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Contrôle de la qualité d'énergie électrique et la gestion des systèmes a Micro-Réseaux

Par

Yasmine AMARA

Soutenu publiquement devant un Jury composé de:

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THESIS OF DOCTORAT LMD

Specialty : Automatic

The electrical energy quality control and the management of micro-Grids systems

By

Yasmine AMARA

Defended in public ahead a jury composed of:

Abdelkader HAMID	Professor	university of Blida 1	President
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Blida, 2020

ملخص

التحكم في المكونات الإلكترونية التي تربط مصادر الطاقة بالأحمال والشبكة الكهربائية يلعب دورًا مهمًا ويعتبر في الوقت نفسه أساس البحوث القائمة في مجال مراقبة الجودة وإدارة الطاقة ل عملية MG ، لكن وحدات التحكم الحالية في الحد الأقصى لتتبع نقطة الطاقة (MPPT) للمحولات التي تربط PVGs و جانب DC للميكرو جريد ، ووحدات التحكم في المحول ثنائي الاتجاه للتخزين الحالي ووحدات التحكم في العاكس التي تربط MG بشبكة التوزيع ليست مناسبة للتغلب على المشاكل التي تواجهها أثناء الإنتاج حيث يتم تطبيقها على مشاكل محدودة. بالإضافة إلى ذلك ، تُكرس الدراسات لتحقيق المدن الذكية والمستدامة. وبالتالي، فإن الهدف الرئيسي من هذه الرسالة هو دمج وتحسين وحدات التحكم الذكية مثل وحدة تحكم المنطق الضبابي (FLC) وتحسين أسراب الجسيمات (PSO) مع وحدات التحكم الإلكترونية. الطاقة، من أجل تحسين أداء جودة وتوصيل الطاقة. بالإضافة إلى ذلك ، اقتراح استراتيجية إدارة بسيطة وفعالة لتسريع التشغيل واستجابة وحدات التحكم.

تظهر عمليات FLCs و HC-PSOs المقترحة والمحسنة المرتبطة باستراتيجية التحكم تحسنًا في أداء واستقرار وجودة الطاقة المستخرجة ,المحولة والمستهلكة في الظروف الجوية المتغيرة وظروف الظل الجزئي. تؤكد عمليات المحاكاة باستخدام منصة MATLAB / SIMULINKأن الإستراتيجية المقترحة تم تكييفها بشكل ملحوظ لتلبية متطلبات المستهلكين وتحقيق شبكة ذكية. لذلك ، يسمح الهيكل البسيط لخوارزمية الإدارة بفوائد اقتصادية بتكاليف منخفضة ل.MG

الكلمات الرئيسية: ميكرو جريد، نظام كهروضوئي ، أجهزة تخزين ، مراقبة أقصى نقطة طاقة ، محول تعزيز ، محول ثنائي الاتجاه ، عاكس ، وضع جزيرة ، وضع متصل بالشبكة ، منصة MATLAB / SIMULINK ، الإدارة ، جودة الطاقة والأداء ،الموصلية الإضافية ,التحكم المنطقي الضبابي ، تحسين سرب الجسيمات ، VOC، عامل الطاقة ، THD

RESUME

Les contrôleurs MPPT (Maximum Power Point Tracking) actuels des convertisseurs reliant les PVG au côté CC, les contrôleurs de convertisseur bidirectionnel du stockage existant et les contrôleurs des onduleurs CC-CA du côté problèmes rencontrés au cours du processus MG car ils sont appliqués à des problèmes limités. De plus, des études sont dédiées à la réalisation de villes intelligentes et durables. En conséquence, l'objectif principal de la présente thèse est de développer des contrôleurs intelligents tels que Fuzzy Logic Controller (FLC) et Hill Climbing Particle Swarm Optimization (HC-PSO) et de les utiliser pour contrôler les interfaces de l'électronique de puissance, afin de gérer le MG processus et améliore la qualité de l'alimentation et les performances fournies. De plus, proposer une stratégie de gestion simple et efficace pour accélérer le fonctionnement et le temps de réponse des contrôleurs.

Les FLC et HC-PSO proposés et améliorés associés à la stratégie de gestion montrent des progrès dans les performances, la stabilité et la qualité de l'énergie extraite, transférée et consommée dans des conditions météorologiques changeant rapidement et des conditions d'ombrage partiel. Les simulations utilisant la plateforme MATLAB / SIMULINK confirment que la stratégie proposée est remarquablement adaptée pour satisfaire les besoins des consommateurs et réaliser un smart grid. Par conséquent, la structure simple de l'algorithme de gestion permet des avantages économiques et une MG sans coût.

Mots-clés: Micro-réseau, Système photovoltaïque, Dispositifs de stockage, suivi du point de puissance maximale, convertisseur boost, Convertisseur bidirectionnel, onduleur, Mode îloté, mode connecté au réseau, Plateforme MATLAB / SIMULINK, Gestion, Qualité de l'énergie, performance, conductance incrémentale, contrôleur de logique floue , Optimisation de l'essaim de particules, VOC, facteur de puissance, THD.

ABSTRACT

The current Maximum Power Point Tracking (MPPT) controllers of the converters interfacing the PVGs to the DC-Side, the existing Storage's Bidirectional converter controllers, and the DC-AC inverters controllers at the MG AC-Side are not appropriately suitable to overcome the actual problems met during the MG process because they are applied to limited problems. Moreover, studies are dedicated to achieve smart and sustainable cities. Accordingly, the main aim of the present thesis is to develop intelligent controllers such as Fuzzy Logic Controller (FLC) and Hill Climbing Particle Swarm Optimization (HC-PSO) and use them to control the power electronics' interfaces, so as to, manage the MG process and enhance the delivered power quality and performances. Furthermore, propose a simple and efficient management strategy to accelerate the operation and response time of the controllers.

The proposed and improved FLC and HC-PSO associated with the management strategy show progress in the performance, stability, and quality of the extracted, transferred, and consumed power under fast changed weather conditions and partial shading conditions. Simulations using the MATLAB/SIMULINK platform confirm that the proposed strategy is remarkably suitable to satisfy the consumers' requirements and achieve a smart grid. Hence, the simple structure of the management algorithm allows for economic benefits and costless MG.

Keywords: Micro-grid, Photovoltaic system, Storage devices, maximum power point tracking, boost converter, Bidirectional converter, inverter, Islanded mode, grid connected mode, MATLAB/SIMULINK platform, Management, Power quality, performance, incremental conductance, fuzzy logic controller, Particle Swarm Optimization ,VOC, power factor, THD.

"العلم إن لم ينفعك لم يضرك"

DEDICATION

I dedicate this modest thesis to my parents for their love, support and prayers.

To my adorable sisters and best friends in this world:

Nadia and her husband Mustafa and their children Louise and Gegourta,

Zahira and her husband Issam and their daughter Maria Malek,

Safia and her husband Ghilas

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Dyhia and her husband Mohammed and their daughter Nélia

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***AMARA YA*SMINE**
2020

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General Introduction

Context

Production requirement for cost-free and sustainable energy has attracted researches and manufacturers to explore more and more renewable and natural energy resources that are accessible over the earth. These renewable energies include hydroelectric, geothermal, biomass, wind, and solar Photovoltaic (PV) that present an optimized solution to fulfil the increase shown in electricity demand resulting from the dependence of all daily life on the electricity. Moreover, conventional electricity production sources such as petroleum and natural gas are limited in quantities and available in only some countries. Unfortunately, these drawbacks will increase the transfer and transportation prices, and will lead to significant losses and power quality problems. Furthermore, great CO_2 quantities are emitted during their operating process that had a negative impact on the environment [1].

In fact, solar activity is the main source behind renewable energies. The earth receives an energy capacity of the order of 1.8×10^{14} MW per year, which is several thousand times higher than the actual electricity consumption. So, solar energy can meet our current and future energy needs [2].

The global power growing of renewable energies made its investigation competitive with conventional fossil fuel sources. According to the statistics of 2017, the added capacity for solar energy is 98GW and is about 52GW for wind energy, however gas and coal grown only with 38GW and 35GW, respectively. According to the same statistics, the investigation in solar photovoltaic energy has increased significantly and taken the top of development and installation compared to the other renewable energies with 32%, followed by wind energy by 10%. China takes the head of global PV energy installation with 23%, followed by the USA with 14%, Japan with 13%, Germany with 13%, Italy with 6%, however, the rest of the world takes only 30% of the total PV installations [3].

It is worth mentioning that thanks to the French scientist Edmund Becquerel, the conversion of solar electromagnetic radiation into electricity (i.e., known as the photovoltaic effect) has been successfully conducted in 1839 [4]. Nowadays, the generation of electricity using PV power knows a large scale of installation in all domains and dominates the other energy sources, due to the availability of solar energy all around the earth. This energy is used to feed satellites, electrical vehicles, for road lighting and boats. In the recent few years, large installations of PV systems have been realised due to the development of new solar cell technologies, in addition to other considerations such as: driving the price-down of many PV technologies and PV equipment, meanwhile, increasing their efficiency as high as possible. Moreover, Photovoltaic Generators (PVGs) do not contain any mechanical parts that emit noise when generating electricity. This makes the PV system the most suitable for buildings and residential cities [3]. In this sense, the PV systems are largely installed and integrated into buildings with different capacities. These systems are known as Micro-Grids (MGs).

Currently, low voltage MGs can reach 10 kW of capacity, connected directly to a low voltage grid, or to others MGs through Point of Common Coupling (PCC), as it can disconnect from the grid and operate in islanded mode [5]. The transition of MG between grid-connected and islanded modes is ensured using a circuit breaker which must be controlled efficiently using an appropriate management strategy for maximum benefit and protection of the renewable PV-MG.

MGs are classified into two distinct types depending on the distributed generation used. Therefore, the first type is known as Direct Current Micro-Grid (DCMG) and it is based only on PV generators to produce DC electricity, and the second type is based on wind generators and known as Alternating Current Micro-Grid (ACMG). The MGs allow the production of energy at a local or a decentralized level to meet the energy needs in rural areas. Their appearances in the industrial, residential and commercial systems are growing rapidly to reduce the electricity prices, increase the reliability of energy systems and save the environment from more CO_2 emissions. DCMG is widely used in residential applications compared to the ACMG, due to the absence of reactive power production and noise during the power generation [6]. Accordingly, numerous projects are focusing on electrical grid PV systems, and MG integration to sell the excess energy produced in order to be consumed by other grid users. According to [7], the grid-connected PV system improved from 29.5 GW in 2012 to 99.1 GW in 2017. This connection is ensured through the synchronization of the MG parameters with those of the grid respecting the IEEE1547 code (voltage level of 120-240V single phase /208-415V three-phase, frequency at 50Hz or 60Hz, and grid voltage must be in phase with the MG current at the PCC) so as to improve the quality of the power exchanged with the grid [8].

To ensure a continuous supply of electricity to the load during low PV power production, two major solutions are proposed; (1) Using a hybrid MG that is based on the interconnection of PVGs with other renewable-energy generators such as wind turbines; (2) Integrating storage devices to store the excess power produced and provide loads with the desired power during low production, grid fluctuation and helps in the management of the PV-MGs

Research motivation

The main objective of integrating PV systems to electrical MG is to ensure cleaner energy, with silent production that can be installed in any place (schools, hospitals...). Unlike other renewable generators such as wind turbines that contain a mechanical part, which makes noise during operation, and increases the risk of breakdowns and therefore the maintenance price of defective parts or that work poorly can be very high. In addition, the prices of devices used in PV systems have declined in recent years, which allowed the increase of investment of this energy source in all domains [9]. Accordingly, the benefits associated with the PV-MG can be divided into two main categories namely technical benefits and economical benefits.

Firstly, the MG technical benefits present all the advantages related to the control mechanism and operation of the MG when transferring the energy to the loads and the grid-tied. This can be achieved through the design of intelligent controllers capable of attenuating voltage swell and sag issues, by ensuring the stability of both voltage and frequency through the control of the active and reactive powers. Hence, reducing the control complexity so as to ensure stable energy supply, with high response time and reduced line faults. The transition between the grid connection and islanded mode must be ensured respecting the IEEE Standards for the voltage and frequency [10]. Secondly, MG economic benefits can be directly related to energy cost reductions. Compared to conventional electricity, which needed high-cost transportation to the rural areas, the self-electricity generation ensures independence from the national grid and benefits of the access energy selling when connecting to the grid. The indirect economic benefits of the MG are the reduction of electrical losses and economizing the capacity of the investment. Additionally, the MG can ensure a high energy supply with high reliability under variable weather conditions, and guarantee a good power quality with the ability to operate in islanded mode. Furthermore, protect the environment through the reduction of greenhouse gas emissions. Moreover, reach the safety and the security during power outages and maintain the continuity of the service [11].

To this end, technical and economic benefits of PV MG have been determined at the first step to implement a MG; some challenging issues are faced in the operation behaviour of the MG to ensure the safety and the security of the equipment, respecting the international applicable standards (IEEE) and take the short circuit current within an allowable value. The intermittent nature of the solar and its variations cause problems of operational ability, durability, and quality of supply. So, the maximization of the production will guaranty the highest benefit from the energy supplied by the sun and absorbed by the PVGs. Additionally, the transition between the islanded and grid-connected modes requires fast detection to ensure the safety and the reliability of the whole system. Hence, the changes appeared in the active and reactive powers must be compensated to attenuate the high harmonic distortions, to avoid any fluctuation or loss that can damage or disturb the energy transfer to the loads. Therefore, regulators must be improved to ensure the synchronization of the MG with the utility grid by regulating both voltage magnitude and frequency at suitable levels and stabilize the MG operating during its disconnection with relatively high power quality. As well as, the MG suffers from the high cost of installation in some areas, so it is necessary to improve the efficiency and the reliability of the MG to minimize the penetration of such problems [12].

In order to optimize the general operation of the MG and transmit the maximum energy to consumers with good quality and desired quantities that can meet their needs in electricity, it is necessary to equip the installation with the required storage capacity (i.e., batteries) to store the excess electricity and supply the energy needs by MG installations during night and shaded days, but they still suffer from high costs and cannot meet the electrical load needs of energy for a long period. Consequently, the PV-MG must be connected to the distribution network to ensure the sustainability of service and stabilize the system. Therefore the design of a suitable power electronics interface (i.e., converters and inverters) is necessary to cut from the high installation cost. Additionally, the improvement of the controllers used is necessary to overcome the drawbacks of the mentioned tasks.

The control of the switching device may be organized according to their control loops of current, voltage, frequency, active and reactive power into two categories, namely direct power control (DPC) that uses the active and reactive power as control variables, and voltage oriented control (VOC) based on orienting the current vector in the same direction as the grid voltage, these controllers are considered as inner loops in the hierarchical control of the MG.

As it has been mentioned before, the technical issues are related to voltage and frequency operation during both grid-connected and islanded modes. To mitigate harmonics and improve the power quality, it is necessary to control the frequency via the output active power control and to compensate the unbalanced voltage through the reactive power control. Under linear load, the droop control functions well, with a constant frequency value of 50Hz. However, under non-linear events where high harmonics are injected to the installation, the control methods require improvements to keep the frequency and voltage at their nominal values and to ensure a unite power factor [13].

Hence, after stabilizing the MG control, it is necessary to synchronize the MG voltage, frequency, and phase angle with the utility grid by employing the Phase Looked Loop (PLL) component.

The control loops can be divided into two categories, namely the outer voltage control loop responsible for generating the reference current value for the inner current control loop, the error between these current values is passed via a regulator to get the switching signal for the power devices.

The outer control loop can be classified according to their role in MG into two categories namely [14]:

- **Grid forming**: adapted in islanded mode to generate the reference voltage and frequency where the inverter operates as a voltage source, to ensure a fast response against perturbation and to stabilize the MG during loads connection/disconnection or power generation variations.
- **Grid following**: in contrast to grid forming the grid following cannot be adapted in islanded MG, since it is responsible for controlling the power balance to the main grid, where the inverter operates as a current source.

Problem statement

Nowadays, the integration of PVGs to MG is a big challenge. Its stability is ensured by the proper control of each element constituting the MG to guarantee the continuity and the durability of the service. However, although the closed-loop control of the power electronics part (i.e. converters and inverters) which ensures the distribution of the load on the various elements of the system, it has some limitations. In addition, several problems can be identified, we mention as an example a wide deviation of the frequency which appears in the case of the reactive power demand, as well as errors due to the disproportionality of the line impedances, the instability of the PV production due to climate changes and its absence during shady days and nights [15]. However, the problem related to the MG strategy is how it could be examined in terms of management and control and how it could be tested and validated to ensure low prices.

In order to enhance the efficiency of the MG and correct the voltages and frequencies states, an appropriate automatic control must be designed; this may be possible through the selection of an intelligent controller capable of improving the power quality under any operating mode, and enhance the grid reliability. As well as, to manage the bidirectional power flow between the MG and the grid. It is necessary to select an appropriate management control that takes into consideration the difference between the production and the consumption so as to stabilize and protect the MG. On the other hand, due to high harmonics injected into the system, it is difficult to maintain a unit power factor and the Total Harmonic Distortions (THD) will be higher. So, it is essential to develop an intelligent controller with high response time capable of adapting the MG to these changes and ensures its stability.

Research contribution

Consequently, this work is developed via double stage PV-MG control architecture. In the first stage, the design of an effective maximum power point tracking technique to enhance the energy extracted from the PV generators under any weather condition is done. PV Generators introduce an important amount of uncertainty in the accessibility of generation. So, battery storage devices are incorporated to compensate for this gap and ensure sustainable load feeding. The control of this latter depends on their State of Charge (SoC) and relates to the DC-link voltage level. So, finding an effective way to maintain the DC-link voltage and to ensure a large lifetime of the storage device presents a challenging task appeared when controlling the MG. This DC-link voltage must be taken at a fixed level, which presents the outer control loop of the inverter. The second stage Control is fulfilled to ensure high power quality, to guarantee a unit power factor and transfer maximum power to the grid. An inner current control loop is necessary to minimize the errors shown in the inverter output voltage and minimize the THD value [16].

To sum up, the main contribution of this thesis is to develop intelligent controllers capable of maintaining the DC-link voltage at the desired level under production trouble and preserving a low current THD value in order to achieve high power quality. Hence, minimizing the cost of MG through the improvement of the management control scheme to get high reliability, stabilize the MG and minimize power loss under both operating modes.

Research objectives

The main objective of this research is to develop simple and intelligent control strategies capable of ensuring high power quality and minimizing loss during the transmission of electrical energy to both, the loads and the grid. This may be possible through stabilizing the current and voltage signals and reducing their THD values to well operate the MG and to ensure high reliability, flexibility, and efficiency. In order to protect the MG during the power production, transmission and consumption, it is necessary to manage the whole system operation modes. To sum up, this research includes power quality improvement and management of a PV-MG.

The objectives of this work are listed as follows:

- Maximize the harvested and transferred energy to the grid under variable weather conditions and partial shading events;
- Maintain the voltage and frequency at desired magnitudes using intelligent controllers under all applied conditions;
- Manage the energy delivered to the load, including storage devices to maximize the benefit from the generated power during its operational lifetime;
- Reduce the THD of both delivered voltage and current to improve the power quality and system reliability, and satisfy the load’s energy demand by minimizing the power loss, and ensuring low harmonic distortions.

Research scope

Micro-grids can be constituted using a single type of energy generators or of several kinds of generators in the case of hybrid generation systems. The present research focuses on low voltage PV-MG connected to the electrical grid through the point of common coupling. On the other hand, the use of wind turbines to produce electrical energy in residential areas is not suitable because of the emitted noise during the production of electricity. So, this MG is built using PVGs and battery storage linked to an inverter DC-side through a boost converter and a bidirectional converter, respectively. The inverter is used to supply AC loads or connect the MG to the electrical grid through a circuit breaker. Regarding the power stage interface, the converters and inverters aim to maximize, stabilize and transfer the power to the consumers, through controlling them by intelligent algorithms. In this research, a management algorithm has been developed using Fuzzy techniques for more effective operation of MGs (i.e., protect the MG installation and control the bidirectional power flow).

