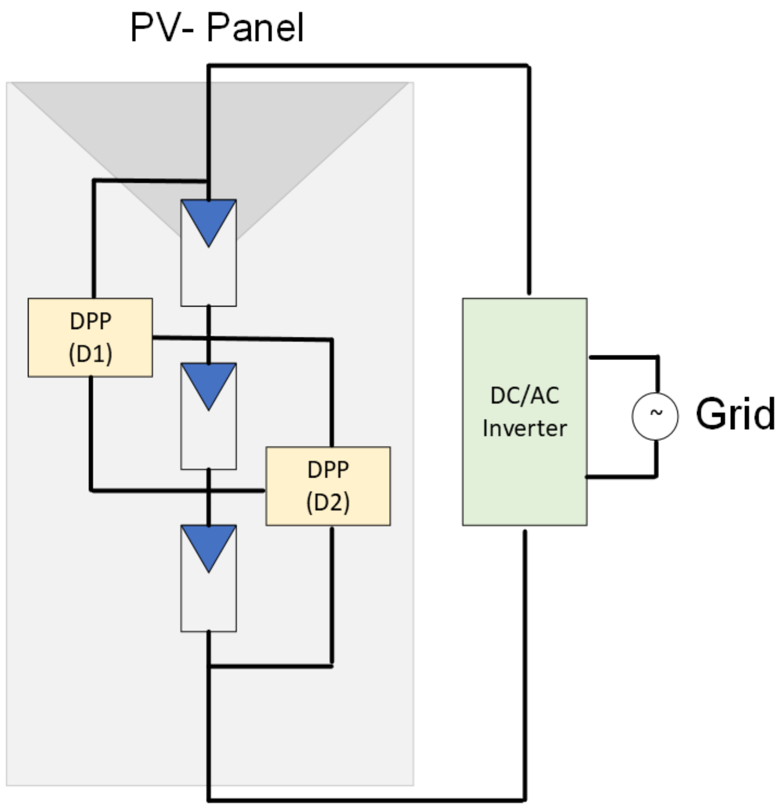


Figure 15. The schematic diagram of the MI with DPP.

The P&O algorithm is employed to track the MPP. The DPP converter operates at a relatively high frequency, thus the PV module voltage is assumed to be constant. Since the PV module voltage is assumed to be static, the PV module current is used as an indicator to decide the direction of the next tracking cycle. The proposed topology in [89] employs two loops to track the MPP. The fast-controlling loop operates the DPP buck-boost converters while the slower loop controls the DC-AC grid-tied inverter. Figure 16 shows the flow chart of the fast-controlling loop of DPP buck-boost converters.

The tracking algorithm will start by measuring the PV module current before perturbing the duty-cycle ratio of the DC-DC converters. Then the DPP converter duty ratio will be updated by adding a perturbing sample. The change of PV module current is sensed and recorded after regularly varying the duty ratio of DPP converters. The new value of the PV module current is compared with the previous value. When the PV module current before perturbation is greater than the PV module current after perturbation, the direction of the tracking process will change, otherwise, the tracking direction will not change.