Significance of the study

The findings of this study ensure technical and economic benefits from the PV MG which known a large scale of installations these last few years. The increasing demand for clean energy with relatively a simple and costless structure justifies the need for effective, reliable and intelligent control approaches. Thus, the MG control approaches of this study will be able to operate the PV system better than the existing techniques, with high power quality and low THD. The management strategy should be accompanied by the storage devices to improve the performance of the installation, and to supply the loads with the energy needed during the islanded mode. Moreover, this proposed scheme will be useful in residential and industrials seats. For both grid connected and islanded modes, to provide the consumers with qualified energy using a fast management strategy. It will also serve as a future reference for researchers on power quality and MG management topics for better designing of PV-MG installations.

The thesis organization

As mentioned before, this thesis work has been oriented towards the study of renewable MGs where we have focused on the improvement of power quality and energy management. In this sense, generalities on electrical MGs have been done, then we justified the choice of the PV-MG, the objectives and the contribution of the thesis had also been mentioned in the introduction. Accordingly, the outline of this thesis is divided as follows:

In **the first chapter**, the control strategies of the PV-MG are detailed. These controllers are divided into three parts, which are: (1) a state of the art of MPPT control algorithms used in PV systems to improve the performance of energy in the MG, including the different phenomena that can degrade the energy delivered by the MG; (2) The management of this energy, including the different methods existing in the literature with their advantages and disadvantages. (3) The different inverter controls and the power quality issues of the MG.

The second chapter presents generalities on PV-MG; we recalled the different elements constituting a PV generation system, going from the cells until the injection to the electrical grid, including details about the PV panel mathematical modelling, operating principal, technologies, and different converters and inverters topologies.

The third chapter focused on the management of standalone PV/Battery MG taking into consideration the partial shading and how to mitigate its effect on the energy delivered to the load. A control algorithm used to improve the quality of the energy, including different phenomena that can degrade the amount of energy delivered by the MG.

The fourth chapter analysis a standalone MG and how to design its components. Then, a comparison to a system without the management strategy is fulfilled to show the features of the power management in improving the operating process of standalone PV/Battery based MG systems.

The fifth chapter deals with an improved fuzzy control scheme for grid connected PV system under variable weather conditions. All tests are carried out by using MATLAB/SIMULINK software. The simulation results show the effectiveness of the proposed method.

Finally, conclusions and future works have been given.

CHAPTER 1: LITERATURE REVIEW

1.1. Overview

The stability and the reliability of the Power electronic connected in parallel in Micro-grids are ensured controlling the voltage and frequency. In the other hand, high disturbance and power quality problems take place when any mismatch occurs. This chapter deals with the current strategies for the control and management of the power converters operating in the DC-MG system.

PVG and Energy Storage System (ESS) are important parts of the electrical MGs based renewable energy. To transmit the generated power, the power electronic devices which are DC-DC converters and DC-AC inverters are required. Various control strategies are developed to meet load demand and transfer the access power to the grid under real conditions by controlling the ON/OFF switching states of the aforementioned power interfaces. These controllers allow the transfer of maximum power to loads and power grid under normal conditions; also, isolate the MG when a disturbance occurs. So, the management of power flow is an important part of this procedure to mitigate power quality issues. Accordingly, reviews on recent researches on control strategies related to MG control, power quality, and management of DC-MG are considered in this chapter.

1.2. Control approaches in distributed systems

As mentioned earlier in the introduction chapter, the technical and economic issues must be largely studied and investigated for both MG inner and outer operating strategies. The smart grid is a great challenge in the actual researches which modernize the existing electrical grid by equipping them with sophistic and new components to achieve high technical and economic benefits, improve the generation sustainability, reliability, security, and efficiency, and overcome the problems related to distribution and transmission from/to the electrical power grid [14]. However, the MG faced several issues related to the power quality during its operating and communications with its neighbouring, and others with the management process. These issues must be considered so as to achieve smart grid operating benefits. In fact, the MG control can be either **Local control,** which maximizes the micro-sources exploration of the available power and stabilize the operating of the MG**; or coordinated control** which includes energy management namely supervisory control [17]. Firstly, the local control enhances the generation level operating efficiency by stabilizing the voltage and frequency under both operating modes of MG: grid-connected and stand-alone modes. So, the technical problems and operation process of the MG related to power quality such as power supply problems, components failures, overloads, and electrical distribution systems overheating must be surmounted to guarantee an uninterrupted, efficient and qualified electrical supply of the future smart grids. Secondly, the coordinated control manages the production, demand, and consumption of the energy at different MG levels; besides, it estimates the market electricity costs in order to optimize the production and the use of the utility grid to ensure high economic dispatch [18].

Recently, control and management problems are largely addressed as important issues of several studies and researches. The importance of the management at the MG level is to stabilize the voltage, frequency and power flows in order to compensate for the sudden increase in load power consumption, and deal with weather variations, hence, ensure a smooth transition between the operating modes of the MG. In fact, the **local control level** or the generation level includes [17] [18]:

1. The control of the DC-DC converters interfacing PVGs to DC-Link, which are also known as Maximum Power Point Tracking (MPPT) techniques;
2. The bidirectional converter controls the energy flow between the ESS and the inverter DC-side. It is divided into three types namely: 1) constant current control (CC), 2) Constant Voltage Control (CV), or 3) Constant Voltage-Constant Current (CV-CC) control;
3. Inverter control namely AC-side Control stabilizes the operating mechanism of the MG by maintaining voltage under unacceptable level and limiting the frequency deviation.

It is difficult to ensure an interlinking to the neighbouring MG, different loads and utility grid focusing only on the local controllers, without any communication between the various components from the generation, transmission to consumption. So, the integration of the management strategy in the **Supervisory** or the **coordinated control** is essential to optimize and control the power flow, meanwhile, ensuring the good MG operating management, depending on the power production-demand, and the state of the whole components constituting the system [17].

1.3. Local Control approaches

1.3.1. Maximum Power Point Tracking (MPPT) techniques

The maximum power point tracking technique known as MPPT is required to operate the PV system at its maximum power point (MPP) in order to increase its efficiency and protect the PVG. Many MPPT algorithms have been studied and developed in the literature; they differ on the number of the used sensors, their complexity, the dependence on the system parameters, the technique of implementation, and their cost [19]. In fact, the first use of the MPPT was for aerospace applications in 1970 [20]. Its first utilization on the PV applications was in 1954 [21], from that to 2020 several researchers focused on developing MPPT techniques to enhance the quality and ensure a high operating efficiency of the PVGs. Several classifications have been done for the MPPT techniques in such a way to distinguish between them. For instance, considering the dependence on the PVG parameters, we can classify them to 1) direct methods which are independent from the PVG evolution such as Perturb and Observe (P&O), Incremental Conductance (INC-Cond) ,feedback voltage or current, Fuzzy Logic based MPPT and Neural Network(NN). 2) Indirect methods require the knowledge of the PVG parameters based essentially on the mathematical relationship of the practical data such as, Fractional open-circuit voltage (FOCV) and Fractional short-circuit current (FSCC) and Luck-up Table [14].

Another classification of the MPPTs is done in [22], where the MPPT technique can be either 1) On-line or also named Hill-Climbing (HC) technique, 2) off-line technique or 3) artificial intelligent technique. Alternatively, the authors in [23], classified these techniques into two categories namely 1) Local MPPT techniques which are in turn divided to conventional, hybrid and intelligent techniques. 2) Global MPPT techniques include Soft computing techniques namely meta-heuristic techniques. The inputs data of the MPPT technique are the instantaneous measured parameters of the PVG, such as: the PVG voltage (V_{pv}), the PVG Current (I_{pv}), the ambient Temperature (T) and Irradiance, whereas the output is frequently the duty cycle of the DC-DC converter switching gate. The improvement of these techniques has known a large scale in recently published research papers so as to enhance, to optimize and to adapt them to different phenomena that hinder the function of the system under standalone or grid-connected situations such as, fast weather variations (irradiance and temperature), connection and disconnection of the generators, dust, partial shading events and faults. Nevertheless, comparisons and analyses of these techniques show that they differ in many aspects, for example, the number of sensors used, complexity, dependence on the system parameters, tracking accuracy and response time, steady-state and dynamic efficiency, the procedure of implementation and cost [22].

From **1954 till now**, several MPPT techniques are periodically enhanced and published. In **1961**, **Hooke et al** [23] proved that the intersection between the (I_{pv}-V_{pv}) non-linear curves with the resistive load value presents the MPP. Whereas, a similar analysis applied to the dynamic load is done by **Biran et al** in **1976**. Moreover, these properties are studied and applied to battery storage by **Braunstein** in **1977** for the same purpose to design the MPP [24].

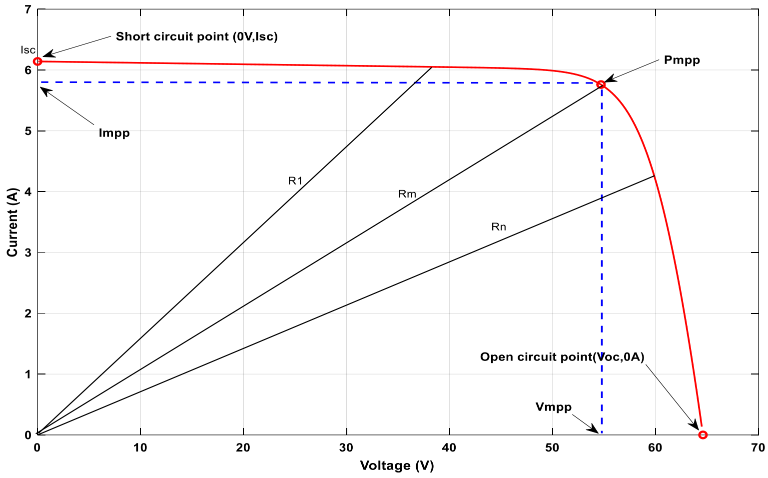


Figure1.1.variable resistance and I-V characteristic curve

1.3.1.1 Conventional methods

1.3.1.1.1 Perturb and Observe (P&O)

The P&O is based on sensing the $V_{pv}(k)$ and $I_{pv}(k)$ of the PVGs then calculating the power ($P_{pv}(k)$) (Equation.1.1), the algorithm designs an initial power position which is not necessary the MPP. The P&O changes the sign of the disturbance $\Delta V_{pv}(k)$ (Equation.1.2), after each measurement of $\Delta P_{pv}(k)$ (Equation.1.3), and increment or decrement the $V_{pv}(k)$ (Equation.1.4), after each iteration until the MPP is reached. This technique had a simple structure that is easy to implement at a low cost. It is able to track the Maximum Power Point (MPP) under normal weather conditions. However, the voltage never reaches its maximum value because of the fixed step size of the reference voltage. So, high oscillations and slow response time under fast variations of irradiance are the major drawbacks of the P&O technique, which lead to considerable power loss [25].

$$P_{pv}(k) = V_{pv}(k) \times I_{pv}(k) \tag{1.1}$$

$$\Delta V_{pv}(k) = V_{pv}(k) - V_{pv}(k-1) \tag{1.2}$$

$$\Delta P_{pv}(k) = P_{pv}(k) - P_{pv}(k-1) \tag{1.3}$$

The output voltage incremented or decremented as:

$$V_{pv}(k) = V_{pv}(k-1) \pm \Delta V_{pv}(k) \tag{1.4}$$

Then, a PI controller is generally integrated to get the appropriate duty cycle value. This process is repeated until getting a power variation equal to zero (MPP achieved). The described algorithm is depicted in Figure.1.2.

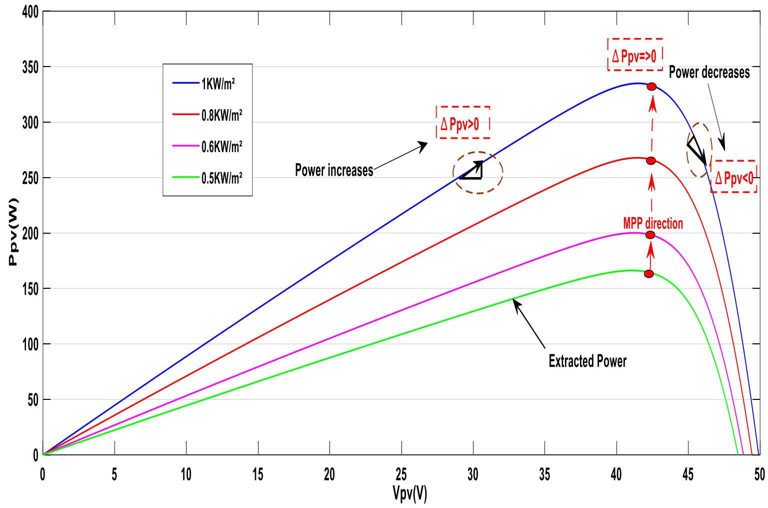


Figure 1.2. Perturb and observe operation

Several improvements had been applied to the P&O technique in order to enhance the accuracy, steady-state, and dynamic tracking efficiency. Some of the widely explored ones in the literature can be listed as follows:

Fox et al, 1979 used the mathematical optimization based Hill-Climbing (HC) that focuses on the local research to constitute the principal of the P&O technique. Then, (**Schoeman et al, 1982)** presented the final version of the classical P&O technique's flowchart [26].

Katan et al, 1996 [27] analysed the transaction problem between the oscillation variation and the tracking speed of the conventional P&O technique. In this study, fixed step size is used to enhance the tracking accuracy and also minimize the oscillation amplitude. Nevertheless, either if the response time of the algorithm was increased; the oscillations were significant and not completely damped.

Hua et al, 2016[28] developed an extra loop that comprised a threshold current parameter technique combining with the classical P&O technique to deal with the fast solar irradiation variations. The efficiency of the planned technique under steady-state and dynamic conditions achieved a value of 83.6%.

Xiao et al, 2004 [29] suggested a modified adaptive hill-climbing (MAHC) technique based on variable step size perturbation. The step size of the voltage is updated to deal with the sudden variations that occur in the irradiation level. The efficiency of the MAHC technique reached 97.3% and 96.3% in steady-state, and dynamic conditions, respectively.

Gomathy et al, 2012 [30] analysed and compared some MPPTs under MATLAB/SIMULINK to a modified fixed step size P&O. The simulation results showed high tracking speed and better performance under all applied circumstances.

Bennett et al, 2013 [31] tackled the trade-off and failures between the oscillation variations and the rapidity under normal and fast variations on the irradiance level. In fact, the variable step size on the voltage ($V_{PV}(k)$) is incremented or decremented comparing the $V_{PV}(k)$ to the voltage at the MPP (V_{mpp}). High efficiency of around 97% is obtained for both steady-state and dynamic analysis.

Selmi et al, 2014 [32] validated the classical P&O experimentally and tested its efficiency under sudden irradiance variations. However, the results are not compared to other existing techniques and the changes in the temperature were not considered.

Killi et al,2015 [33] suggested the Drift-free-P&O technique to follow the accurate MPP under high solar insulation caused by the incorrect choice taken by the P&O technique. In fact, the Drift-free-P&O technique is based on overcoming this drift by considering the output PVG Voltage ($V_{pv}(k)$) and observing the $I_{pv}(k)$ and $P_{pv}(k)$ deviations. Both steady-state and dynamic efficiencies are improved, and the oscillations are diminished. However, the technique deviated from the MPP under low irradiance levels.

A. Elbaset et al, 2016 [34] implemented a modified P&O MPPT using an embedded microcontroller. This technique is fulfilled to design the right duty cycle during fast weather changes and overcome the drawbacks of the classical technique. Simulations and experimental validations using an embedded microcontroller under real weather measurements showed excellent results. However, this method is applied in low power value for a single PVG (80 W) and a constant load. So, its application for large power will not guarantee the same results.

Alik et al, 2017 [35] proposed a Modified P&O with a checking algorithm under various solar irradiation using low-cost micro-controller. In fact, the checking algorithm is added to identify the voltage at the MPP (V_{mpp}) and harvest the maximum power. Simulations using a DC-DC boost converter in MATLAB/SIMULINK platform showed zero ripples at load side with high tracking efficiency (100%).

Amara et al, 2018 [36] presented an implementation of the classical P&O technique to a standalone double stage PV system. High performance (98.9%) and slow tracking speed are obtained through MATLAB/SIMULINK analysis. However, the analyses under variable irradiance or load conditions are not considered. Moreover, the used P&O was not compared to the existing techniques studied in the literature.

Dhaouad et al, 2019 [37] implemented P&O algorithms using Arduino microcontroller for a PV system under fast irradiance level changes. An increase in the efficiency and a decrease in the cost of the overall system are achieved. However, the algorithm is tested only for DC system without any comparison to the other existing MPPT techniques.

1.3.1.1.2 Incremental Conductance (Inc-Cond)

The incremental Conductance (Inc-Cond) is developed to handle the low efficiency and high oscillations and other limits of the P&O techniques. The Inc-Cond is based on incrementing or decrementing instantaneous conductance ($I_{pv}(k)$ /$V_{pv}(k)$) depending on the slop of power (dP/dV). The MPP is reached when dP/dV is zero, increased on the left of the MPP and decreased on its right side (Figure.1.3).

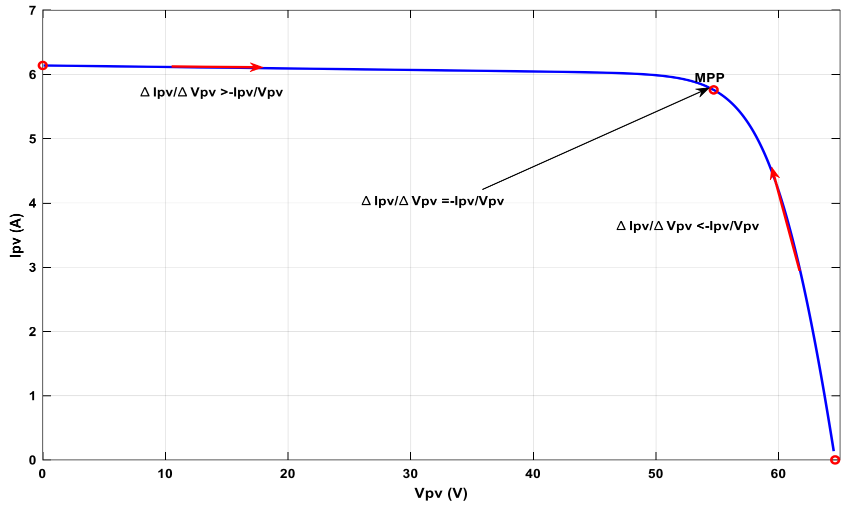


Figure.1.3. Incremental conductance based MPPT

Wasynezuk et al, 1983 [38] discovered the conventional Incremental Conductance (Inc-Cond) technique. Improvements are proposed and applied to this version. Then, **Hussein et al, 1995** [39] presented the final flowchart version of the classical Inc-Cond. Then, many improvements are reported in the literature to improve the efficiency and quality of the system stated as in the following orders:

Sugimoto et al, 1997 [40], **Brambilla et al,1999** [41] and **Mahamudul et al, 2013** [42] proposed modified versions of the conventional Inc-Cond technique to enhance the tracking speed, decrease the steady-state error and enhance the dynamic efficiency. However, a fixed perturbation step size is used which leads to significant loss under dynamic conditions.

Cha et al, 2008 [43] implemented the Inc-Cond technique to deal with the trade-off between the oscillation amplitude and the tracking speed. In fact, the comparison to the conventional Inc-Cond technique showed a decrease in the oscillations amplitude while the tracking speed is the same as that of the conventional Inc-Cond technique.

Mei et al, 2011 [44] developed a variable step size current controller based on the incremental resistance technique to attenuate the steady-state oscillations and enhance the tracking speed under dynamic surroundings. High efficiency of around 97% is achieved, but a low tracking precision is obtained compared to the existing Inc-Cond.