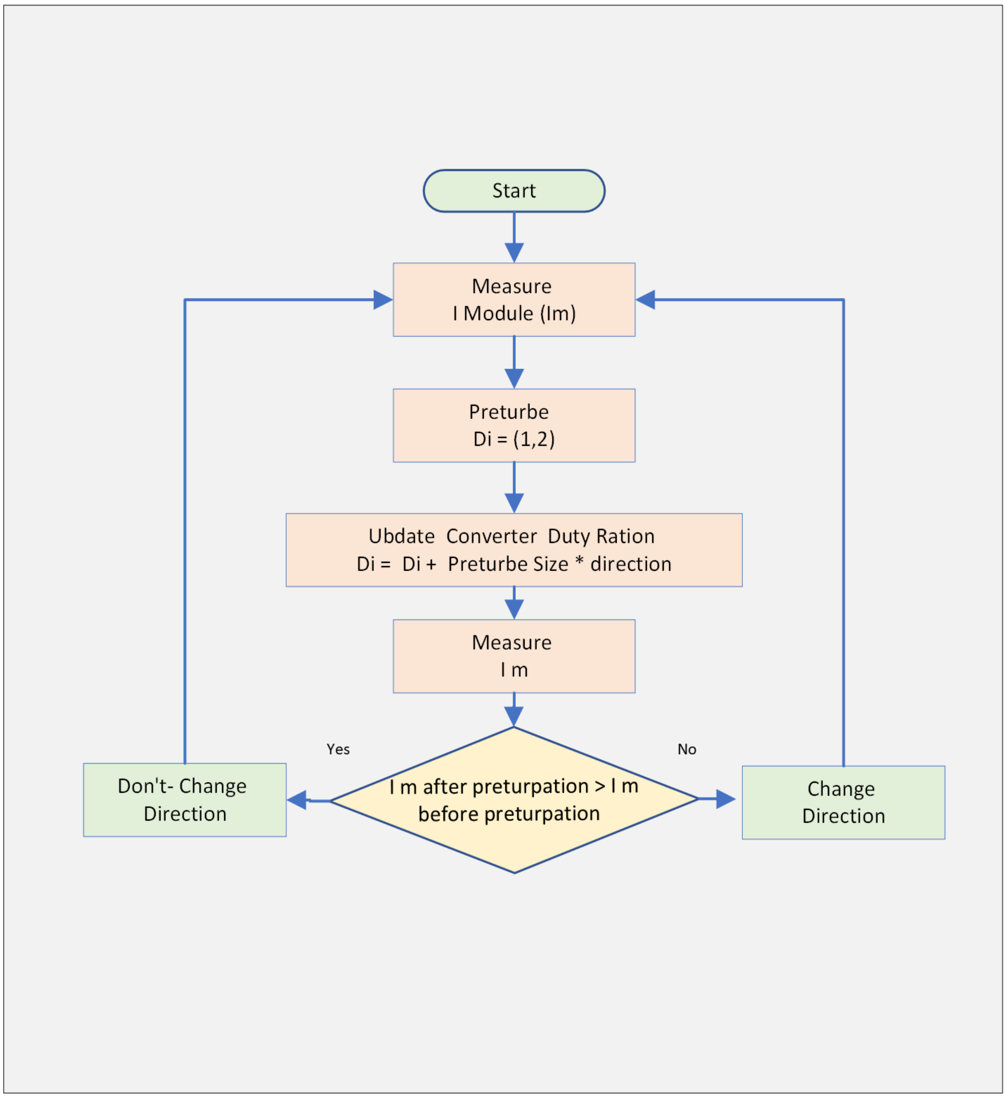


Figure 16. The flowchart illustrates the algorithm for operating the DPP and balancing the current between PV SM.

Technical comparison results of some DMPPT topologies at the PV SM are illustrated in Table 1. It summarizes power electronic devices that are used to obtain the maximum power of PV SM. It illustrates that the P&O tracking algorithm is employed to track the maximum power of PV SM for most proposed converters. This is to reduce the overhead complexity of MPPT controllers. However, some research modified the conventional P&O algorithm to enable tracking the maximum power of each SM using a single MPPT system. It can be also noticed that several research has proven a significant increase in power harvesting due to employing DMPPT at the PV SM level. From a power converter perspective, it can be seen that several research relies on conventional power electronic circuits including Buck, Boost, and flyback converters. Some others use DPP topologies to equalize the current of the PV module by redirecting the SM current flow according to the irradiation level.

Table 2. Comparison between different power electronic optimization studies to solve mismatch issues inside an individual PV panel.

Ref.	Rated Power (W)	Topology	Arrangement	MPPT Algorithm	Efficiency (%)	Improvements	Limitations
[86]	200 W	Synchronous Buck	Series	P&O	≈ 98	Increase power harvesting by (20 %)	Local Maximum point controller
[87]	-	Buck	Series	P&O	-	Less component	Single MPPT for three SMs
[88]	100 W	Synchronous Boost	Parallel	P&O	≈ 96	Improve efficiency due to using GaN technology	Operating regardless of mismatch condition
[89]	60W	Synchronous Buck-Boost	DPP	P&O	= 95	The capability of commercial inverter integration	Communication between neighboring DPP
[90]	60W	Bidirectional flyback	Parallel	-	≈ 98	Reduce mismatch level by (25 %)	A large number of current sensors
[91]	245W	DPP architecture with synchronous flyback converters	Parallel	DMPPT algorithm	-	Improve power extraction by 10.19%	Large storage element required for decoupling purposes
[92]	-	DPP with central Boost	DPP	P&O	-	Accurate MPP tracking	Complex controlling process
[93]	-	Full Bridge Converter FBC	Series	P&O	-	Novel topology to apply DMPPT at a finer level	No experimental validation
[94]	300W	Synchronous Boost with Series Virtual Port DPP	DPP	Modified P&O	-	A single current sensor is required	More Components

5. Discussion and recommendation

Distributing the MPPT controller to obtain the maximum available power from each PV SM individually enables maximizing the overall power generation of the PV module, especially under the effect of the mismatch issue. The accuracy of the MPPT system is improved due to employing The DMPPT approach at the PV SM level and the multiple MPP problem caused by bypass diodes is significantly mitigated. The performance of PV power electronic converters is slightly different according to the converters' characteristics and the material used in the manufacturing process. The MPPT controller techniques have been thoroughly reviewed in this study. This section presents a discussion of the power converters for applying the DMPPT strategy to increase the power generation of the PV module and improve the overall efficiency of the PV system.

The future associated power electronic converters used for employing the DMPPT approach at the PV SM should expand to fulfill the technological development in the power circuit topologies, the MPPT techniques, semiconductor materials, the power quality requirements, and grid standards. The new power electronic devices should be developed with fewer components, better efficiency, and reduced cost to effectively apply the DMPPT approach at the PV SM level. These converters are expected to achieve the following recommendations:

The value of the input capacitors plays an important role in determining the lifetime of the power electronic converters. Thus, introducing a new decoupling circuit is needed. The new power electronic devices' efficiency should be improved due to applying soft switching techniques. Soft switching technologies not only improve the PV system's efficiency but it is also can increase the lifetime of the power electronic converters.

The power electronic switch is a basic element in the design of the power converters and choosing switches with lower switching and conduction losses enables achieving better efficiencies. It has been proven that GaN and SiC based power electronic switches can achieve better efficiency and effectively minimize power losses. The on-state resistance between the drain and the source of such switches is relatively low which minimizes the conduction losses of the switch. Also, high switching frequencies are achievable with minimal switching losses

In terms of power quality, galvanic isolation is not mandatory nowadays, however many researchers consider it in the design stage since it protects against electrical faults. Anti-islanding detection is another feature that should be considered in the new designs, the detection strategies should be swift and accurate to coop with the power grid failure. The power quality is directly affected by THD, therefore the THD should be minimized to improve the power electronic devices. The power quality discussion can not be completed without emphasizing the importance of achieving and maintaining a unity power factor system.

The development of a novel MPPT controller is important to maintain the voltage level and help achieve the maximum available power from the PV side. The new MPPT controllers should be able to pump up the extra power and maintain MPPT in the daytime and enable compensation mood during night time.

5. Future Trend of the Grid-Tied MI

The partial and full shading effect on the PV systems can be unpredictable and unavoidable in most scenarios. Partial shading might be a result of several conditions including trees and building shadows, clouds, and birds dropping. The electrical characteristics of the shaded part of the PV system become different from the unshaded part. The percentage of irradiation level on the PV SM is directly proportional to the amount of generated power. Thus PV SM with high irradiation level can generate more power compared to PV SM with a low irradiation level. The PV system will be limited by PV SM with the lowest irradiation level causing a mismatch between PV SMs.

The PV SM mismatches have a negative impact on the performance of the PV system. The series connection of the SMs results in limiting the PV module current by SM with the lowest output current. Harvesting each SM maximum power individually not only significantly increases power capturing of the PV module but also mitigates the power losses. DMPPT at the SM level aims to obtain the true available power by summing the individual maximum power of the three SMs of a single PV module. The new optimized power electronic topologies are expected to be invented to further improve the PV system performance and achieve better efficiencies. These topologies are needed to overcome the currently associated limitations and provide reduced-size components. Large band-gap devices such as GaN and SiC might be a promising solution to enhance the PV system efficiency and use small components by allowing higher switching frequency.

One major issue that reduces the PV system power generation is the mismatch between PV SMs during unbalanced power generation. The mismatch phenomena might occur as a result of several reasons; however, partial shading can be the most common contributing factor to this concern. The behavior of the PV SM is different according to the environmental conditions of each SM. PV SMs are a part of the PV panel and they are internally connected. Thus, applying the DMPPT strategy at the SM level requires breaking the interconnection between SMs. Therefore, PV panel manufacturers might revise the current PV panel electrical arrangement inside the PV panel junction box and provide a new electrical layout considering the capability of integrating a new power converter to implement DMPPT at the PV SM level.

Working at the PV SM level and adding optimized power electronic converters can increase energy harvesting in different types of PV systems. The amount of harvested energy extracted from the PV system can significantly increase when more DMPPT is implemented among PV SM, especially under the partial shading effect. Proposing new power electronic converters that offer better efficiency and improve the overall performance of the PV system should be the focus of associated future work. Employing these optimized power electronic converters at the PV SM can mitigate the mismatch concerns and maximize power harvesting.

6. Conclusions

This paper discussed the DMPPT strategies which are used as a practical solution to mitigate the mismatch problem in different types of PV system topologies. The DMPPT approaches have been evaluated and compared for the PV string, PV module, and PV SM systems. As the DMPPT is applied to a finer level, a more accurate MPP can be achieved, and the mismatch loss issue can be effectively minimized. It has been concluded that the most practical level where the DMPPT approach can be applied is the PV SM level. Thus, the main focus of this paper is to evaluate and compare the different power electronics converters used for applying DMPPT level at the SM level. Also, this study examines the MPPT algorithm used to track the maximum power for different PV SM topologies. It has been concluded also that most PV SM control designs use or modify the conventional P&O tracking algorithms to avoid further complexity in the PV system design stage.