Hsieh et al, 2013[45] suggested a power increment technique to improve the existing Inc-Cond and enhance the tracking speed. However, this algorithm cannot detect the change in irradiance.

Yue et al, 2014 [46] proposed a revised Inc-Cond algorithm where the incremental voltage step size changes adaptively based on the slope of the operating points in two successive tracking steps of the PV power-voltage (dP/dV) curve. The revised Inc-Cond MPPT algorithm can quickly follow the MPPs and eliminate the oscillation around the real one. The effectiveness of the proposed technique is demonstrated using simulation. The comparison to the conventional Inc-Cond demonstrates the robustness and enhancement in the dynamic performance.

Putri et al,2015[47] implemented an Inc-Cond to control the duty cycle of buck-boost converter. Simulations using MATLAB/SIMULINK and comparison to the P&O algorithm showed elimination of the oscillations around MPP and better performance compare to P&O. However, Inc-Cond presents a slow time response.

Zakzouk et al,**2016** [48] proposed a low-cost variable step-size Inc-cond depending only on the PVG power change (ΔP),and eliminating the division on the PVG voltage change (ΔV). The algorithm was simulated and validated experimentally using low-cost microcontroller. The results show a cut-down system cost, fast response time with enhanced transient performance, and low steady-state oscillations around the MPP under all the tested conditions.

Sahoo et al 2016 [49], **Anuradha et al ,2017**[50] and **Motahhir et al, 2018** [51] modelled variable step size Inc-Cond MPPT techniques. Simulations are analysed under different conditions such as constant and variable loads, fast irradiance and temperature changes. Comparisons of the results to that obtained using Inc-Cond with fixed step size showed faster steady-state and dynamic response with high operating rang and efficiency exceeded 96%.

However, the modified techniques require more improvement and hardware implementation to prove their feasibility.

Farayola et al 2017 [52] presented a comparative study between conventional Inc-Cond, Inc- Cond with fixed step and Incremental Resistance through variable step size using a Cuk converter. The system is simulated using MATLAB/SIMULINK. Better performances are obtained using the variable step size method. However, this system was not simulated under irradiance variations and luck of comparison analysis considering the simplicity and cost.

Several others conventional MPPT techniques which are the Fractional Short Circuit Current, Fractional Open Circuit Voltage , Ripple Correlation Control (RCC), sweep current or voltage methods, load Voltage and load current minimization, dP/dV or dP/dI feedback control, predictive model, sliding control, and also around 100 conventional MPPTs algorithms are recently reviewed in [19,23,25].

1.3.1.2 Intelligent methods

This section gives a brief description of the most artificial intelligent algorithms and some of their applications in the PV MG to track the MPP.

1.3.1.2.1. Fuzzy logic Control (FLC)

Lotfih A Zadeh, 1965 [53] introduced the first Fuzzy logic control (FLC) theory in the university of California at Berkeley. FLC mimics the method of human intelligence. It is constituted based on linguistic variables with IF-THEN rule. FLC consists of three main stages: 1) fuzzification,2) rule based inference, and 3) defuzzification. Firstly, the fuzzification converts the input values to linguistic values. Then, the inference system determines the output linguistic values based on the input numerical values. Finally, the defuzzification determines the output control (Figure 1.4). It offers a robust control of nonlinear systems since it does not require the knowledge of the system's mathematical model such as robotics, aircraft and temperature control applications. Accordingly, it is introduced to enhance and ameliorate the extraction of MPPT in MG applications, such as:

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{1.5}$$

$$\Delta E(k) = E(k) - E(k-1) \tag{1.6}$$

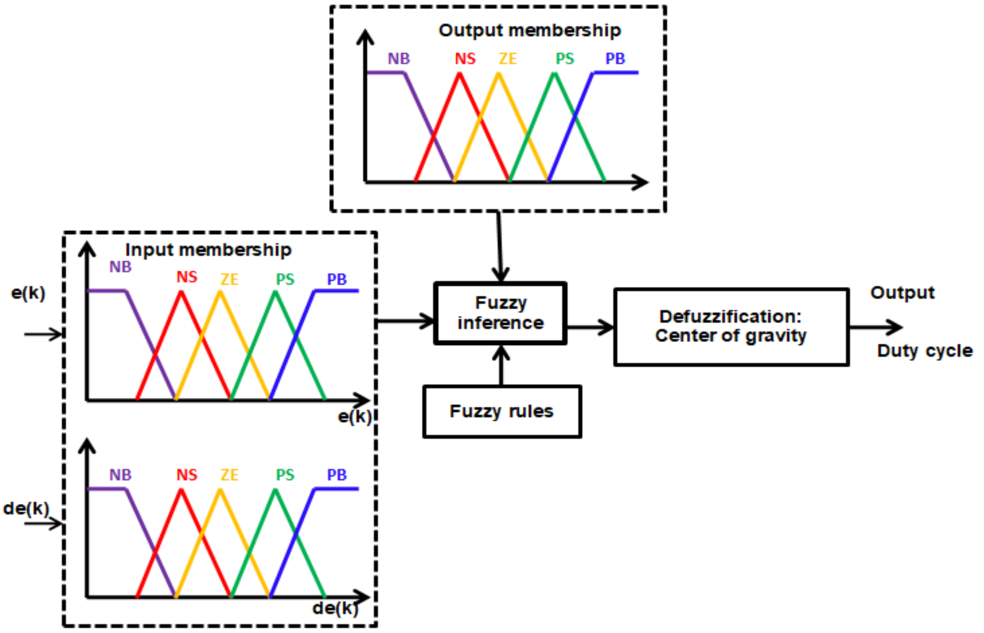


Figure 1.4. Fuzzy Process

Wu et al, 2000 [54] designed an FLC single-stage converter applied for powered lighting PV application. The proposed FLC can regulate both the charging and discharging current, and can effectively improve the dynamic and steady-state performance. Besides, simulation and implementation using a single-chip microprocessor and comparison to conventional P&O verified the feasibility, robustness and effectiveness of the FLC.

Chiu et al, 2010 [55] proposed a Takagi–Sugeno (T-S) fuzzy-model-based MPPT (T-S fuzzy MPPT) control without searching the MPP or evaluating irradiance. Besides, under disturbance and uncertainty, robust MPPT is assured through advanced gain strategy. So, the numerical results and experimental validations show that this MPPT enhanced the extracted power compared to traditional techniques, hence, improved the stability and assured zero tracking error.

Rakhshan et al ,2018[56] developed a Polynomial Fuzzy Model-Based Approach based on standard Takagi-Sugeno (T-S) fuzzy models and Linear Matrix Inequality (LMI), to increase the performance and efficiency of the solar photovoltaic. Hardware in the Loop (HiL) simulation was used. The results show the robustness and effectiveness of the controller.

REZK et al, 2019[57] designed and implemented a New Adaptive Fuzzy Logic-based MPPT Control for grid connected PV system. The implementation of the system was fulfilled using C-block in PSIM environment and validated experimentally through prototyping of 75-watt PV module. The obtained experimental results coincide with the obtained simulation results, which verify the superior performance and fast convergence with simple implementation compared to the conventional MPPT techniques. A high tracking efficiency and fast dynamics by reaching steady-state point within 0.01 s that facilitate its integration to GMPPT searching technique.

1.3.1.2.2. Neural network (NN)

The human intelligence is an efficient and powerful calculating machine with high learning aptitudes which can deal with real difficulties that the Computing PC cannot solve. In fact, the Artificial Neural Network (ANN) model is constituted by layers of neurons which model the process of the human brain. Each neuron models the behaviour of the brain cell activity. Where it collects the weights input product and yield a notice act according to this sum. Many ANN are developed such as hop-field neural network, radial basis neural network, and feed forward neural network. Besides, ANN is based on a learning algorithm. It is widely applied in modelling, forecasting, control and pattern classification. It is worth mentioned that back-propagation algorithm is the most adapted and used. This later is based on comparing the ANN output with the required calculated one. The error is utilized to update the neurons weights in the learning process of the ANN. Due to the high control efficiency of this technique; it is widely adopted and applied in several situations to optimize the operating process of the MPP in PV-MG. Since 1988, the Neural Networks was integrated on the MPP based on the weight matrix to speed up the MPP searching process. The hardware of the MPP was more closely matches the brain that the mathematical model originally selected [52]. Figure 1.5 illustrates the principle of the Neural Network based MPPT.

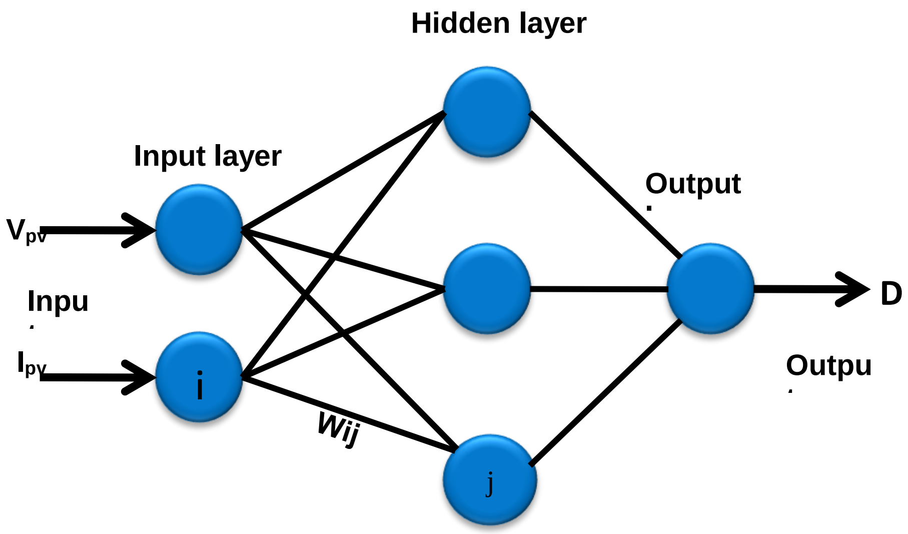


Figure 1.5. Neural Network Based MPPT

Faris et al, 2013 [58] designed a MATLAB/SIMULINK NN-MPPT based on back-propagation strategy using twenty nodes only in the hidden layer which speed the execution time and reduces its complexity. The NN-MPPT is tested under solar irradiance variations and ambient temperature, successful MPP accuracy and efficiency are obtained comparing to conventional P&O and FLC based MPPT. However, experimental validation and further improvements are required to efficiently use the NN in the PV domain.

Khanam et al, 2018 [59] implemented a Levenberg-Marquardt algorithm for NN-MPPT to deal with the effect of irradiance and temperature on the produced power and voltage of the PV system and predict the exact MPP. Comparison to P&O and the system without MPPT demonstrated the accuracy and quickness of NN-MPPT.

1.3.1.3. Global MPPT Techniques (Bio-inspired algorithms)

It is important to find new and better solutions to handle problems of the existing solutions to improve both the power quality and the MG operation. However, local search depend on the initial conditions and limited to specific situations. On the other hand, sudden changes will deteriorate the effectiveness of the algorithm and lead to a reduction of the convergence speed. Accordingly, to perform the global optima and enhance the convergence rate, several algorithms that achieve a good solution in acceptable timescale, high quality and performance are proposed and improved. Swarms are programming techniques of learning using real-world methods equitable for large data and complex situations to obtain adequate solutions within equitable time. The most popular and explored techniques are Firefly Algorithm (FA), genetic algorithm (GA), Artificial Bee Colony Algorithm (ABC), Ant Colony Optimization (ACO), Differential Evolution Algorithm (DE), cuckoo search (CS), Slap Swarm Optimization(SSO) and Particle Swarm Optimization (PSO) which have versatility in optimization process in various study and hybridization techniques.

These methods based on stochastic optimization have shown their consistency under PSCs. Where we can mention some developed methods as follow:

1.3.1.3.1. Cuckoo Search(CS)

Farag et al, 2019 [60] Compared MPPT based PSO and Cuckoo Search (CS) algorithms in harvesting the MPP from PV resources. The system is implemented using MATLAB/SIMULINK software and compared to conventional P&O under irradiance, temperature variations, and PSC. The PSO outperforms CS during transient state, whereas CS identifies the GMPP accurately compared to PSO. So, further improvements are required to both techniques to more benefit from their advantages.

Mosaad et al, 2019 [61] reviewed and compared a novel MPPT based on CS algorithm to extract the GMPP. In fact, CS used the random walk of levy flight in the searching process. CS tracks the MPP efficiently. This is proved comparing results with some existing methods namely Inc-Cond and ANN where high tracking speed and accuracy are accomplished.

1.3.1.3.2. Particle Swarm Optimization (PSO)

Ishaque et al, 2013 [62] improved PSO-MPPT to reduce the steady state oscillations for the PV system. The system was simulated under step changes in irradiance and load, and PSO conditions. Additionally, simulation and experimental validations show that PSO outperforms HC methods in term of performance, tracking speed, and low oscillations. Figure 1.6 presents the flowchart of conventional PSO based MPPT.

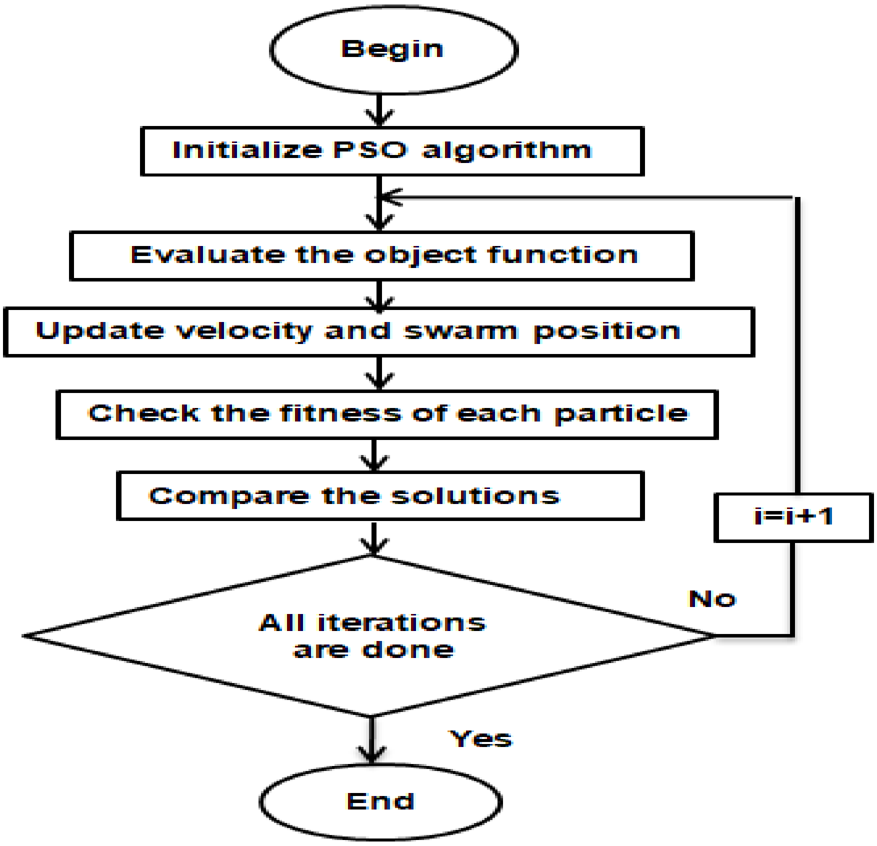


Figure.1.6. Conventional PSO technique

Renaudineau et al, 2014 [63] applied a PSO based MPPT for Distributed PV Power Generation to determine the operating point depending on the dc bus parameters. The practical validation to improve the performance and feasibility of the approach are validated in a laboratory prototype. The overall efficiency is performed by comparing theoretical and experimental curves. However, comparison to existing strategies is necessary for more improvement of the applied PSO.

Kermadi et al, 2015 [64] proposed a modified PSO based MPPT to decrease the time wasted for PV with a Li-ion Battery system under PSC through the use of variable sample time during the learning phase . Improvements in the tracking speed and accuracy in tracking the global peak at any condition are achieved. However, no comparisons to existing techniques or experimental validation are performed.

1.3.1.3.3. Artificial Bee Colony (ABC)

Yi et al, 2014 [65] proposed a new swarm intelligent technique based on Bee Colony behaviour to deal with the optimization problems. ABC solution is the food source not an individual's honeybees whereas in other techniques such as PSO each individual swarm represents a possible solution.

Salmi et al, 2016 [66] used ABC based MPPT for PV system using solar irradiation and temperature to track the optimal duty cycle. Comparison to P&O using MATLAB/SIMULINK showed an improvement in speed, robustness, oscillations attenuation, and efficiency under meteorological change conditions.

1.3.1.3.4. Ant Colony Optimization (ACO)

Dorigo et al, 1990 [67] introduced an Ant Colony Optimization (ACO) algorithm to deal with problems of optimization. It is based on probabilistic algorithm for discovery of optimal paths using the behaviour of ants searching for food.

Titri et al, 2016 [78] employed Ant Colony Optimization (ACO) as an MPPT to control PV systems. The obtained results of ACO MPPT were analysed and compared to the well-known conventional P&O and to intelligent controllers like ANN-MPPT, FLC-MPPT, FL Optimized Genetic Algorithm-MPPT, Adaptive Neuro-Fuzzy Inference System (ANFIS)-MPPT and PSO-MPPT. Best performance in terms of accuracy, stability convergence, and robustness at steady state conditions have been achieved by ACO-MPPT. But the method was not validated experimentally and the PSC was not considered.

1.3.1.3.5. Differential Evolution (DE) and Genetic Algorithm (GA)

Hadji et al, 2018 [69] focused on exploring the GA through four steps 1) selection,2) crossover, 3)mutation and 4) insertion applied to individuals through a fitness function to select the optimum individual which represents the MPP. The results are validated experimentally using a test bench under partial shading, and comparisons to P&O and Inc-Cond proved its stability and oscillations attenuations.

Kumar et al 2015 [70] presented an overview of GA for MPPT of solar PV system. Comparisons to P&O and Inc-Cond methods have been conducted based on the previous research studied in the literature under different applied conditions. However, no simulation or experiment is presented to validate the theoretical analysis.

Bhagat et al 2017 [71] applied Differential Evolution (DE) and Genetic Algorithm (GA) based MPPT Controller to tune the PID parameters and enhance the extracted PV power. The difference between the two methods is that the GA is based on mutation and crossover to generate the next off springs, whereas, the DE uses mutation and selection methods to generate the off springs. Then, the fitness of the individual is calculated and the low fitness is stimulated to the next estimation. Finally, the process of the algorithm stops and returns the final fitness when one of the ending criteria is achieved. Results proved that the DE technique is more efficient then GA in tracking the MPP, besides, the two methods give better performance, low steady-state error compared to P&O and Inc-Cond techniques.

1.3.1.3.6. Slap Swarm Optimization (SSO)

Mirjalili et al, 2017[72] developed a novel bio-inspired algorithm named Slap Swarm Optimization algorithm (SSO) to simplify the research and to improve optimization mechanism efficiency. It was applied to seek the GMPP by **Mohamed et al, 2019**[73] where the stability improved and power fluctuations are reduced. It is a metaheuristic optimization method uses different slap chains and the swarm of individuals to ensure the rapid and high-quality search for the global and adequate optimum.

Yang et al, 2019[74] proposed an improved SSO technique named Mimetic Slap Swarm Algorithm (MSSO) based on the existing SSO to deal with PSC and fast varying weather conditions for PV system under mimetic computing structure , and using wide and deep search. Four studies are carried out under MATLAB/SIMULINK: 1) start-up test, 2) step change of solar irradiation,3) ramp change of solar irradiation and temperature, and 4) field atmospheric data of Hong Kong. The obtained results are then compared to eight existing techniques Inc-Cond, GA, PSO, ABC, CSA, Grey Wolf Optimizer (GWO), SSO, and Teaching-Learning-Based Optimization (TLBO), respectively. Then, validation is undertaken using the hardware-in-the-loop (HIL) experiment through DSpace platform. According to the results, high improvements in the generated energy with fast GMPP tracking efficiency compared to the aforementioned techniques are obtained.

1.3.1.4. Improved MPPTs

Improved MPPTs methods or known as hybrid MPPTs are obtained by combining the aforementioned techniques (Conventional and intelligent techniques) so as to surmount their drawbacks and adapt them to different phenomena occurring during operation. Some of the developed and implemented ones can be listed as follow:

Soedibyo et al,2017 [75] combined P&O with Inc-Cond to track the MPP under partial shading conditions. The simulation results indicated that the power output of the module covers 99.4% of the load demand in the investigated system.

Zengrui et al, 2016 [76] proposed a novel MPPT technique for PV system using an improved version of PSO technique and variable step P&O. Firstly, the PSO pursuits the global maximum power point (GMPP) . Then, the variable step P&O technique tracks the GMPP perfectly under partial shading conditions.

FLC has been hybridized with various Soft Computing (SC) techniques such as: Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Artificial Neural Network (ANN) and Ant Colony Optimization (ACO) to track the MPP. However, hybrid FLC-SC techniques have high complexity, as they need to process the three stages of FLC as well as to test a population of duty cycles or voltages by SC techniques. This makes the Hybrid FLC-SC MPPTs the most cumbersome and complex algorithms. To get rid of the latter mentioned drawbacks, meanwhile, improving the PV system efficiency, FLC has been largely hybridized with conventional MPPTs.

Mayere et al, 2019 [77] proposed an adaptive Fuzzy Logic based P&O using 25 fuzzy rule-based. Fast convergence and tracking speed are shown simulating the algorithm under Partial Shading Condition. However, the algorithm needs more improvement and experimental validations to confirm its effectiveness for large scale PV system.

Bouchakour et al, 2019 [78] presented a comparative study of P&O-PI and fuzzy-PI MPPT techniques and their optimisation using GA and PSO for photovoltaic water pumping systems to optimize the efficiency of the motor and maximize the PVG power . The simulation results are presented and discussed to show the effectiveness of the FLC-PI controller optimised by PSO regarding the other methods, in terms of stability, dynamic, and steady-state efficiency.

Nabti et al, 2019 [79] proposed an intelligent fuzzy discrete proportional-integral-derivative (FL-DPID) MPPT for battery charging control to enhance battery life time and to reduce power loss. The controller algorithm is based on regulating the delivered power to the battery by considering the transition response and the ripples in the output voltage and current. Nine fuzzy rules have been used to achieve better tracking performance compared to conventional P&O and Inc-Cond.

Vadim et al, 2017 [80] proposed a hybrid FLC-HC MPPT control technique to surmount the drawbacks of using fixed step size HC methods, FLC-HC MPPT varies the step size to improve the response time under fast variations of irradiance. However, oscillations around the MPP are the main limits of this MPPT

Radjai et al, 2014 [81] presented a combination of P&O and FLC. Low oscillations, high efficiency in tracking the MPP are achieved using the proposed strategy compared to conventional P&O. However, the steady-state oscillations could not be completely eliminated. Moreover, Hybrid FLC-P&O MPPT suffers from slow response time, which causes significant power loss under fast variations of irradiance.

Ratna et al, 2014 [82], **Cazac et al, 2017** [83], **Monfered et al, 2012** [84] proposed hybrid MPPTs based on Inc-Cond and FLC to track the MPP. The evaluation of these MPPTs depends on the type of membership functions, number of fuzzy rules, and the tracking performance under different operating conditions. A hybrid Inc-Cond-FLC control technique is proposed in [82], the ratio of derivative power and voltage, as well as the variation of this ratio are calculated and employed as the FLC inputs. The FLC output is passed through a PI control to regulate the switching converter duty cycle. The MPPT shows an improved efficiency and reliability in tracking the MPP; however, using 49 fuzzy rules in addition to a PI controller increases the complexity of the control and slows its response time. A combination of FLC (9 fuzzy rule) and Inc-Cond has been experimentally tested in [83], the algorithm may fail to achieve the accurate MPP for some operating conditions. The proposed MPPT in [84] employs FLC with 25 rules which are designed by considering the incremental conductance principle to generate the appropriate duty cycle for a buck-boost converter. No comparison with the existing MPPTs has been done to show the tracking efficiency of this MPPT.

The use of HC-PSO to track MPP has shown high reliability compared to the others bio-inspired techniques and allows the direct control of the duty cycle , avoiding the use of hybrid controllers to get the gate switch control such as PSO-ANFIS proposed in [85],and PSO-PID variable step size MPPT controller presented in [86].

Rahma et al, 2014 [87] combined FLC and PSO approaches to find the membership functions (MFs) to deal with the errors incorporated during the design of the FLC and achieve accurate results. Improvement is shown compared to the FLC. However, this MPPT has a high complexity and requires sophisticated electronic board to be implemented.

Liu et al, 2017 [88] combined the Inc-Cond and PSO to deal with the shadow appear in PV array. In fact, Inc-Cond is used to track MPP under normal and stable conditions, but during PSC event, the MPP is located accurately using PSO. Simulations improved that the coordination of the algorithm based on PSO and Inc-Cond, where this later can fall in tracking precision. So, high efficiency and reduced hardware cost are achieved.

Tang et al, 2017 [89] combined Fractional-order and FLC to enhance and optimize the tracking accuracy in weather variations. In fact, the algorithm used the alpha factor to contract the fuzzy domain and minimize the searching time for the MPP. Simulations are done using MATLAB/SIMULINK, and implementation on the Field Programmable Gate Array (FPGA) board is done. Results show an improvement in steady-state and transient performance simultaneously compared to some existing FLC techniques.

1.3.2. The bidirectional converter controls and Management Algorithm

To manage the power balance in both operating modes of the DC-MG (grid-connected and islanded), DC-DC bidirectional converters are incorporated between the ESS and the DC-Link. The local control of this converter will order the battery to provide energy in steady-state conditions when the PVG is not capable; in this case, the converter works in boost mode, while the battery charges when a surplus production is detected. In this case, the converter works in buck mode. In fact, the State of Charge (SoC) is used as an index to decide either the battery will charge or discharge, hence the slope indicates the rated level of the battery charge/discharge [17].

To stabilize and analyse the operating modes of the MG, numerous controller methods have been developed for bidirectional DC-DC converter applications associated with the problem of two power flow directions. So, three techniques are included in the battery charge/discharge management topic:

Constant Voltage control (CV) keeps the voltage at constant value by providing only current which unfortunately degrades the current profile, and has a negative impact on the battery lifetime. On the other hand, the **Constant-Current control** (CC) maintains the current at variable voltage output. The combination of these two methods on **Constant Voltage-Constant Current** (CV-CC) uninterrupted power supply ensures high efficiency, ease control structure resulting in low cost. Indeed, the control process monitors both voltage and current using conventional and advance control strategy to adjust the duty ratio of the bidirectional DC-DC converter [90] [91].

During the constant current control mode (CC). In this case, the battery is in charging mode and the bidiractional converter works in buck mode. While the CV mode allows the delivration of a fixed voltage value to compensate the luck of energy production at the DC-link level through the boost converter as schematized in Figure 1.7

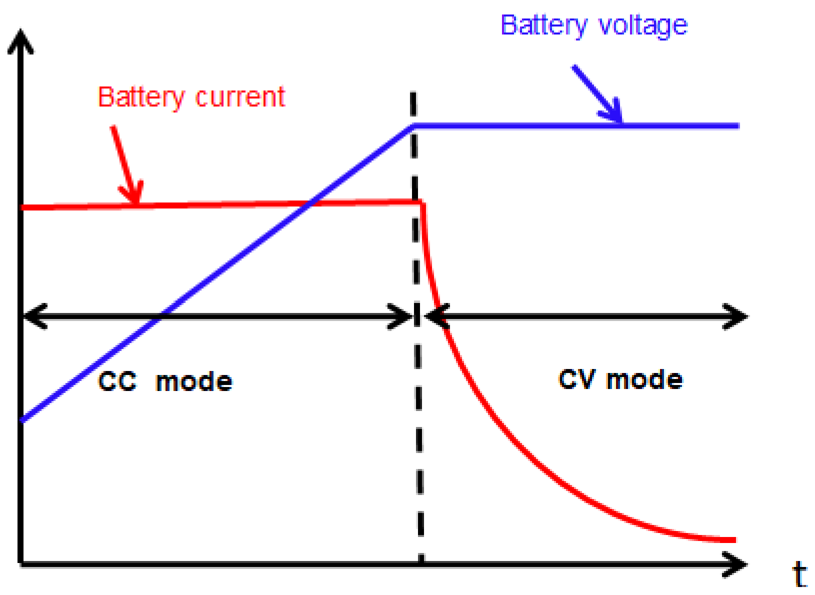


Figure.1.7. Battery CC-CV evolution

MAs are involved depending on the application requirements and their primary energy sources. Various energy management strategies are developed to control MGs by maintaining the state of charge (SoC) under acceptable range, satisfy the load requirement, and guarantee an affordable grid.

Gaurava et al, 2015 [90] detailed an energy management system for a PV-Battery MG. In fact, the charging and discharging of the battery is fulfilled through four operating modes:1) PV supplies load and charges the battery;2) PV supplies load only; 3) Battery supplies load and finally, 4) when load requirement is achieved using both PV-Battery energy. In fact, a Lead-acid battery is used as storage device. Moreover, logic control using ideal switch and Multiport switch for PV array and batteries, respectively, to switch between the aforementioned operating modes are done and simulated under MATLAB/SIMULINK. However, details about the controllers adopted for the interfaced power electronic are not considered, moreover, the algorithms lack of experimental validation.

Reyasudin et al, 2019 [91] analysed and presented an optimized management energy based on uncertainties of solar power generation, PV shading and load variation. The structure is modelled using MATLAB/SIMULINK. The approach is performed to optimize the energy generation and consumption based on predictive control.

Meng et al, 2016 [92] gave a literature review on existing supervisory control and management strategies of MG. In fact, the hierarchical control, constraints, optimizations and solution approaches used including centralized and decentralized techniques applied to variable energy generation in different fields to ensure reliable of MG are done.

Hasan et al, 2008 [93] proposed a novel strategy for the battery management system to achieve high efficiency of a PV system. In fact, the DC-bus power and SoC and the classical PID are investigated to accomplish this aim. The SoC is considered as a key parameter in the management strategy. If the SoC is below 90% and the DC-link power is sufficient to charge the battery, the bidirectional converter works in buck mode and charges the battery. Alternatively, if the SoC is above 40% and the load needs power, in this case, the bidirectional converter works in boost mode to deliver power to the load. When the battery power is insufficient, it switches to halt mode. Successful coordination between production and consumption are achieved with efficient control and confirmed through Simpower of SIMULINK. However, the system is not validated for grid-connected mode and experimentally.

Tavakoli et al ,2018 [94] developed an optimal management battery energy storage system to enhance the grid resilience and PV generations operational prices based on an optimized strategy of the energy management system control to deal with the intermittent PV generations and electricity cost incorporating Conditional Value at Risk (CVaR). Improvements are shown considering the commercial operational cost through the analyses and performance evaluation of the results under MATLAB simulation.

Koohi-Kamali et al, 2014 [95] proposed a power management system photovoltaic, diesel, and battery storage plants inside the grid connected MG tested under sunlight, temperature and load variations. To ensure the uninterruptable power supply and deal with the power fluctuations resulting from solar and loads variations, constant current is used for the battery charge/discharge process. Simulations are done using PSCAD software under different aforementioned conditions that showed satisfactory service supply under operator and demand sides.

Singh et al, 2017 [96] elaborated a Solar-Battery power management algorithm for residential consumers tested under grid-connected and islanded modes. The management strategy is fulfilled using a battery current control done by comparing a reference current to the battery current before passing it via PI control. Then, the modulation gates is ensured using AND logic. This process allows the charge/discharge of the battery and operates the bidirectional converter in buck/ boost mode depending on PV power, SoC, and load profile. The system is implemented in PASCAD software.

An et al , 2019 [97] developed a voltage-current double closed loop control for DC-MG composed of PVGs hybrid storage (accumulator-super-capacitor) and DC-load. Indeed, to control the bidirectional converter interfacing the storage devices to the DC-link side, a Fuzzy controller tunes the parameters (K_p and K_i) of the PI controller according to the voltage changes in the control loop, so as to follow its reference value. Besides, the existing PI control is utilized in the current loop. Comparisons to the PI control shows an improvement in term of accuracy, stability, overshoot minimization, and response time.

Bharath et al, 2018 [98] provided an improved voltage which is applied to renewable DC-MG, so as to control a bidirectional converter under various environmental factors. Two individual PI controllers are combined with a logic circuit to control the bidirectional buck/boost based on the DC-bus voltage.

Blaabjerg et al, 2020 [99] proposed a hybrid PV-battery systems to control the power balance to battery load and grid side in both operating modes (connected and islanded). Where, the system works in grid-connected mode during adequate conditions and islanded mode when faults occur. To this end, the control of charging/discharging process is fulfilled by investigating battery current and SoC in Constant-Current control technique. The details of the operating principle are done. However, the controllers design is not considered which makes its reformulation difficult.

Tephiruk et al, 2018 [100] applied fuzzy logic controller for a battery energy storage system to enhance the performance of an islanded micro-grid composed of hydro and solar PV energy sources. In fact, to deal with the problem of active power and reactive power uncertainties from RES, the design has been simulated and verified the DIgSILENTPowerFactory software. Comparisons to robust control demonstrate that FLC outperforms the robust control in term of attenuating fluctuations on voltage and frequency, simple structure, steady-state and dynamic performances.

Sreeleksmi et al,2017 [101] used a Fuzzy controller to manage PV-Battery based micro-grid using PV power, SoC and load condition to control the buck/boost switching signals to discharge/charge the battery. Experimental analysis and hardware implementation showed fast decision taken by the FLC and coordination between the generation, consumption and storage.

Angalasewari et al, 2017 [102] proposed a fuzzy control to manage load consumption in grid-connected MG investigating solar power and integrating battery storage. In fact, the system is tested by MATLAB/SIMULINK using critical and non-critical loads, under variable irradiance level. However, the details about the charge /discharge of the battery are not detailed as well as the system is tested only for grid connected mode.

Nastshed et al, 2013 [103] implemented a hierarchical control for hybrid standalone power system including PVGs, wind turbine, PEMFC, and battery storage. The online energy management is based on fuzzy control to optimize the power flow and to maintain SoC below 40%-80%.

Several other works are developed using **Coordinate** or **Supervisory** approaches to improve the efficiency, quality, and to manage the MG energy flow either at the local or global levels integrating advance and intelligent controllers, using hybrid storage energy systems or improved the power electronic interfaces. For instance, **(Song et al, 2019)**[104], used a fuzzy controller in a hybrid PV-Wind-Battery Based Three Level Converter to manage the power using the DC-Link voltage and the SoC . **(Yumurtaci et al, 2013)** [105],and **(Faria et al,2019)**[106], implemented an ANN for hybrid energy storage system in a micro-grid power management to maintain a constant DC-link voltage and battery SoC , compensate the variations in renewable energy power, and deal with the problems met on conventional methods. Moreover, meta-heuristic strategies are also incorporated in the management of the MGs for the global and local optimization, as, **(Hazem Mohemmd et al, 2019)** [107] designed a PSO controller to minimize cost of energy and handle the economic problems of a standalone hybrid renewable energy system which comprises wind turbine, Tidal, PV and batteries. **(Hossain et al, 2019)** [108] applied a modified PSO technique for real-time energy management in grid connected MG, in order to, optimize the battery charging/discharging operation, and minimize energy waste and costs.

1.3.3. Inverter AC-side Control

The electricity produced and stored in the storage devices has a DC-form. In order to feed ac consumers the inverters are incorporated and controlled. In this way, based on the data acquired from the grid and the inverter DC-side i.e. active and reactive powers, DC and AC voltages and currents, and frequency, the control of the inverter AC-side can be organized and classified into two categories namely **direct power control**(**DPC**) which depends on the instantaneous active and reactive powers (P/Q) (Figure.1.8), developed by (**Ohnishi et al ,1991**) [109] , then (**Noguchi and Takahachi ,1998**) [110] detailed the principal of the algorithm which is based on the instantaneous active (P) and the instantaneous reactive (Q) powers control instead of direct flux and torque of the inductor machines. It is important to know that the instantaneous active power control is obtained from the DC-link voltage controller, whereas the reactive power control is obtained from the external of the controller (generally kept equal to zero in PV-MG). Errors between the commands and the expected feedback power are passed through a hysteresis control. Where the gates switch ON/OFF state is done utilizing a lookup table. Or, through an **indirect power control method** named **Voltage oriented control** (**VOC**). This technique depends on the change between stationary coordinates αβ and synchronous rotation coordinates dq and guarantees high dynamic and static performance via an inner current loop and PWM modulator, as depicted in Figure.1.9.

It is important to know that frequency and voltage deviations are the mains parameters that must remain constant to ensure stability, efficiency, and quality of the imbalanced power between the generation and demand. These two parameters must respect the international standards as will be explained in Chapter.2. Moreover, the DC-link voltage must be kept at desired limits to obtain accurate AC current waveform. In fact, the DC-link voltage is fixed in the inverter specifications according to, line to line RMS voltage peak value, besides, the appropriate choice of the passives filters components plays an important part in improving the quality of the current (minimize the THD).

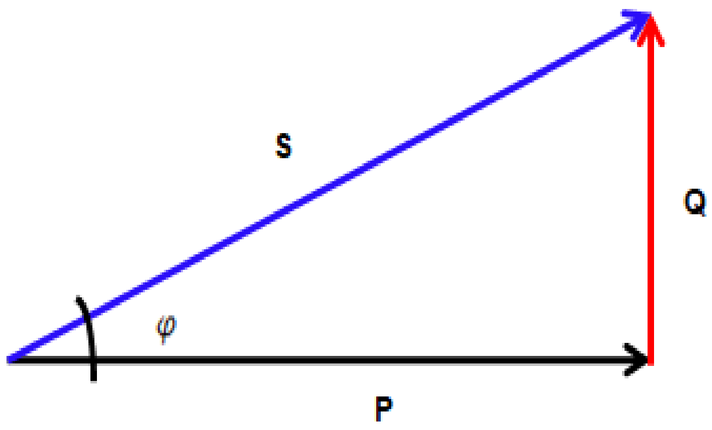


Figure.1.8. P/Q operating of single phase inverter

$cos(\varphi)$ represent the power factor

S is the apparent power $S = \sqrt{P^2 + Q^2}$(VA)

P the active power $P = S\cos(\varphi)$ (W)

Q the resctive power $Q = S\sin(\varphi)$ (VAR)

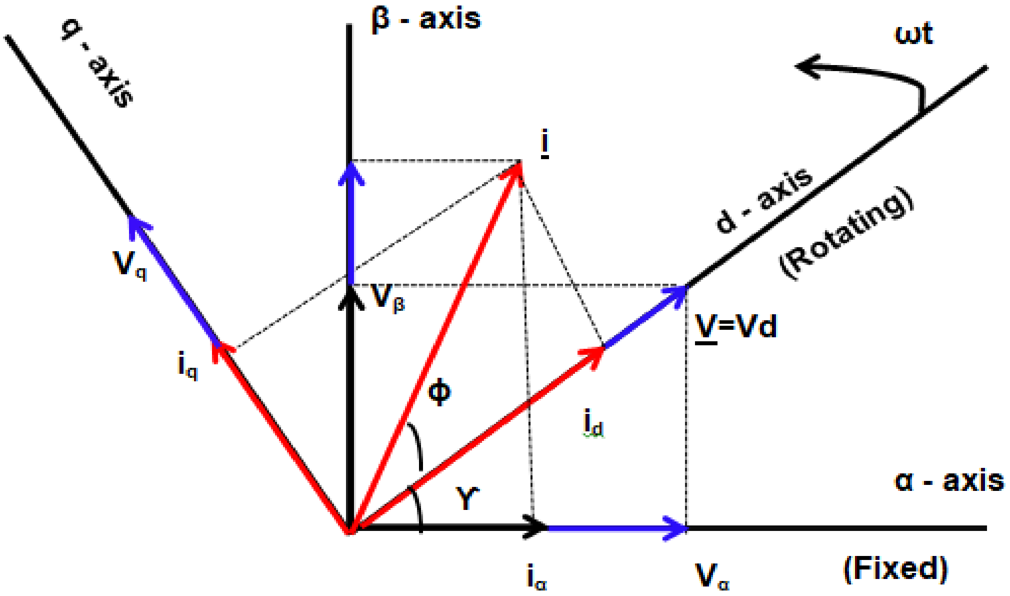


Figure.1.9. Principle of d-q

Both DPC and VOC strategies have the same main objectives such as obtaining pure sinusoidal (current and voltage) waveforms, low THD value, unit power factor (high power quality), and high static and dynamic performance.