This review paper presents a comprehensive comparison between different power electronic converters that are used to implement the DMPPT approach at the PV SM. Although the P&O MPPT algorithm might be the most commonly used tracking algorithm due to its simple implementation, the lack of tracking accuracy is a major concern of this technique. The future research should focus on utilizing the new MPPT approaches such as Artificial Intelligence (AI) and optimization algorithms approaches to improve the accuracy of MPPT methods.

Author Contributions

Conceptualization, A.D.; methodology, Y.A. and A.D.; software, Y.A. and A.D.; validation, Y.A. and A.D.; formal analysis, Y.A. and A.D.; investigation, Y.A. and A.D.; resources, X.M. and A.D.; data curation, Y.A. and A.D.; writing—original draft preparation, Y.A.; writing—review and editing, X.M. and A.D.; visualization, Y.A. and A.D.; supervision, A.D. and X.M.; project administration,

A.D. and X.M.; funding acquisition, A.D. and X.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Data Availability Statement: Not Applicable

Conflicts of Interest: The authors declare no conflict of interest

References

1. A. Zahedi, "A review of drivers, benefits, and challenges in integrating renewable energy sources into electricity grid," Renewable and Sustainable Energy Reviews, vol. 15, no. 9, pp. 4775–4779, 2011.
2. C. D. Iweh, S. Gyamfi, E. Tanyi, and E. Effah-Donyina, "Distributed generation and renewable energy integration into the grid: Prerequisites, push factors, practical options, issues and merits," Energies, vol. 14, no. 17, p. 5375, 2021.
3. E. Kandemir, N. S. Cetin, and S. Borekci, "A comprehensive overview of maximum power extraction methods for PV Systems," Renewable and Sustainable Energy Reviews, vol. 78, pp. 93–112, 2017.
4. S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," IEEE Transactions on Industry Applications, vol. 41, no. 5, pp. 1292–1306, 2005.
5. "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," in IEEE Std 1547-2003 , vol., no., pp.1-28, 28 July 2003.
6. IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces," in *IEEE Std 1547.1-2020* , vol., no., pp.1-282, 21 May 2020.
7. "IEEE Approved Draft Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems Amendment 1," in IEEE P1547.1a/D5, December. 2014 , vol., no., pp.1-19, 1 May 2015.
8. Badawy, A. Current Source DC-DC and DC-AC Converters with Continuous Energy Flow. Ph.D. Thesis, University of Strathclyde, Glasgow, Scotland, 2015.
9. D. G. Infield, P. Onions, A. D. Simmons, and G. A. Smith, "Power quality from multiple grid-connected single-phase inverters," IEEE Transactions on Power Delivery, vol. 19, no. 4, pp. 1983–1989, 2004.
10. Abdelsalam, A.K.; Massoud, A.; Darwish, A.; Ahmed, S. Simplified Generic On-Line PWM Technique for Single Phase Grid Connected Current Source Inverters. 2012 Twenty-Seventh Annu. IEEE Appl. Power Electron. Conf. Expo. 2012.
11. Darwish, A.; Ahmed, S. A Single-Stage Three-Phase DC / AC Inverter Based on Cuk Converter for PV Application. 2013 7th IEEE GCC Conf. Exhib. 2013, 384–389, doi:10.1109/IEEEGCC.2013.6705809.
12. Darwish, A.; Massoud, A.M.; Ahmed, S. Single Phase Grid Connected Current Source Inverter: Mitigation of Oscillating Power Effect On The Grid Current. IET Conf. Renew. Power Gener. (RPG 2011).
13. Darwish, A.; Holliday, D.; Finney, S. Operation and Control Design of an Input- Conversion Scheme for Offshore DC Wind Systems. IET Power Electron. 2017, 10, 2092–2103, doi:10.1049/iet-pel.2016.0885.
14. E. Kabalcı, "Review on novel single-phase grid-connected solar inverters: Circuits and control methods," Solar Energy, vol. 198, pp. 247–274, 2020.
15. J. Lee, B. Chang, C. Aktas, and R. Gorthala, "Economic feasibility of campus-wide photovoltaic systems in New England," Renewable Energy, vol. 99, pp. 452–464, 2016.
16. M. Haegermark, P. Kovacs, and J.-O. Dalenbäck, "Economic feasibility of solar photovoltaic rooftop systems in a complex setting: A Swedish case study," Energy, vol. 127, pp. 18–29, 2017.
17. A. C. Duman and Ö. Güler, "Economic Analysis of grid-connected residential rooftop PV systems in Turkey," Renewable Energy, vol. 148, pp. 697–711, 2020.
18. S. Rodrigues, R. Torabikalaki, F. Faria, N. Cafôfo, X. Chen, A. R. Ivaki, H. Mata-Lima, and F. Morgado-Dias, "Economic feasibility analysis of small scale PV systems in different countries," Solar Energy, vol. 131, pp. 81–95, 2016.
19. C. Li, D. Zhou, and Y. Zheng, "Techno-economic comparative study of grid-connected PV power systems in five climate zones, China," Energy, vol. 165, pp. 1352–1369, 2018.
20. A. Sagani, J. Mihelis, and V. Dedoussis, "Techno-Economic Analysis and life-cycle environmental impacts of small-scale building-integrated PV systems in Greece," Energy and Buildings, vol. 139, pp. 277–290, 2017.
21. Z. Chen, F. Blaabjerg, and J. K. Pedersen, "A multi-functional power electronic converter in Distributed Generation Power Systems," IEEE 36th Conference on Power Electronics Specialists, 2005.
22. R. Ramakumar and J. E. Bigger, "Photovoltaic systems," Proceedings of the IEEE, vol. 81, no. 3, pp. 365–377, 1993.
23. W. Xiao, M. S. El Moursi, O. Khan, and D. Infield, "Review of grid-tied converter topologies used in photovoltaic systems," IET Renewable Power Generation, vol. 10, no. 10, pp. 1543–1551, 2016.
24. V. Sridhar and S. Umashankar, "A comprehensive review on CHB MLI based PV inverter and feasibility study of CHB MLI based PV-Statcom," Renewable and Sustainable Energy Reviews, vol. 78, pp. 138–156, 2017.
25. M. Díez-Mediavilla, M. I. Dieste-Velasco, M. C. Rodríguez-Amigo, T. García-Calderón, and C. Alonso-Tristán, "Performance of grid-tied PV facilities based on real data in Spain: Central Inverter Versus String System," Energy Conversion and Management, vol. 86, pp. 1128–1133, 2014.
26. A. Mohapatra, B. Nayak, P. Das, and K. B. Mohanty, "A review on MPPT techniques of PV system under partial shading condition," Renewable and Sustainable Energy Reviews, vol. 80, pp. 854–867, 2017.
27. F. Belhachat and C. Larbes, "A review of Global Maximum Power Point tracking techniques of photovoltaic system under partial shading conditions," Renewable and Sustainable Energy Reviews, vol. 92, pp. 513–553, 2018.
28. J. Ahmed and Z. Salam, "A critical evaluation on maximum power point tracking methods for partial shading in PV systems," Renewable and Sustainable Energy Reviews, vol. 47, pp. 933–953, 2015.
29. Y.-H. Liu, J.-H. Chen, and J.-W. Huang, "A review of maximum power point tracking techniques for use in partially shaded conditions," Renewable and Sustainable Energy Reviews, vol. 41, pp. 436–453, 2015.