The use of the inner current control loop and PWM block in the VOC enhances the system performance. However, high costs are required and low power factor is obtained compared to DPC. In the other hand, the use of the line current and voltage to estimate power requires high simple frequency to deal with the changes in the estimated value. So, every technique has its advantages and disadvantages, some of them are listed in Table1.1 below:

Table 1.1. Comparison between DPC and VOC [13] [17] [109]

method	Advantages	Disadvantages
DPC	• No inner current loop • No PWM block • High power factor • Decoupled power control(active and reactive powers) • Simple algorithm	• Variable switching frequency • Requires enhanced digital-to-analogue (A/D) converter and microprocessor. • Require high simple time and inductance
VOC	• Fixed switching frequency • High stability through the inner current control • Improved PWM techniques can be integrated. • Cheap A/D converter	• low power factor compared to DPC • complex algorithm • Require stationary and coordinate transformation.

In view of all that, several controllers are integrated and improvement in the literature to overcome the drawbacks of the existing techniques, increase their behaviours to benefit from their advantages and surmount different power quality problems met during the operating under both modes (grid connected and islanded):

BERBAOUI et al, 2011 [111] applied a VOC for low voltage distributed system where a PI controller is compared to a PI control with capacitor voltage error feed-forward. Details modelling of the voltage and current control in decoupled control are done for a grid-connected single-phase distributed inverter. Simulations are fulfilled during start-up and under load transient operation where good performance is achieved. However, a comparison that shows the difference between the two controllers is not done.

(**Monfaredet al, 2012**) [112] applied a VOC to a single-phase inverter where PI control is considered, improved dynamic response is obtained compared to the existing approaches. However, this scheme utilizes a fixed generator which makes the method unapplied to variable input sources without modifications in the control. (**Cai et al, 2017**) [113], adapted a VOC in a double stage PVS. However, these researches focus only on the islanded mode without considering the presence of the grid or the influence of the climatic conditions. In order to control the active and reactive currents, two strategies of VOC are compared and studied in (**Rokrok et al, 2018**) [114]. Several others researches developed and enhanced the VOC controllers scheme (**GAO et al, 2019**) [115]. These controllers aim at improving the accuracy and the magnitude of the outputs through the minimization of the Total Harmonic Distortion (THD). However, the controllers' schemes always require modifications to adapt them to different scenarios or need information about the filter parameters.

1.4. Power quality and Management challenge

As mentioned in the previous sections, the power quality control and energy management are the challenging tasks to consider during the MG operating either in grid connected or islanded modes. In fact, the operating of the micro-grid depends on several parameters: system configuration, energy quality, control strategy, power products uncertainty, load characteristics (linear, non-linear, balanced, unbalanced…), connection and disconnection of the Micro-sources, variations in voltage and frequency. The control adopted in this case plays an important part in improving the quality and monitoring the whole system [95] [102]. So, to improve the power quality it is important to improve the following variables:

- Stabilize the delivered power from the Micro-sources ;
- Compensate voltage sag and swell;
- Control the frequency;
- Maintain the voltage at PCC at required level;
- Compensate the unbalanced phase;
- Compensate the harmonics;
- Eliminate the voltage and current harmonic distortions ;
- Ensure an uninterruptable power supply to the load.

The management-based strategy provides an accurate power distribution, fast transient response, high power quality and reduces circulating power among the MG components. However, implementation of these methods needs the knowledge of the state of every component and the energy requirement. Moreover, due to the demand variations, it is not easy to manage the system.

As mentioned before, the management at global level is related to the energy prices and economic dispatch, whereas the local management level is related to the energy shared among the MG. This latter is considered in this thesis to deal with several Power Management issues such as [12] [105]:

- Energy loss among distributed generators;
- Battery over charge and deep discharge ;
- Maintain the load power under variables irradiance and temperature;
- Stabilize the DC-link voltage;
- Enhance the response of the system to different phenomena;
- Ensure the quality and continuality of the required energy.

1.5. Conclusion

With recent benefits in power quality and management operation of the photovoltaic systems, DC-MGs have been considered as effective solutions. Proper control of a MG in both grid-connected and islanded operating modes meets many challenges. Islanded mode control is more challenging, as utility grid does not exist to provide stable voltage and frequency. In this case, the MG must maintain the frequency and voltage around the nominal values and limit the current and voltage THD values. While in grid connected mode, appropriate active and reactive power sharing, grid stability, and voltage quality must be ensured.

This chapter reviewed the most controllers to be considered in DC-PV-Battery based MG during both operating modes which are grid connected and islanded modes. A detailed description of the controllers developed in the literature for the inner loops (MPPT, Battery control, P/Q and VOC for the inverter) and DC voltage control as an outer control are studied and numerous methods are discussed and their limits are cited. Finally, power quality and management challenges are briefly explained.

- It can be concluded that fuzzy and PSO controllers are more accurate in MPPT tracking.
- The review concludes also that the hybridization of Fuzzy controller is widely used in MG control loops which achieve high accuracy;
- CC-CV controller allows the switch between CC charge mode and CV when the current decreases gradually with SoC to ensure efficiency of the battery operation;

- The use of the indirect method (VOC) for the inner loop of the MG's inverter control is more efficient compared to P/Q technique to ensure the current stability and monitoring the switching device;
- This review serves as a reference for researches interested in DC-MG control, management, and power quality improvement.

CHAPTER 2: Microgrid based Photovoltaic System Configuration

2.1. Overview

In modern society, Photovoltaic energy becomes a competitive source compared to other existing electrical generation sources due to its advantages, which are: noiseless, safe, eco-friendly and almost no maintenance is required. Photovoltaic generators (PVGs) are introduced in micro-grid (MG) to generate electricity in a decentralized and coordinated way, and to avoid power losses caused by the long transmission lines.

The accurate design of the MG components plays a significant role in maximizing the produced energy. It is indispensable to insert the Energy Storage System (ESS) within the MG installation. Moreover, the power electronic devices (DC/DC converters and DC/AC inverters) are incorporated and controlled to feed loads and to link the MG to the electrical grid.

2.2. Micro-Grid Concept

Recently, a great attention has been given to renewable energy technologies to replace conventional sources (i.e., coal, petrol and natural gas).Distributed Energy Sources (DES) incorporated within the micro-grid can be divided into two main technologies, which are[116][117]:

2.2.1. Distributed generator technologies

Several distributed generator technologies are integrated to constitute modern micro-grid, including conventional and renewable generators which can be listed as follow

- Fossil fuel generation
    - Coal
    - Petrol
    - Natural gas

- Renewable energies
    - Wind turbine
    - Wave energy
    - Small hydro
    - Photovoltaic
    - Thermo-solar
    - Biomass
    - geothermic

2.2.2. Energy Storage System (ESS) technologies

The manner of storing energy differs from technology to other (kinetic or potential energy) and can be distinguished to five categories:

- Thermal technologies (heat or cold): Heat storage in tanks or rock caverns, Sensible heat storage, Molten salt, Latent heat storage, Hot silicon technology, molten (recycled) aluminium.
- Electrical technologies (electromagnetic or static fields): super capacitors, super conducting magnetic energy, ultra-capacitor, and double layer capacitor.
- Mechanical technologies(kinetic or potential energy): Flywheels, Pumped hydro , Compressed Air Energy storage (CAES) technology
- Electrochemical technologies(chemical binding energy)
    - Batteries (lead acid, nickel-cadmium, nickel-metal-hydride (NI-MH), sodium-nickel-chloride)
    - Redox flow batteries (Vanadium Redox Battery (VRB) , Zinc/bromine)
    - Hydrogen (electrolizer and fuel cell)
- Chemical technologies: hydrogen, synthetic natural gas.

2.2.3. Definition

Micro-Grid is defined as a cluster of distributed sources, power electronic devices, and loads that can work in an isolated mode or incorporated into the electrical grid. The DESs along a MG are comprised of numerous independently controlled power generating sources in order to constitute a reliable and flexible grid infrastructure. This operation perspective ensures the sustainability of MG even though some of the sources disconnect from the generation cycle. The excessive generation is managed by using Energy Storage Systems (ESSs) and power feeding to the utility grid. The connection and disconnection of the MG to the grid are performed concurring to technical and economic conditions. DESs along a MG are regulated by various controllers so as to comprise a flexible and reliable grid infrastructure. This operation guarantees the sustainability of MG despite the fact that a portion of the sources disconnects [118].

The surplus production is managed by associating ESSs and incorporating the installation with the utility grid. The introduced power capacity of MGs changes from a few kilowatts to megawatts. The main objective of installing MGs is to feed power to customers in isolated regions and sell the surplus to other grid users.

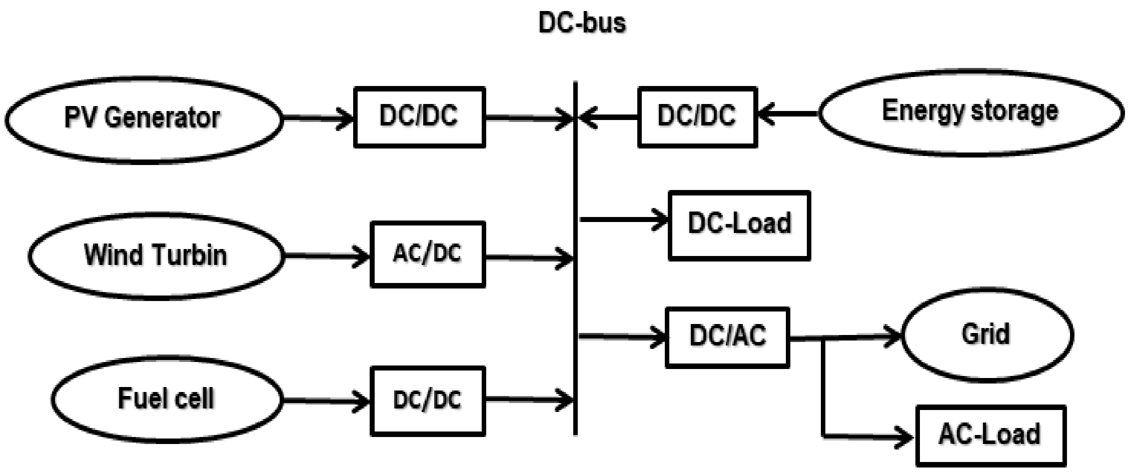


Figure 2.1 hybrid DC-Micro-Grid architecture

The reducing petroleum products, power quality issues, flexibility and resiliency issues of conventional grid infrastructure, and degraded system structures have encouraged grid enhancements and MG investigations. The suitably planned MGs are important to improve the reliability and quality of the utility grid by minimizing faults.

The DESs in MG contain Renewable energy sources such as wind energy, photovoltaic energy, fuel cell, and MGs regulators that are responsible for local and distributed control processes. Data picked up from different DESs, loads, and ESSs are used to design appropriate controllers for MG. Also, a consistent power electronic system is important to perform optimal and economic MG operations and provide feeders with the required power. Accordingly, an Energy Management System (EMS) is important to manage the power flow at different MG levels (production, storage, and consumption). The ESSs provide power in an optimal way during generation shortage or at peak periods of demand. Therefore, the EMS must establish energy for one or more days [119].

The Figure2.2 below illustrates the corporate EMS for MG.

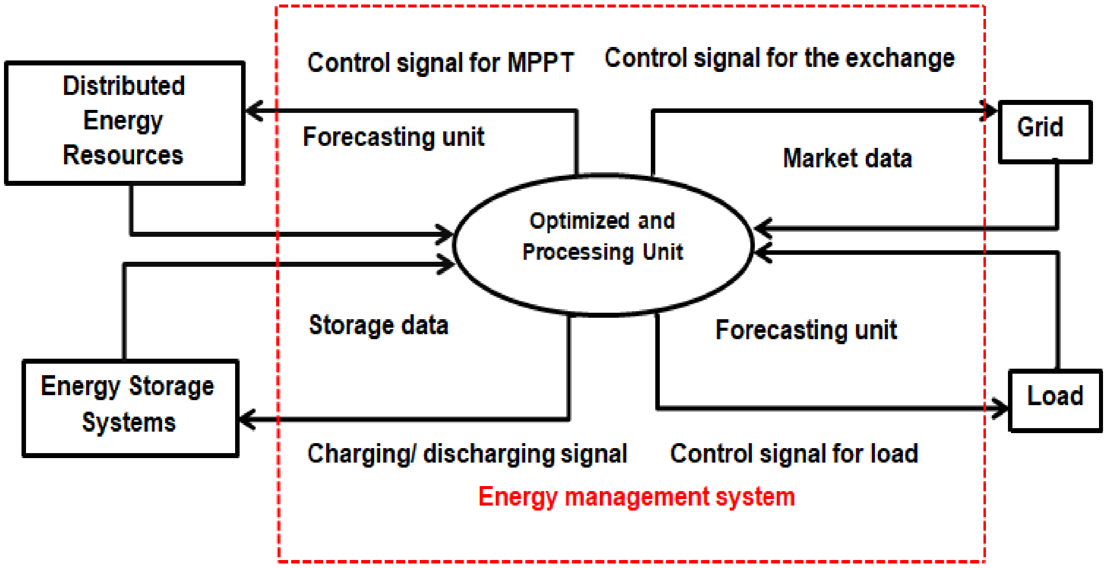


Figure2.2 micro-grid energy management system

The main purpose of constituting a MG based on renewable power conversion system is to give self-sufficiency from petroleum derivatives sources, by surmounting their disadvantages in electricity production, for example, high costs and pollution. Accordingly, ensure sustainable and smart power generation.

The system should be appropriately structured considering environmental measures subject to physical and operational limitations, reliability, and economic procedures.

A hybrid MG combines more than one type of energy conversion system. There are different kinds of hybrid MG, with various arrangements of renewable energy systems (i.e., wind and solar energy sources, etc.), conventional energy systems (i.e. Petroleum, fossil fuel, etc.), and accompanied by storages systems (batteries, hydrogen/ fuel-cell, hydropower, flywheel etc.). The aggregated amount produced is used to feed different loads along with the system. The design and sizing of the Micro-sources are essential in the selection of such systems. The coordination and control of the Micro-sources outputs are important to benefit from these sources, to enhance working performance, to improve operational control and dispatch, and to minimize the production costs [120].

2.3. Structure of the proposed Micro-Grid

The DC-bus topologies in DC-MGs are classified into three groups namely: single-bus, multi-bus, and reconfigurable bus. The single-bus configuration shown in figure 2.3 is commonly used in industrial and some residential applications by associating PVGs and ESS to a single DC-bus. It is currently explored by researches in low voltage DC-MG.

On the other hand, the multi-bus DC-MG configuration is illustrated in Figure 2.4. This kind of topology increases reliability and power rates by combining several single-buses DC-MGs. The automated configuration and connection between buses have been well reviewed in the literature [121][122]. Despite the bus structure, the protection, reliability, management, control, and the sustainability of the MG are the main objective to achieve high power quality and manage the energy produced and transferred to loads and the main grid.

Accordingly, due to the simplest structure and cost-effectiveness of the single-bus configuration, it is adapted to constitute the proposed MG in the present

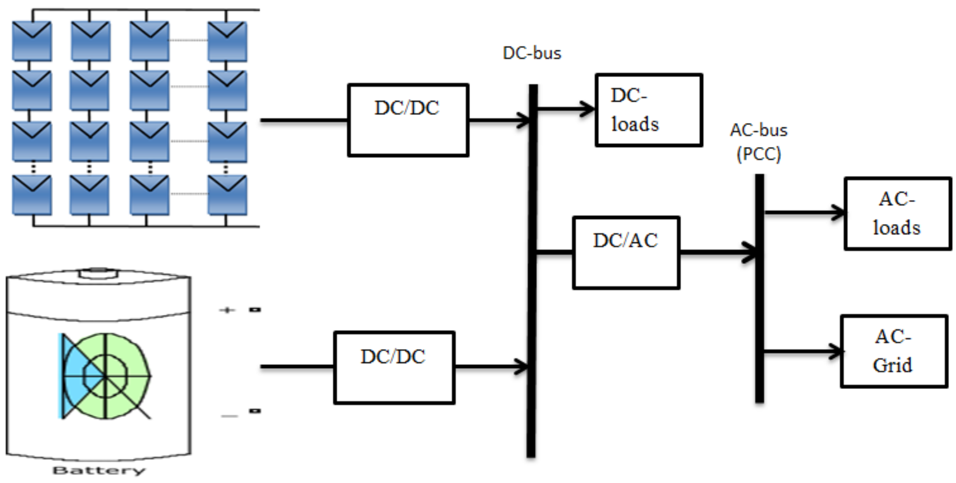


Figure2.3 Bloc diagram of a single bus DC-Micro-Grid

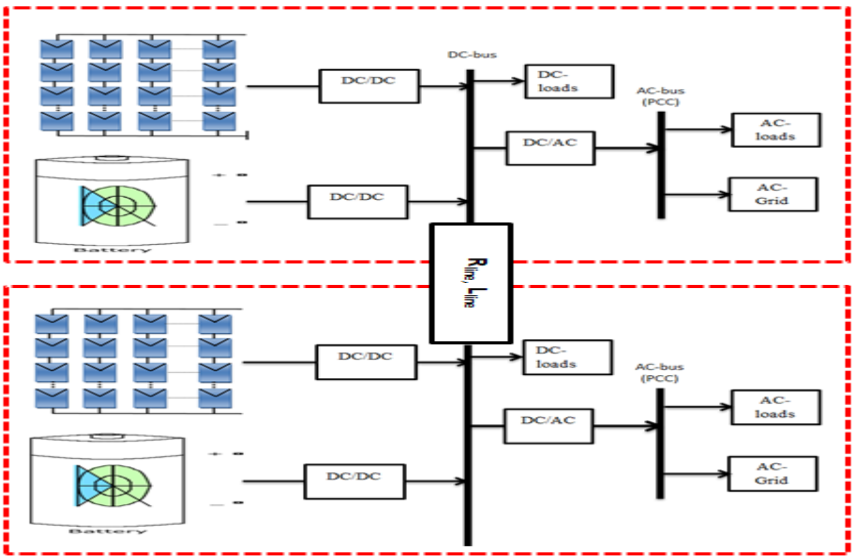


Figure.2.4 Structure of a Multi-bus DC-Micro-Grid

2.3.1. Distributed Energy Resources

The integration of ESS is beneficial for MG to ensure the uninterruptable power supply under both operation modes, grid-connected and islanded modes.

2.3.1.1. Photovoltaic Power Plan

Solar radiation is composed of photons that can be absorbed by a semiconductor material constituting a P-N junction called the PV cell. This causes the generation of electrons and holes that allowed the cell to deliver a DC voltage of the order of 0.5 to 1V. So the PV cell cannot be associated alone. The connection of several identical cells in series increases the value of the output voltage by keeping the same output current while the parallel connection increases the output current at a given voltage. The construction of a PV panel based on the parallel connection of PV cells is generally not suitable because a large current requires a section of wiring and protection. In addition, low voltage causes relatively high losses. For these reasons, the series connection is the most suitable for the construction of the PV panels available in the market [123].