30. N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, “Optimization of perturb and observe maximum power point tracking method,” IEEE Transactions on Power Electronics, vol. 20, no. 4, pp. 963–973, 2005.
31. A. Safari and S. Mekhilef, “Simulation and hardware implementation of incremental conductance MPPT with direct control method using CUK converter,” IEEE Transactions on Industrial Electronics, vol. 58, no. 4, pp. 1154–1161, 2011.
32. T. Noguchi, S. Togashi, and R. Nakamoto, “Short-current pulse-based maximum-power-point tracking method for multiple photovoltaic-and-converter module system,” IEEE Transactions on Industrial Electronics, vol. 49, no. 1, pp. 217–223, 2002.
33. Z. Zeng, H. Yang, R. Zhao, and C. Cheng, “Topologies and control strategies of multi-functional grid-connected inverters for Power Quality Enhancement: A comprehensive review,” Renewable and Sustainable Energy Reviews, vol. 24, pp. 223–270, 2013.
34. Y. Bae, T.-K. Vu, and R.-Y. Kim, “Implemental Control Strategy for grid stabilization of grid-connected PV system based on German grid code in symmetrical low-to-medium voltage network,” IEEE Transactions on Energy Conversion, vol. 28, no. 3, pp. 619–631, 2013.
35. E. Romero-Cadaval, G. Spagnuolo, L. G. Franquelo, C. A. Ramos-Paja, T. Suntio, and W. M. Xiao, “Grid-connected photovoltaic generation plants: Components and Operation,” IEEE Industrial Electronics Magazine, vol. 7, no. 3, pp. 6–20, 2013.
36. N. Altin and S. Ozdemir, “Three-phase three-level grid interactive inverter with fuzzy logic based maximum power point tracking controller,” Energy Conversion and Management, vol. 69, pp. 17–26, 2013.
37. S. Ozdemir, N. Altin, and I. Sefa, “Single Stage Three Level Grid Interactive MPPT inverter for PV Systems,” Energy Conversion and Management, vol. 80, pp. 561–572, 2014.
38. N. Altin and İ. Sefa, “DSPACE based adaptive neuro-fuzzy controller of grid interactive inverter,” Energy Conversion and Management, vol. 56, pp. 130–139, 2012.
39. D. C. Martins, “Analysis of a three-phase grid-connected PV power system using a modified dual-stage inverter,” ISRN Renewable Energy, vol. 2013, pp. 1–18, 2013.
40. D. Picault, B. Raison, and S. Bacha, “Guidelines for evaluating Grid Connected PV system topologies,” 2009 IEEE International Conference on Industrial Technology, 2009.
41. M. Balato and M. Vitelli, “Optimization of distributed maximum power point tracking PV applications: The scan of the power vs. voltage input characteristic of the inverter,” International Journal of Electrical Power & Energy Systems, vol. 60, pp. 334–346, 2014.
42. F. Wang, T. Zhu, F. Zhuo, and Y. Yang, “Analysis and comparison of FPP and DPP structure based DMPPT PV system,” 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), 2016.
43. T. Zhao, Z. Ju, H. Wang, X. Wei, X. Li, and S. Zhang, “The Distributed Maximum Power Point Tracking Method and application in the PV grid-connected generation,” 2010 International Conference on Intelligent System Design and Engineering Application, 2010.
44. M. Vitelli, “On the necessity of joint adoption of both Distributed Maximum Power Point Tracking and central maximum power point tracking in PV Systems,” Progress in Photovoltaics: Research and Applications, vol. 22, no. 3, pp. 283–299, 2012.
45. N. Femia, G. Lisi, G. Petrone, G. Spagnuolo, and M. Vitelli, “Distributed maximum power point tracking of photovoltaic arrays: Novel approach and system analysis,” IEEE Transactions on Industrial Electronics, vol. 55, no. 7, pp. 2610–2621, 2008.
46. Z. Salam and M. Z. Ramli, “Distributed maximum power point tracker for additional energy harvesting during partial shading of PV System,” 2015 First Workshop on Smart Grid and Renewable Energy (SGRE), 2015.
47. D. Shmilovitz and Y. Levron, “Distributed maximum power point tracking in photovoltaic systems—emerging architectures and control methods,” Automatika, vol. 53, no. 2, pp. 142–155, 2012.
48. L. B. Bosman, W. D. Leon-Salas, W. Hutzel, and E. A. Soto, “PV system predictive maintenance: Challenges, current approaches, and opportunities,” Energies, vol. 13, no. 6, p. 1398, 2020.
49. A. Barchowsky, J. P. Parvin, G. F. Reed, M. J. Korytowski and B. M. Grainger, "A comparative study of MPPT methods for distributed photovoltaic generation," 2012 IEEE PES Innovative Smart Grid Technologies (ISGT), Washington, DC, USA, 2012.
50. R. A. Marques Lameirinhas, J. P. Torres, and J. P. de Melo Cunha, “A Photovoltaic Technology Review: History, fundamentals and applications,” Energies, vol. 15, no. 5, p. 1823, 2022.
51. S. Lyden and M. E. Haque, “Maximum power point tracking techniques for photovoltaic systems: A Comprehensive Review and Comparative Analysis,” Renewable and Sustainable Energy Reviews, vol. 52, pp. 1504–1518, 2015.
52. "IEEE Application Guide for IEEE Std 1547(TM), IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," in IEEE Std 1547.2-2008 , vol., no., pp.1-217, 15 April 2009.
53. A. Darwish, S. Alotaibi and M. A. Elgenedy, "Current-Source Single-Phase Module Integrated Inverters for PV Grid-Connected Applications," in IEEE Access, vol. 8, pp. 53082-53096, 2020, doi: 10.1109/ACCESS.2020.2981552.
54. A. Darwish and M. A. Elgenedy, "Current-Source Modular Medium-Voltage Grid-Connected System With High-Frequency Isolation for Photovoltaic Applications," in IEEE Transactions on Energy Conversion, vol. 34, no. 1, pp. 255-266, March 2019
55. Darwish, A.; Massoud, A.; Holliday, D.; Ahmed, S.; Williams, B. Generation, performance evaluation and control design of single-phase differential-mode buck–boost current-source inverters. IET Renew. Power Gener. 2016, 10, 916–927
56. E. P. Wiechmann, P. Aqueveque, R. Burgos and J. Rodriguez, "On the Efficiency of Voltage Source and Current Source Inverters for High-Power Drives," in IEEE Transactions on Industrial Electronics, vol. 55, no. 4, pp. 1771-1782, April 2008.