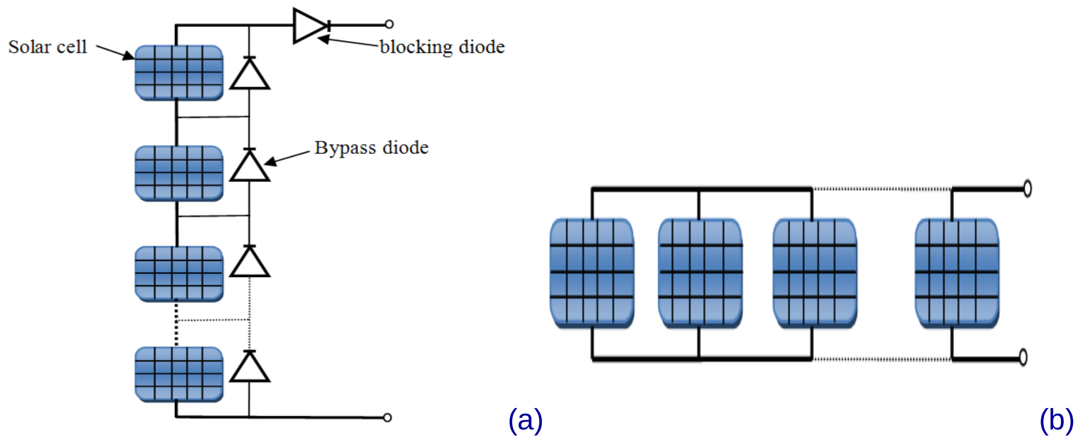


Figure 2.5 (a) Series connection of PV cells, (b) Parallel connection of PV cells.

Additionally, a PV panel consists of a series combination of several PV cells, built using a semiconductor material generally silicon. The output power can vary according to the environment conditions of temperature and irradiance. Bypass and blocking diodes are usually included in the construction of PV panel for reasons of protection (as in Figure 2.5). To this end, a blocking diode is placed in series with PV panel to avoid the current flow in the opposite direction to the PV panel. Whereas the bypass diodes are placed in anti-parallel with the PV panel to enhance the output voltage. For instance, when the PV panel is partially shaded, the current produced by the unshaded cells can flow through the bypass diode to avoid hot spots events [124].

The series connection of PV panels (i.e. string) increases the output voltage. While the parallel connection of PV panels or strings (i.e. PV array) leads to increasing output current and achieving a satisfactory output power (Figure. 2.6).

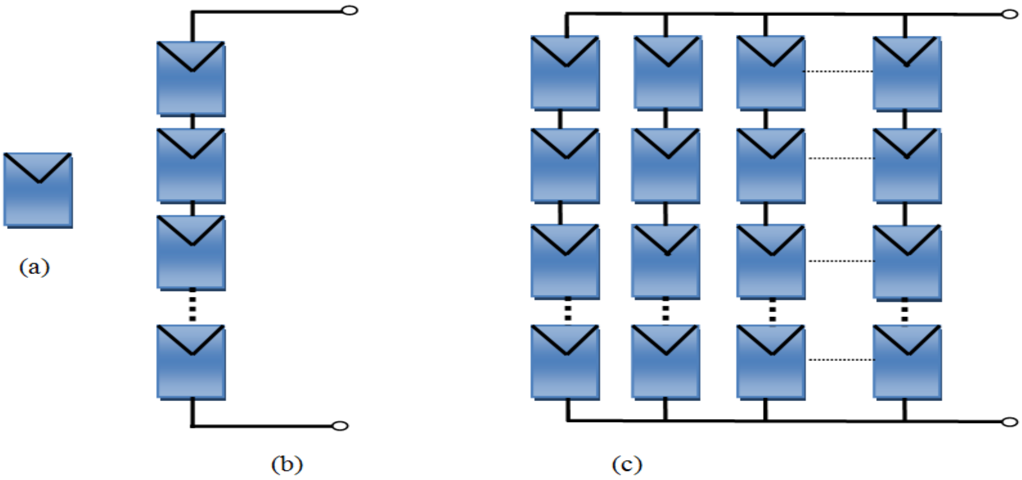


Figure 2.6 (a) PV panel, (b) PV string, (c) PV array.

The systematic model of a PV cell can be modelled by electrical components as illustrated in Figure 2.7.

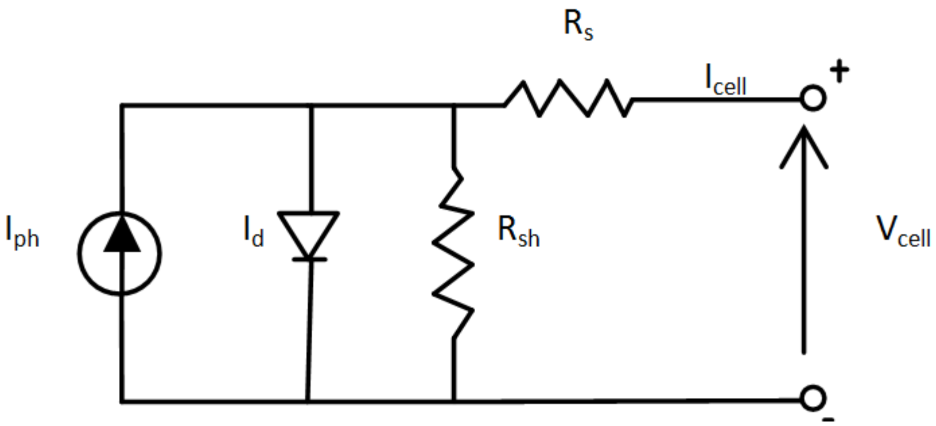


Figure2.7 Equivalent circuit of a single diode PV cell

The equivalent mathematical model of the PV cell current is done by (Eq.2.1) where the PV cell related power depends on its surface area and its technology. Moreover, this power is highly influenced by the short-circuit current (I_{SC}), the shunt resistance (R_{sh}), the ideality factor of the diode (η), and series resistance (R_S).

$$I_{cell} = I_{ph} - \left(\left[\exp\left(\frac{V_{cell} + I_{cell} R_s}{\eta V_T}\right) - 1 \right] - \frac{V_{cell} + I_{cell} R_s}{R_{sh}} \right) \quad (2.1)$$

The I_{ph} represents the produced current and depends only on the level of sunlight striking the PV cell. V_T is thermal voltage and V_{cell} is the voltage measured between the PV cell's electrodes. This equation assumes an imperative role in solar based power plant modelling studies since it gives associated analysis information for current and power variations against the yield voltage of the PV module (i.e. P-V and I-V characteristics).

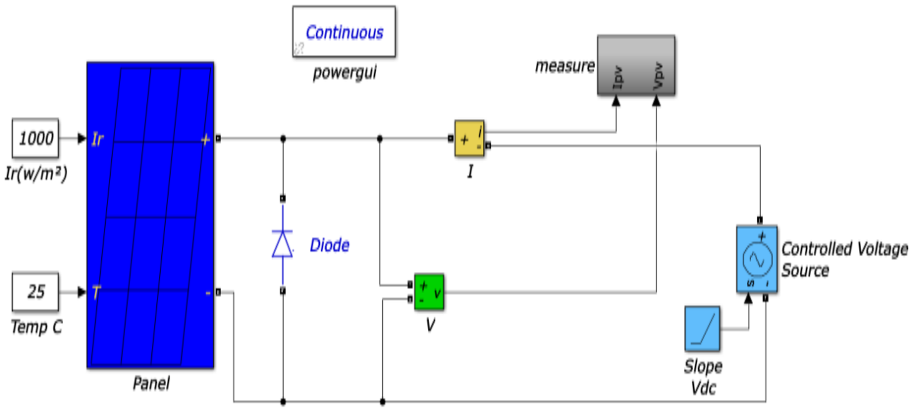


Figure 2.8 Simulink model of the direct connection of a panel with the variable resistance

Weather conditions of temperature and irradiance affect on the Maximum Power Point (MPP). Accordingly, Maximum Power Point Tracking (MPPT) techniques are associated to harvest maximum power from panels under different weather conditions. So, the design and modelling of the PV system is important to investigate and benefit from the MG generated energy.

The direct association of the PV panel with a variable resistance as in Figure 2.8, allows the extraction of the characteristics (I-V) and (P-V) under different levels of irradiance and temperature. The I-V and P-V curves are depicted in Figure 2.9, Figure 2.10, respectively.

The produced current and voltage of the PV panel have been made by increasing solar irradiance amount from 500 W/m^2 to 1000 W/m^2 that causes an increase in the delivered PV panel power. The short-circuit current value is directly proportional to the intensity of the incident irradiance, but the open circuit voltage does not vary in the same proportions but remains almost identical even at low irradiance , as depicted in Figure 2.10.

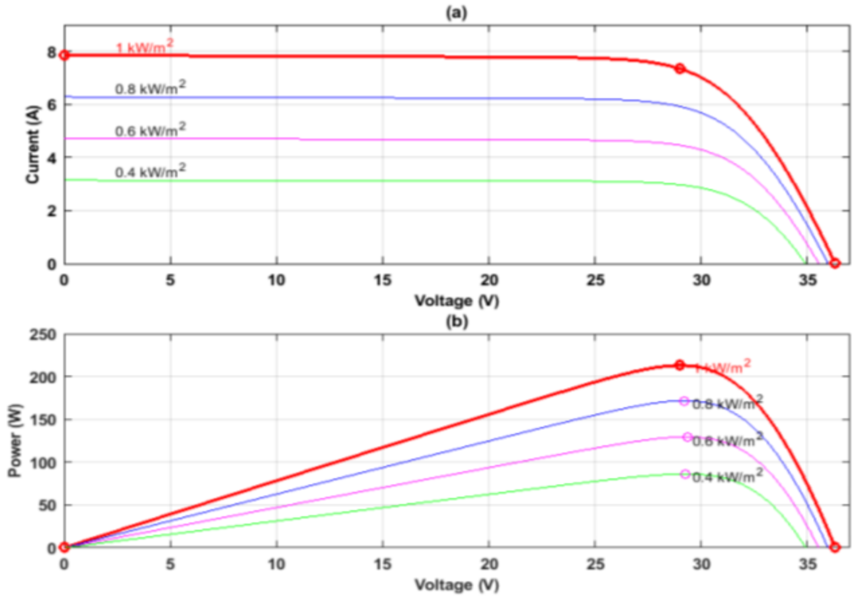


Figure 2.9 The I-V characteristic and P-V characteristic curves of the PV panel under varying irradiance values and temperature of 25°C

The temperature has a negligible influence on the value of the short-circuit current. The output power of the PV Panel decreases by about 0.5% with each degree of temperature rise above 25 ° C.

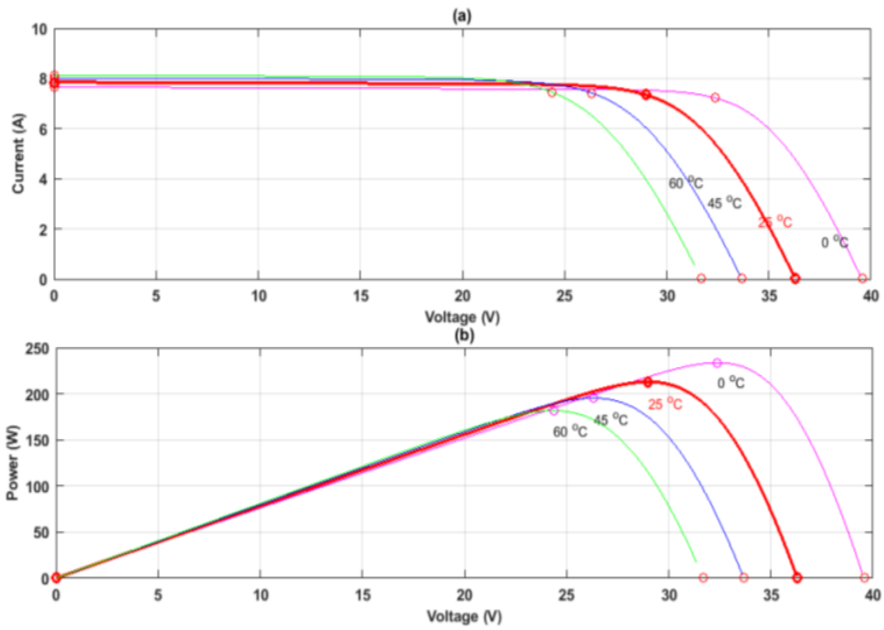


Figure 2.10. The I-V characteristic and P-V characteristic curves of the PV panel under varying temperature values and irradiance of 1000W/m²

2.3.1.2. Energy Storage System

The principal goal for ESS incorporation in MG is the compensation for the intermittent and random power produced from PVGs. The category, capacity and distribution of the associated ESS in DC-MG are designed depending on the structure of the DC subsystems, capacity of the PVGs and the type of the supplied loads. Right now, various approaches for designing storage capacity and their integration to the MGs are presented. Typically, large storage capacities are widely used in MG applications to satisfy the power demand for long periods of power interruption. Whereas, small storage capacities are employed to provide power at peak demands. In each specified case, it is essential to study and well understand the operation, the potential energy deficiency in MG, the time of the function and the power generation control [125].

To benefit from grid management using storage devices associated with a renewable energy source, the appropriate application choice for the system is necessary for the given economic context. The choice of battery technology will depend essentially on the investment cost and the battery life within the operating conditions corresponding to the selected application. In the case of low voltage MG applications, where the consumption is of residential and industrial type (220V-400V), the operating power is of the order of 1kW to 10kW. Several storage devices are included in PV installations: Lead-acid batteries are currently the most used in PV applications. They are mainly preferred because of their tradeoff between acceptable cost and satisfactory efficiency. However, they suffer from a short lifetime. By comparing Nickel-Cadmium (Ni-Cd) technology to lead acid technology, it is worth mentioning that Nickel-Cadmium (Ni-Cd) technology has a higher cost. Many efforts should be done to make Ni-Cd a competitive technology for PV applications. In view of Lithium-ion (Li-ion) technology, this one can be considered the most promising in the future. Its lifetime and performance makes it the best electrochemical accumulator commercially available. However, the cost is still significantly high compared to lead acid technology. Researchers and producers are working together for the same purpose which is, reducing the cost of Li-ion technology to be the most interesting technology for PV based MG applications

[126][127].Flywheel, super-capacitors, compressed air energy, and some other storage devices are also employed within the MG applications [127].

The presence of storage devices ensures better electrical charges satisfaction during the periods of absence of the primary supply.

For autonomous micro-grids, the storage devices have the high initial cost of the system compared to the other components and devices. That is why the management of the energy between the production and consumption plays an important role in the economic plan. Therefore, combining the PV field with batteries reduces fuel consumption and minimizes electricity costs. Moreover, the hybridization of storage to accumulate energy may satisfy the load requirement for a long period [128].

Some physical characteristics of batteries frequently associated with the PV system in MG are listed in Table 2.1.

Table 2.1 key characteristics of Energy Storage devices [129][130][131].

Type	Energy density (wh/kg)	Specific power (W/kg)	Depth of Discharge (DOD)	Unit capital cost ($/kWh)	Recycling efficiency (%)	Self-discharge per day
Lead acid	25-50	75–300	200–1000	100-300	75-85	Low
Nickel Cadmium (Ni-Cd)	50-60	~200	>1500	300-600	70-75	high
Li-Ion	75~200	500~2000	1000~10000	300~2500	85~97	medium
NI-MH	60~120	250~1000	180~2000	900~3500	65~80	high
VRB	10~30	80~150	>12000	150~1000	75~90	negligible
SuperCap	2.5~15	10000+	5000+	>10000	~100	medium
Flywell	10~30	400~1500	20000+	1000~5000	>90	high
CAES	5~10(wh/L)	<1(W/L)	-	<50	~70	Very low

2.4 Power electronic topologies used in DC Micro-Grid system

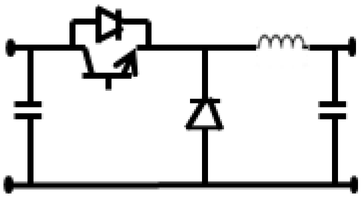
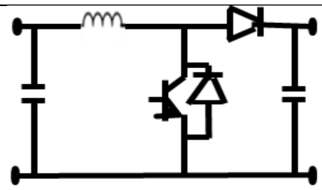
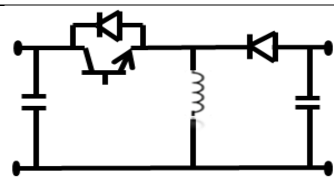
The direct connection of the PVG to a load can damage the PVG and may lead to high power losses, especially under fast variations of irradiance. To this end, the PVG should never be used without a power stage interface (e.g. Boost, Buck, Buck-Boost, Single-ended primary-inductor converter (SEPIC), flyback, etc.). The latter is always controlled by one of the existing Maximum Power Point Tracking (MPPT) techniques to maintain the operating point at it maximum power, meanwhile, to maximize the tracking efficiency. On the other hand, bidirectional (Buck-boost) power converter is usually associated with the battery for charging or discharging process. Furthermore, the introduction of power inverters (i.e. half-bridge and full-bridge topologies) permits the grid connection and feeds the AC-loads.

2.3.2. DC-DC Converters

DC-DC converters are electronic devices mostly consisting of a capacitor, an inductor and switching devices (i.e. IGBT, MOSFE,...,etc.).Those components worked together to convert the input DC voltage to another form of DC voltage, either by stepping it up or down. The most widely used DC-DC converters in MGs are: boost, buck, buck-boost, SEPIC, flyback, cuck, Zeta, bidirectional ….etc. The structure and some specifications of most used converters in MG applications are given in Table2.2. The choice of the converter topology depends on the load requirement. For instance, buck converters are useful for installations that need a high current and relatively a low voltage compared to the DC-DC input voltage and current. On the contrary, a boost converter is employed. Nevertheless, if the installation needs to step-up and step-down voltage automatically, a buck-boost converter is necessary. In the PV installations, the duty cycle of these converters represents the relationship between the output voltage of the PVG (V_{pv}) and output voltage of the DC-DC converter (V_{dc}) [132] [133].

The main task of the DC-DC converter is not only to get the desired voltage at its output, but also, maximizing the extracted power from the PVG and managing the power flow to the ESS through an adequate control strategy. The extraction of the MPP is ensured by using a MPPT controller that takes advantage of the PV panel parameters (i.e. the measured current, voltage or power of the panel, the solar radiation striking the PVG interface or the ambient temperature, etc.).

Table2.2. Conventional DC-DC converters: Structure, Parameters, advantages and drawbacks [31 [36] [42] [125] [132].

	Buck Converter	**Boost converter**	**Buck-boost converter**
Scheme			
Duty cycle	$\frac{V_{dc}}{V_{pv}} = D$	$\frac{V_{dc}}{V_{pv}} = \frac{1}{1-D}$	$\frac{V_{dc}}{V_{pv}} = \frac{-D}{1-D}$
ΔV_{PV}	$\frac{(1-D)I_{pv}}{fC_{pv}}$	$\frac{DV_{dc}}{8C_{pv}Lf^2}$	$\frac{(1-D)I_{pv}}{2fC_{pv}}$
ΔI_L	$\frac{D(1-D)V_{pv}}{fL}$	$\frac{DV_{pv}}{fL}$	$\frac{DV_{pv}}{2fL}$
ΔV_{dc}	$\frac{(1-D)V_{dc}}{8LC_{dc}f^2}$	$\frac{DI_{dc}}{fC_{dc}}$	$\frac{-DV_{dc}}{2fC_{dc}Ri_{dc}}$
C_{PV}	$\frac{(1-D)I_{pv}}{f\Delta V_{pv}}$	$\frac{DV_{pv}}{8\Delta V_{pv}f^2L}$	$\frac{(1-D)I_{pv}}{2f\Delta V_{pv}}$
L	$\frac{2(1-D)V_{pv}}{f\Delta I_L}$	$\frac{DV_{pv}}{f\Delta I_L}$	$\frac{DV_{pv}}{2f\Delta I_L}$
C_{dc}	$\frac{(1-D)V_{dc}}{8Lf^2\Delta V_{dc}}$	$\frac{DI_{dc}}{f\Delta V_{dc}}$	$\frac{-DV_{dc}}{2f\Delta V_{dc}Ri_{dc}}$
Advantages	• Simple circuit structure • Limited load's current ripples • High efficiency	• High output Voltage value can be obtained. • Switch can be easily driven regarding ground, as compared to high side or isolated drive necessary for buck or buck-boost converter. • The input current is continuous which means it is easy to filter and meet electromagnetic interference requirements.	• Step-up and step-down of voltage is possible with minimum component count. (Cuk, Sepic, Zeta uses almost double component count) • Less costly compared to most of the other converters
disadvantages	• Discontinuous current input which requires smooth input inductor. • No isolation between supply and low voltage section and can have potential safety problem	• Large output capacitor is required to reduce ripple voltage as output current is pulsating. • Slower transient	• Input current and charging current of the output capacitor is discontinuous resulting in larger filter size and more EMI issues. • The output is inverted

	• Separate protection is needed to protect the circuit against short circuit current, across the diode path. • Polarity reverse is not possible • Unidirectional output current	response and difficult feedback loop compensation due to presence of right half zero in continuous conduction mode (CCM) of the boost converter.	which introduces complexity in the sensing and feedback circuit. The sensed voltage is negative so an inverting opamp is required for feedback and closed loop control. • The efficiency is poor for high gain i.e. very small or large duty cycle. Therefore, high gain operation cannot be achieved with this converter. Efficiency can be as poor as 60% for a duty cycle of 0.7 or 0.3. Whereas it has 90% efficiency for duty cycle of 0.5. • There is no isolation from input to output which is very critical in many applications like the power supply of gate driver of power semiconductors. • This converter is difficult to control. The transfer function of this converter contains a right half plane zero which introduces the control complexity.

2.3.3. DC-AC inverters

The continues-alternative conversion has the responsibility of transforming a continuous voltage/or current signal into an alternating voltage/or current signal of desired amplitude, frequency and phase. This transformation takes place in a power electronic device called an inverter (or DC-AC converter). Two groups of inverters are distinguished: voltage source inverters (VSI) and current source inverters (CSI), depending on the DC input source: voltage source or current source. They are used in PV applications to feed alternative loads and connect the system to the distribution grid. The inverter perfectly synchronizes its output current and voltage at a frequency of 50 Hz equivalent to that of the utility grid. The grid voltage ideally equals to 230V /380V (single-phase/ three phases) [134][135].

The most known topologies of inverters are half-bridge, full-bridge single-phase or three-phases. Generally, single-phase inverters are used for low range power applications while three-phase inverters are widely explored in medium and high power applications, but also integrated with low voltage applications. The half-bridge inverter has simple structure, low cost and can be controlled easily. However, the harmonics produced at its output are important compared to single-phase full-bridge inverter. Multi-level inverters are also developed to achieve a high power quality and improve the performance of the MGs [136][137]. The inverter adopted in the next chapters is a full bridge single phase illustrated in Figure 2.11.

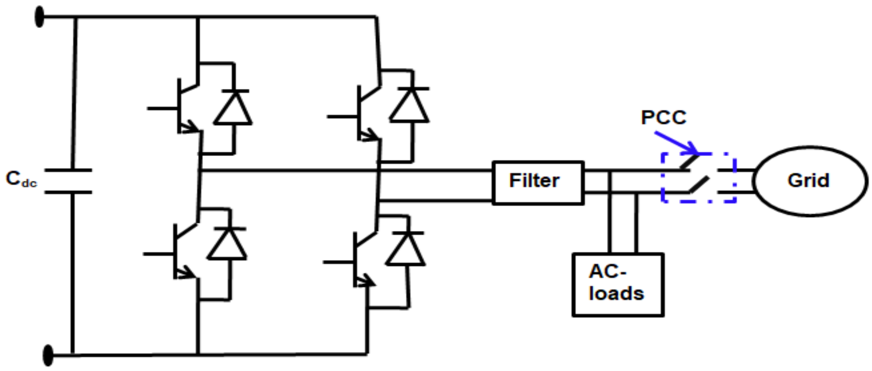
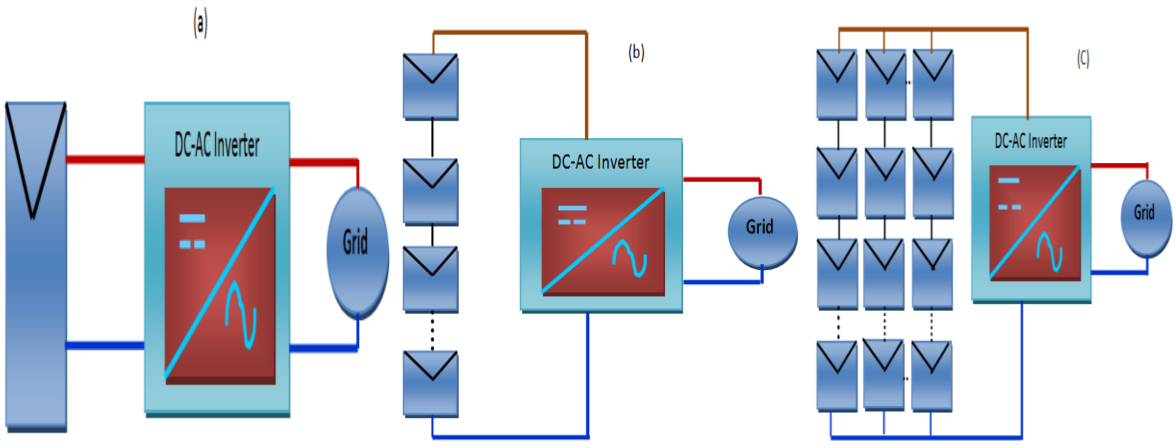


Figure2.11. Full bridge single-phase inverter topology.

The implementation of an inverter coupled to the power grid is done with the agreement of the organization of electrical energy distributor for security reasons. An inverter coupled to the network must constantly monitor these disturbances and immediately interrupt the injection in case of failure or break. This is absolutely necessary to allow a safe involvement on the grid.

According to Figure 2.12, in the case of module inverter, each PV module has an individual inverter. For the most important installations, all the inverters are connected in parallel with the alternating current. The modular inverters are mounted in close proximity to the corresponding PV module However; the String inverters are the most used containing eight (or more) PV modules connected in series. While centralized inverter transforms the DC current produced by several strings connected in parallel to the alternating form [138].

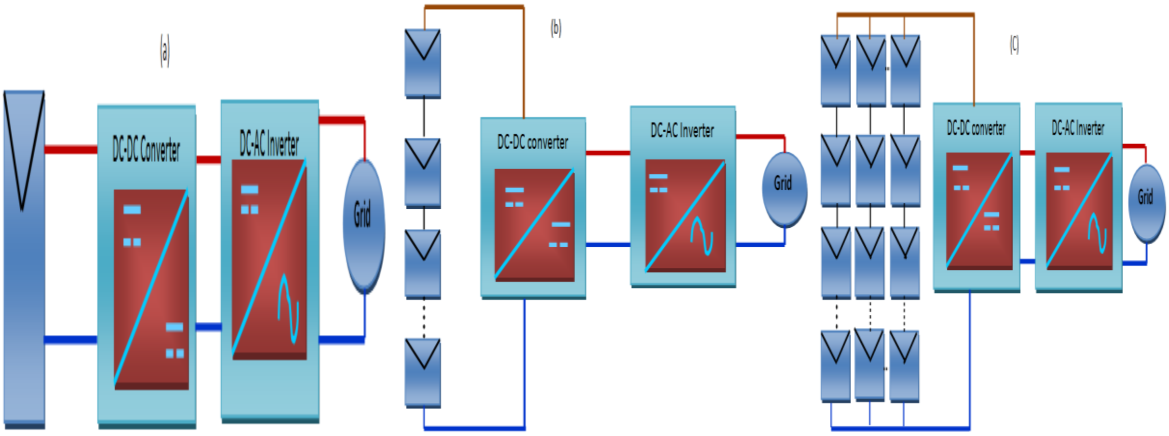


(a) (b) (c)

Figure2.12. Single stage configuration (a) module inverter,(b) string inverter, (c) centralized inverter

For higher power transfer, it is possible to connect several string inverters in parallel on the MG AC-side, due to their installation costless. The meaning of this concept is to use a larger number of inverters of the same category. This later reduces production costs and brings additional benefits: if an inverter fails, only the production of the string concerned fails, while in case of the centralized inverter if the inverter fails all the installation fails [139].

The installation may be either a single-stage conversion (Figure2.12) or a double-stage conversion (Figure2.13). In the case of double stage conversion, a DC-DC converter is placed between the generators and the inverter DC-side. These converters present additional protection for the system, facilitate the transfer of the PV energy and aid on stabilizing the power. A high DC-bus capacitor is used at the inverter DC-side to compensate for the voltage fluctuations [36]. As for the single stage configuration the double stage configuration can be modular, string or centralized, as shown in Figure. 2. 13. bellow:



(a) (b) (c)

Figure. 2. 13. Double stage configuration (a) module inverter,(b) string inverter, (c) centralized inverter.

2.4. Operational types of Micro-Grids

Each MG should be improved to meet specific necessities. The grid-connected mode is performed after satisfying the international standards. The IEEE Std 1547-2003 (Standard for Interconnecting Distributed Resources with Electric Power Systems) [140] is one of the helpful international standards for the interconnection of distributed generators with the utility grid. The IEEE Std 1547-2003 standard offers guidance for voltage and frequency control processes, basic necessities, islanding avoidances, performance tasks, test conditions, and maintenance requirements. The MG design requires comprehensive controllers in addition to DERs that are involving the infrastructure. The MG controllers design should respect several international standards as IEEE Std 2030.7 (IEEE Standard for the Specification of Micro-Grid Controllers) [141] which is one of the most widely followed standards . The IEEE Std 2030.7 defines technical requirements for MG controllers and fundamental specifications of MG energy management system. Therefore, this standard provides guidance for two main control functions of transition and dispatch areas. The center control functions enable MGs to work in islanded and grid-connected modes. The transition between grid-connected and islanded-modes needs automatic controllers and an appropriate management strategy to ensure a smooth transition between the two modes by synchronization and resynchronization process. The power controls are also needed to ensure the stability and the management of the active and reactive power flow.

The regulators are included to control MGs in a standardized, scalable and interoperable framework. The international standards guarantee the operation of different MGs that are organized by utilizing wide range sources, controllers, electronic devices, and loads. The incorporation or detachment of sources and loads to MG requires local and central controllers' improvement to guarantee the security of DG in MG. In this way, to evaluate the performance of the MG controllers another standard must be respected. IEEE Std 2030.8 (Standard for the Testing of Microgrid Controllers) [140], gives direction on controller analyzing tools, controller functions in islanded and grid-connected operation modes, power flow management, load monitoring, and local control issues [12] [14].

The DESs are incorporated to the MG AC-bus by using suitable power converter devices. Each MG is associated with a circuit breaker at PCC to disconnect from the utility grid during faults event or for maintenance reasons [15] [90].

Generally, the micro-grid can operate either connected or islanded to/from the utility grid. The transition between these modes is essential to be considered. The difference between the two modes is the manner how to stabilize and control the voltage and frequency. In grid-connected mode, frequency and voltage references are imposed by the utility grid. However, in islanded mode, these parameters are fixed by the micro-Grid itself [92].

2.4.1. Grid Connected Mode (ON Grid)

In grid-connected mode, the main grid imposes the frequency and voltage amplitudes to synchronize the MG, so as to ensure the import/export of the energy from/to the grid. The components used over the MG installation must provide or absorb power respecting these frequency and voltage values. In this case, the MG delivers the power produced by the DG sources to the utility grid.
The main disadvantage of this operating mode is the slow response of the control signals when variations occur at the output power [92] [99].

2.4.2. Standalone Mode (OFF-Grid)

In remote areas, where the grid is not available (i.e. rural areas, military bases, hospitals … etc.), the main grid is faulty, market policies conditions of connection are not satisfied, or during maintenance and test periods, the micro-grid works in islanded mode (off-grid) to satisfy the local energy consumption. Under such conditions, the use of various generation sources or incorporation of storage devices are necessary to keep the power balance, moreover, local control process may preserve the voltage and the frequency within standard limits to guarantee the stability and quality of the MG[92].

2.4.3. Transient Operating Mode

When the standards of connection are not satisfied, the main switch breaker at PCC is turned off to island the MG from the main grid in order to ensure its protection and reliability. In order to maintain the power flow and avoid distortions, the stage of transition must be very quick and smooth.

The reconnecting stage allows the transition of the MG from islanded to grid connected mode. In this stage, active and reactive power balance, frequency, voltage, amplitude, and phase respect the maximum permissible deviations (2% for frequency and 5 % for amplitude), and the switching breaker at PCC will be turn ON to exchange power with the grid [99].

2.5. Conclusion

The progress in the development of the PV market and MG installations requires accurate data about the energy production/consumption, climatic conditions as well as advanced controllers for MGs to ensure a high energy quality delivered to the load or the utility grid.

This chapter has presented in detail the essential parts composing MG installations, including PVGs, batteries, controllers and power electronics interfaces. The types of MGs, as well as, the most widely used international standards are also discussed. It is highly recommended that the design of MG installation takes into consideration the two well-known operating modes which are: islanded and grid connected modes. Considerable power losses can occur as a result of partial shading conditions or fast variations of irradiance. To this end, the next chapter will focus on improving the MG operation through involving an MPPT control strategy that is able to deal with the aforementioned problems.

Chapter 3 PV-Battery Management under Partial Shading Conditions using an improved HC-PSO

3.1. Overview

In the first chapter, the most used MPPTs for controlling low voltage MGs have been reviewed. One of the aforementioned techniques is HC, it has almost the same principle as P&O MPPT. In fact, HC output is the duty cycle, while the P&O requires PI controller to get the duty cycle. Thus, they share the same advantages, which are: simple algorithm structure and low cost. However, when the irradiance is time varying or under partial shading conditions, usually, these methods fail to accurately track the MPP and show high oscillations around it due to the use of a fixed step size within its algorithm. Obviously, this will lead to high power loss and low tracking efficiency.

This chapter presents a novel Management Algorithm (MA) for a hybrid PV/battery islanded Micro-Grid. In this algorithm:

- A tuneable power stage for both the PVG and the battery is controlled separately;
- A MPPT technique based on hybridizing Hill Climbing and Particle swarm optimisation (HC-PSO) is developed and successfully employed to achieve the MPP;
- A double PI control loop is designed to manage the bidirectional buck-boost converter, interfacing the battery storage to the load side through Constant-Current/ Constant-Voltage (CC-CV) control mode.

Simulations are performed using MATLAB/ SIMULINK software where two cases are considered. In the first case, an analysis under standard conditions is carried out where the rated power is sufficient to charge the battery and supply the load. In the second case, an investigation under partial shading is performed to test the consistency of the MA. Finally, a comparison of the proposed method with the well-known HC is carried out to prove its performance and features.

3.2. Hybrid PV Battery Micro-Grid

As shown in Figure.3.1, a DC/DC boost converter interfaces the PVG with the load side, while a bidirectional converter interfaces the battery with load side. These converters are controlled separately by employing the proposed MA. The purpose of the latter is to ensure the availability of power, meanwhile, to satisfy the load demand of energy and to reduce faults.

When a lack of power is detected during varying weather conditions or PSCs, the MA order the controller to bring the required load energy from that already stored in the battery. On the contrary, it enables storing the excess of the produced energy by the PVG in the battery. Moreover, the overcharge and the deep discharge of the battery are avoided by the MA.

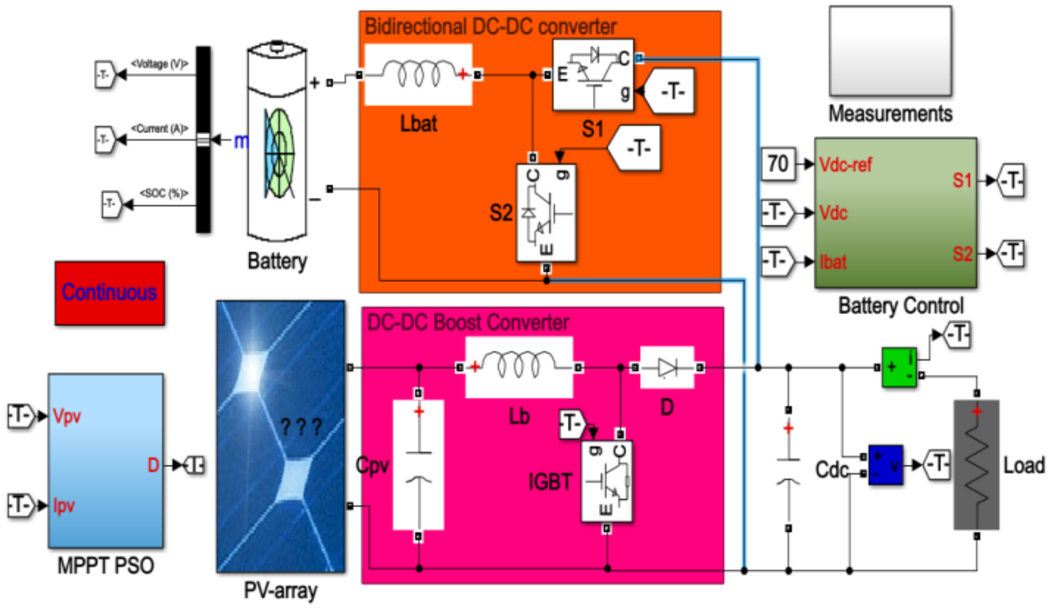


Figure.3.1. Simulink implementation of thePV/Battery system

3.3. MPPT Control Mode

3.3.1. Partial Shading effect

The partial shading event occurs when a part of the PVG is shaded and the remaining parts are fully illuminated by the sun, that is to say, there exist at least two levels of irradiance come across the surface of one PV module. This phenomenon leads to two or more power peaks on the P-V characteristic curve of the PVG (i.e. one global MPP and one or more local MPPs).

3.3.2. The proposed Hill-Climbing Particle Swarm Optimization MPPT

PSO is a bio-inspired meta-heuristic technique reviewed in the first chapter. The main advantage of this method is the high capability of distinguishing the global MPP among Local MPPs. However, this method uses random quantities (r_1 and r_2) as in Equation.3.1. Moreover, the use of a PI controller at the output of the algorithm for generating the converter duty cycle leads to increasing the response time of the algorithm under fast variations of irradiance as well as the implementation price [142].

$$V_i^{k+1} = w \times V_i^k + C_1 r_1 (P_i^k - X_i^k) + C_2 r_2 (P_g^k - X_i^k) \tag{3.1}$$

Each PSO interaction leads to a particular velocity to estimate and to approach a local or a global best position. To benefit from the advantages of the PSO method in tracking and reaching the best position, meanwhile, avoiding the use of a PI controller, a PSO MPPT based on the HC principle is adopted in the present chapter.

The search mechanism of the HC-PSO aims to locate the global MPP among the existing Local MPPs. Then, it sets the DC-DC converter to maintain the Global MPP operating point. This can be achieved through well initializing the following parameters: initial position, velocity vector…, etc, evaluating the fitness of each particle, selecting the best position over the local positions, calculating the velocity and the position of the populations (Equation.3.1, Equation.3.2). Then, the aforementioned steps will be repeated until achieving the best position (i.e.,duty cycle). An appropriate tuning of parameters w, c1, and c2 employed in the velocity equation plays an important part in improving the PSO behaviour [142]. The algorithm is summarized in the flowchart of Figure.3.2.