57. Y. Zhou, Y. Liu, M. Su and Y. Sun, "A Single-phase Voltage Source Inverter With Lower-Voltage-Rated Capacitor and Ripple Power Decoupling Function," 2020 15th IEEE Conference on Industrial Electronics and Applications (ICIEA), Kristiansand, Norway, 2020.
58. R. A. Eshkaftaki and C. N. M. Ho, "Half-Bridge Current Source Inverter for Grid-Connected Applications," 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2022.
59. F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power Electronics as efficient interface in Dispersed Power Generation Systems," IEEE Transactions on Power Electronics, vol. 19, no. 5, pp. 1184–1194, 2004.
60. L. Hassaine, E. OLias, J. Quintero, and V. Salas, "Overview of power inverter topologies and control structures for grid connected photovoltaic systems," Renewable and Sustainable Energy Reviews, vol. 30, pp. 796–807, 2014.
61. Ankit, S. K. Sahoo, S. Sukchai, and F. F. Yanine, "Review and Comparative Study of single-stage inverters for a PV system," Renewable and Sustainable Energy Reviews, vol. 91, pp. 962–986, 2018.
62. T.-F. Wu, C.-H. Chang, L.-C. Lin, and C.-L. Kuo, "Power loss comparison of single- and two-stage grid-connected photovoltaic systems," IEEE Transactions on Energy Conversion, vol. 26, no. 2, pp. 707–715, 2011.
63. D. Nguyen and B. Lehman, "An adaptive solar photovoltaic array using model-based reconfiguration algorithm," IEEE Transactions on Industrial Electronics, vol. 55, no. 7, pp. 2644–2654, 2008.
64. L. Chen, A. Amirahmadi, Q. Zhang, N. Kutkut, and I. Batarseh, "Design and implementation of three-phase two-stage grid-connected module integrated converter," IEEE Transactions on Power Electronics, vol. 29, no. 8, pp. 3881–3892, 2014.
65. S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "Power inverter topologies for photovoltaic modules-A Review," Conference Record of the 2002 IEEE Industry Applications Conference. 37th IAS Annual Meeting (Cat. No.02CH37344), 2002.
66. D. C. Martins, "Analysis of a three-phase grid-connected PV power system using a modified dual-stage inverter," ISRN Renewable Energy, vol. 2013, pp. 1–18, 2013.
67. T. Q. Tran and A. V. Truong, "MPPT voltage regulating in three-phase grid-connected photovoltaic system," Science and Technology Development Journal, vol. 15, no. 2, pp. 50–61, 2012.
68. Boemer, Jens C., Karsten Burges, Pavel Zolotarev, Joachim Lehner, Patrick Wajant, Markus Fürst, Rainer Brohm and Thomas Kumm. "Overview of German Grid Issues and Retrofit of Photovoltaic Power Plants in Germany for the Prevention of Frequency Stability Problems in Abnormal System Conditions of the ENTSO-E Region Continental Europe.", 2012.
69. S. Ayswarya and P. Prabhu, "Leakage current suppression for transformerless inverter for Grid Connected PV Power Systems," 2014 International Conference on Electronics, Communication and Computational Engineering (ICECCE), 2014.
70. Y. Bae and R.-Y. Kim, "Suppression of common-mode voltage using a Multicentral photovoltaic inverter topology with synchronized PWM," IEEE Transactions on Industrial Electronics, vol. 61, no. 9, pp. 4722–4733, 2014.
71. D. Leuenberger and J. Biela, "PV-module-integrated AC inverters (AC modules) with subpanel MPP tracking," IEEE Transactions on Power Electronics, vol. 32, no. 8, pp. 6105–6118, 2017.
72. H.Renaudineau et al., "A PSO-Based Global MPPT Technique for Distributed PV Power Generation," in IEEE Transactions on Industrial Electronics, vol. 62, no. 2, pp. 1047-1058, Feb. 2015.
73. M. O. Badawy, S. M. Bose and Y. Sozer, "A Novel Differential Power Processing Architecture for a Partially Shaded PV String Using Distributed Control," in IEEE Transactions on Industry Applications, vol. 57, no. 2, pp. 1725-1735, March-April 2021.
74. B. J. Pierquet and D. J. Perreault, "A Single-Phase Photovoltaic Inverter Topology With a Series-Connected Energy Buffer," in IEEE Transactions on Power Electronics, vol. 28, no. 10, pp. 4603-4611, Oct. 2013.
75. X. Zhang, M. Chen, Y. Fu, and Y. Li, "A step-down partial power optimizer structure for photovoltaic series-connected power optimizer system," *2018 IEEE International Power Electronics and Application Conference and Exposition (PEAC)*, 2018.
76. Rabiul Islam, M.; Mahfuz-Ur-Rahman, A.M.; Muttaqi, K.M.; Sutanto, D. State-of-The-Art of the Medium-Voltage Power Converter Technologies for Grid Integration of Solar Photovoltaic Power Plants. IEEE Trans. Energy Convers. 2019, 34, 372–384.
77. G. R. Walker and P. C. Sernia, "Cascaded DC-DC converter connection of photovoltaic modules," in IEEE Transactions on Power Electronics, vol. 19, no. 4, pp. 1130-1139, July 2004.
78. S. Qin, A. J. Morrison, and R. C. Pilawa-Podgurski, "Enhancing micro-inverter energy capture with sub-module differential power processing," 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014, 2014.
79. J. -M. Kwon, B. -H. Kwon and K. -H. Nam, "Three-Phase Photovoltaic System With Three-Level Boosting MPPT Control," in IEEE Transactions on Power Electronics, vol. 23, no. 5, pp. 2319-2327, Sept. 2008.
80. H. Keyhani and H. A. Toliyat, "Single-Stage Multistring PV Inverter With an Isolated High-Frequency Link and Soft-Switching Operation," in IEEE Transactions on Power Electronics, vol. 29, no. 8, pp. 3919-3929, Aug. 2014,
81. C. A. Rojas, M. Aguirre, S. Kouro, T. Geyer and E. Gutierrez, "Leakage Current Mitigation in Photovoltaic String Inverter Using Predictive Control with Fixed Average Switching Frequency," in IEEE Transactions on Industrial Electronics, vol. 64, no. 12, pp. 9344-9354, Dec. 2017
82. Y. Alharbi and A. Darwish, "Control of Cuk-Based Microinverter Topology with Energy Storage for Residential PV Applications," Energies, vol. 16, no. 5, p. 2293, Feb. 2023.
83. Q. Surirey, R. Hernandez-Vidal, H. Renaudineau, S. Kouro and B. Cabon, "Sub-module photovoltaic microinverter with cascaded push-pull and unfolding H-bridge inverter," 2017 IEEE Southern Power Electronics Conference (SPEC), Puerto Varas, Chile, 2017.

84. R. Bell and R. C. Pilawa-Podgurski, "Decoupled and distributed maximum power point tracking of series-connected photovoltaic submodules using differential power processing," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 3, no. 4, pp. 881–891, 2015.
85. S. Strache, R. Wunderlich, and S. Heinen, "A comprehensive, quantitative comparison of inverter architectures for various PV systems, PV cells, and irradiance profiles," IEEE Transactions on Sustainable Energy, vol. 5, no. 3, pp. 813–822, 2014.
86. R. C. Pilawa-Podgurski and D. J. Perreault, "Submodule Integrated Distributed Maximum Power Point Tracking for solar photovoltaic applications," IEEE Transactions on Power Electronics, vol. 28, no. 6, pp. 2957–2967, 2013.
87. T. Zhu, X. He, T. Guan, F. Wang, H. Yi, and F. Zhuo, "An integrated single inductor-single sensor based photovoltaic optimizer with an optimal current point tracking strategy," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), 2017.
88. O. Khan, W. Xiao, and M. S. Moursi, "A new PV system configuration based on submodule integrated converters," IEEE Transactions on Power Electronics, vol. 32, no. 5, pp. 3278–3284, 2017.
89. S. Qin, C. B. Barth, and R. C. Pilawa-Podgurski, "Enhancing microinverter energy capture with submodule differential power processing," IEEE Transactions on Power Electronics, vol. 31, no. 5, pp. 3575–3585, 2016.
90. C. Olalla, D. Clement, M. Rodriguez and D. Maksimovic, "Architectures and Control of Submodule Integrated DC–DC Converters for Photovoltaic Applications," in IEEE Transactions on Power Electronics, vol. 28, no. 6, pp. 2980-2997, June 2013.
91. R. Bell and R. C. N. Pilawa-Podgurski, "Decoupled and Distributed Maximum Power Point Tracking of Series-Connected Photovoltaic Submodules Using Differential Power Processing," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 3, no. 4, pp. 881-891, Dec. 2015.
92. F. Wang, T. Zhu, F. Zhuo and H. Yi, "An Improved Submodule Differential Power Processing-Based PV System With Flexible Multi-MPPT Control," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, no. 1, pp. 94-102, March 2018.
93. F. Flores-Bahamonde, J. Rojas, S. Kouro, A. M. Llor, C. A. Rojas and M. A. Perez, "Sub-modular Power Optimizers Based on Partial Power Converters for Utility Scale PV Plants," IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, Portugal, 2019.
94. L. Lin, J. Zhang, and S. Shao, "Differential power processing architecture with virtual port connected in series and MPPT in submodule level," IEEE Access, vol. 8, pp. 137897–137909, 2020.