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{3.2}$$

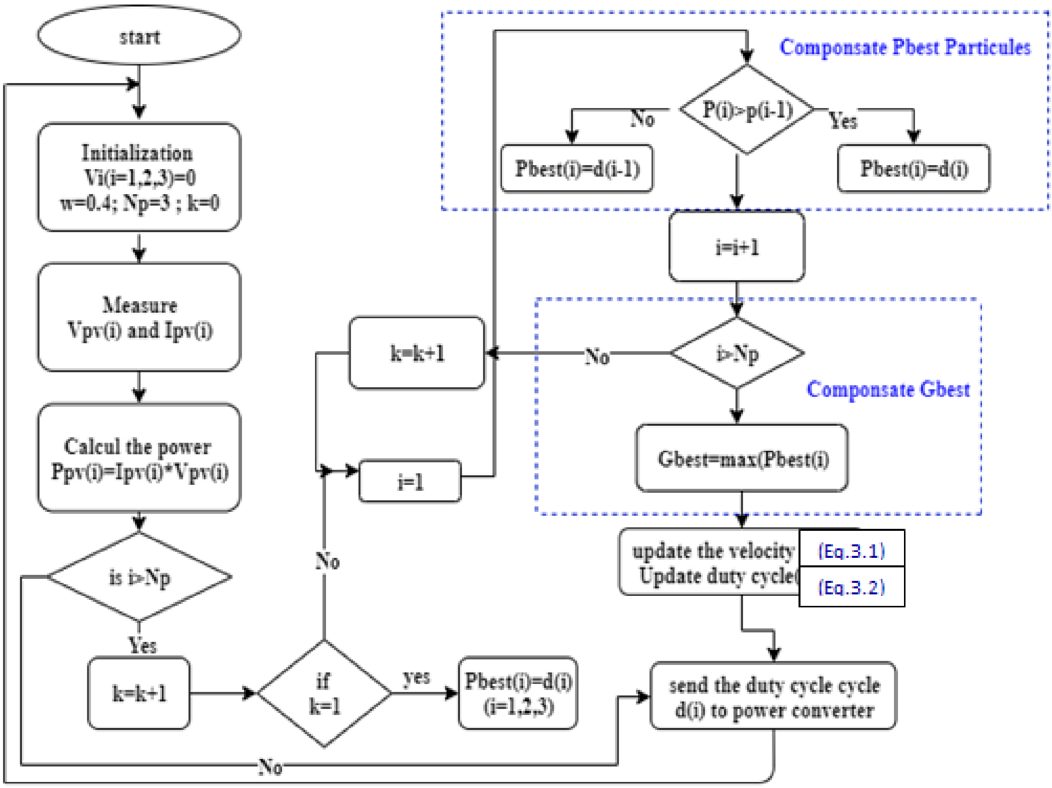


Figure.3.2.Flowchart of the proposed HC-PSO

3.4. Load Control Mode

A simple feedback voltage control strategy is used to ensure a constant voltage delivered to the load by controlling the duty ratio of the boost converter. Whereas, the PI controller is selected to achieve low steady-state error and Ziegler Nichols technique is adopted to select the proportional gain K_p (i.e., aims to eliminate the static error between the output voltage and its reference) and the integral gain k_i(i.e.it aims to decrease the settling time and maintaining the system stability during transient states). This controller is depicted in Figure.3.3 and expressed as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau \tag{3.3}$$

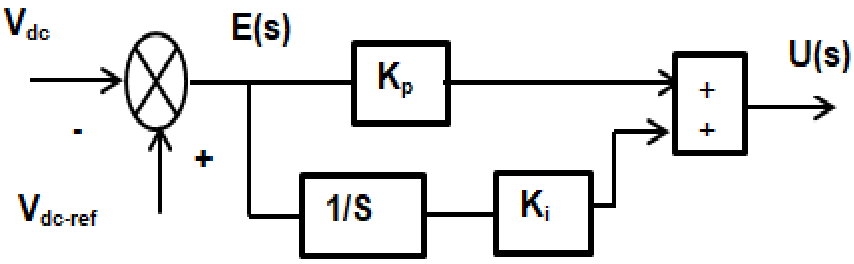


Figure 3.3. Feedback constant voltage control PI loop.

3.5. Storage device

The use of battery storage ensures continued energy supply to the load and guarantees its stability. When a lack of power is detected during varying weather conditions and PSC, the battery storage discharges to compensate it. But during peak production, it stores the excess power. Effectively, the MA may ensure security, satisfy the load demand for energy, and reduce faults. The available power should be higher or equal to the load power and the overcharge or deep discharge of the battery must be avoided.

3.5.1. Battery Modelling

The model of Li-ion battery is adapted in this chapter due to its long lifetime and high performance compared to other existing electrochemical accumulators. The model of this latter is available in the MATLAB/ SIMULINK library, with the discharging characteristics shown in figure.3.4.

During discharging mode, the battery voltage is obtained with[143][144]

$$V_{bat}=E_0-\frac{KQ}{Q-\int i_{bat}dt}i_{bat}^{*}-\frac{KQ}{Q-\int i_{bat}dt}\int i_{bat}dt+A.\exp(-B\int i_{bat}dt) \quad (3.4)$$

During charging mode the voltage is expressed as [143][144]

$$V_{bat}=E_0-\frac{KQ}{\int i_{bat}dt+0.1Q}i_{bat}^{*}-\frac{KQ}{Q-\int i_{bat}dt}\int i_{bat}dt+A.\exp(-B\int i_{bat}dt) \quad (4.5)$$

Where: E_0 is the battery constant voltage, K is the polarization constant, Q corresponds to the maximum battery capacity, i_{bat} and i_{bat}^{*} denote the battery current and filtered current, respectively. A and B are exponential voltage and capacity, respectively.

The state of charge (SoC) can be calculated depending on the initial SoC value (SoC_0),the battery capacity Q and the output current i_{bat} by [143]:

$$SoC = SoC_0 - \frac{1}{Q}\int i_{bat}dt \tag{3.6}$$

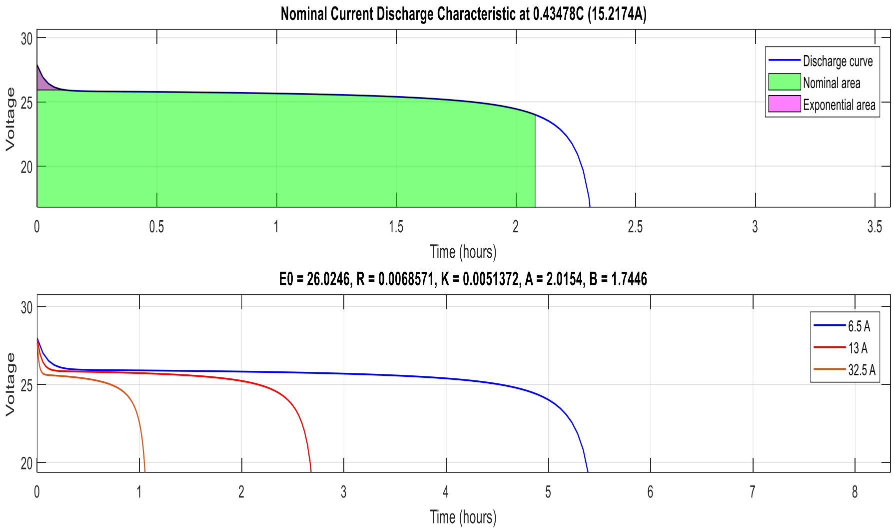


Figure.3.4 Nominal current discharge characteristics

3.5.2. Bidirectional converter control design

The Constant Current-Constant Voltage (CC-CV) is used to control the bidirectional converter and to switche between the buck and the boost modes. During the CC mode, the battery is charging at a constant current, once the battery is fully charged and achieves its nominal voltage value, the system switches to boost mode and works in a CV mode leading to the power profile schematized in Figure.3.5.

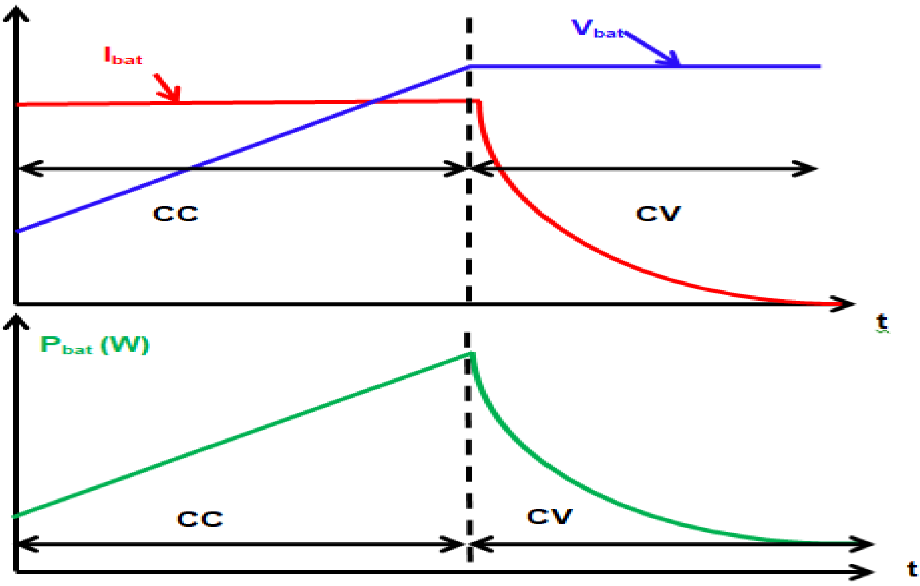


Figure.3.5 CC-CV battery modes

According to Figure.3.6, the buck-boost converter is controlled through an outer dc-voltage loop and an inner battery current loop in a cascade configuration.

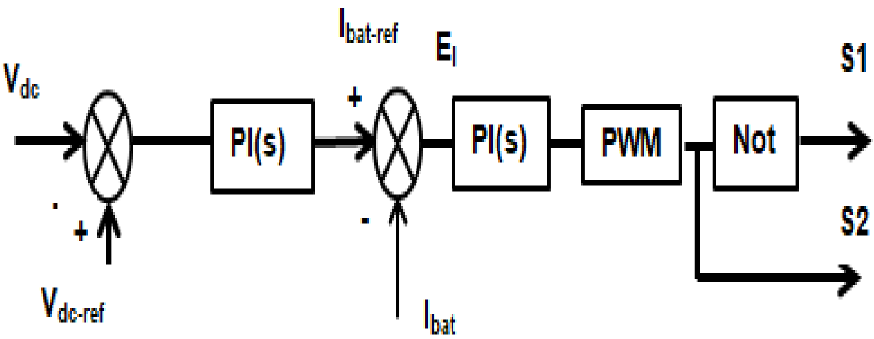


Figure.3.6 Battery control

The transfer function of this configuration can be obtained by linearizing the converter as follows:

$$\frac{V_{dc}(s)}{I_b(s)} = \frac{(1-D)(sR_{dc} - sL_{bat})}{1 + sR_{dc}C_{dc} + (1-D)^2} \tag{3.7}$$

$$\frac{I_{batc}(s)}{d(s)} = \frac{2 + sR_{dc}C_{dc}}{(s^2 L_{bat}C_{dc} + \frac{sL_{bat}}{R_{dc}}) + (1-D)^2} \times \frac{V_{bat}}{R_{dc}(1-D)} \tag{3.8}$$

Where, L_{bat}, V_{bat}, R_{dc} , C_{dc} are the battery current, battery voltage, output resistance, and output capacity, respectively

3.6. Proposed Management Strategy

An improved MA is introduced and tested under varying atmospheric conditions and PSC. The proposed stand-alone PV/Battery system considers the PV control to optimize the MA operation while maintaining a constant power flow to the load. The optimal operation can be achieved by considering the advantages of HC-PSO, which uses the principle HC method of a direct control strategy (i.e., no PI controller at the output). The flowchart of the MA is depicted in Figure.3.7, and can be explained as follows:

When the DC voltage is higher than its reference value (V_{dc}- V_{dcref}> 0) and SoC higher than 95%, the MG operates in load mode. In this case, the battery is fully charged, so, the PV should switch to the load control mode to protect the battery and satisfy only the load need. However, when the (SoC< 95%) the battery stores the excess power and the MA works in MPPT mode.

When the difference (V_{dc}- V_{dcref}) is negative and the battery SoC is below an acceptable level (45% ≤ SoC ≤ 95 %), the MG operates in MPPT mode, or else, the procedure must be turned OFF. Otherwise, the DC voltage may collapse and damage the installation. In this case, the system works on load mode to satisfy the load demand.

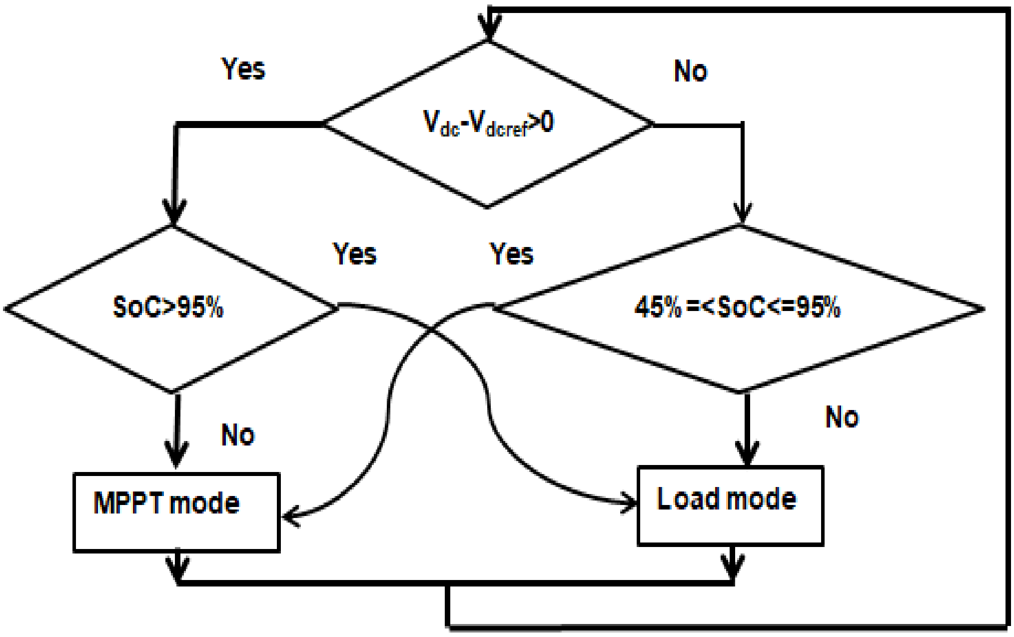


Figure3.7.Flowchart of the proposed Management Algorithm

3.7. Simulations and discussions

Several tests have been carries out to achieve high performance of the proposed HC-PSO and well select the best initial parameters of PSO which are: w=0.8, C1=C2= 0.5. Low random value leads to an increase in the settling time. In other hand, if this value is higher, the GMPP may not be reached by the MPPT. Simulations using MATLAB/ SIMULINK software have been carried out to test the system performance. The designed SIMULINK model is depicted in Figure.3.1.

A PV array of 724.2 W is used as a generation source, composed of three-parallel connected strings; each one of them has two series-connected PV modules. The extraction of the MPP is ensured using the HC-PSO technique during MPP mode and constant voltage (i.e. using the conventional PI controller) during load mode. The management strategy ensures the control of the bidirectional DC-DC converter by supplying or storing energy depending on load demand as detailed in the previous section. The simulation parameters of the whole implemented system are given in Table 3.1.

TABLE 3.1. SIMULATION PARAMETERS

	Symbol	Parameter	Value
PV Module	P_{MPP}	Maximum power	724.2W
	V_{MPP}	Voltage at P_{max}	17V
	I_{MPP}	Current at P_{max}	7.1 A
DC-DC Boost Converter	L_b	Boost inductance	0.1 mH
	C_{PV}	PV capacitor	550 µf
	f_S	Switching frequency	20 kHz
Battery	L_{bat}	Battery inductance	0.3mH
	C	Rated Capacity	35Ah
	V_{bat}	Battery voltage	24V
	f_S	Switching frequency	20 kHz
Load	V_{dc}	Load voltage	70 V
	P_{dc}	Load power	400W
	F_n	Nominal frequency	$1e^{-5}$ Hz
	C_{dc}	DC-Link Capacitor	550 µf

3.7.1. Under standard test condition

Figure 3.8, Figure 3.9 and Figure.3.10 show the measured current, voltage and power of the PV array, the load and the battery, respectively, under Standard Test Condition (i.e., STC: 25 °C and 1000W/m^2). According to these results, HC-PSO can effectively track the exact MPP.

It can be seen from Figure.3.9 that the load power is still at the same level thanks to the MA. Whereas the waveforms of Figure.3.10 indicate that the battery is charging to store the excess power. In fact, the negative current sign indicates that the battery is in charging mode, so in this case, the SoC is rising.

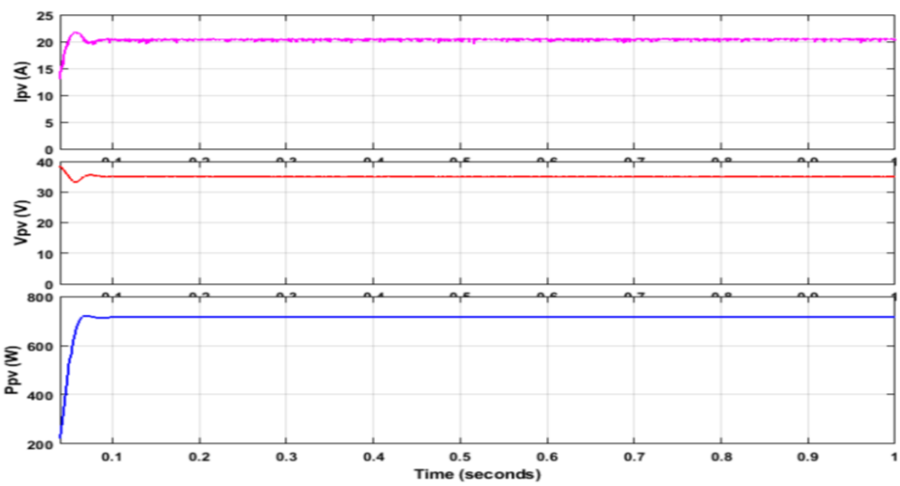


Figure. 3.8. PVG output current, voltage and power

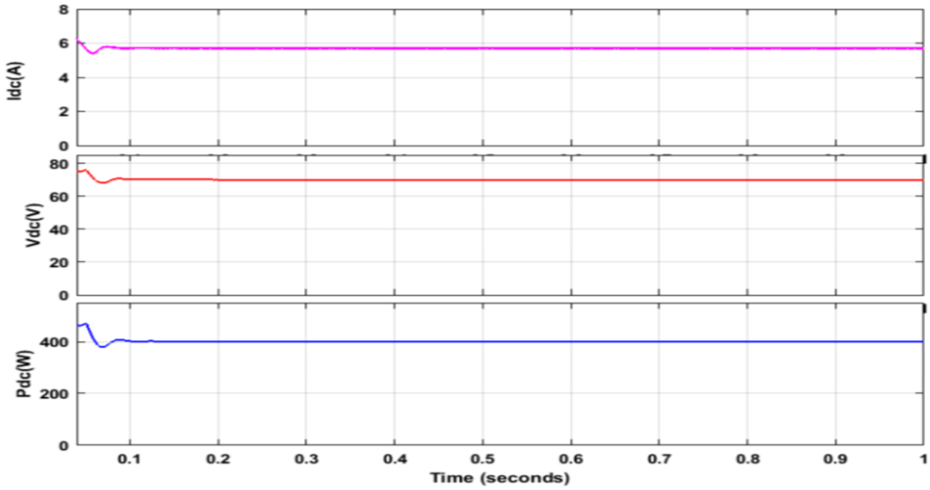


Figure.3.9. Load current, voltage and power

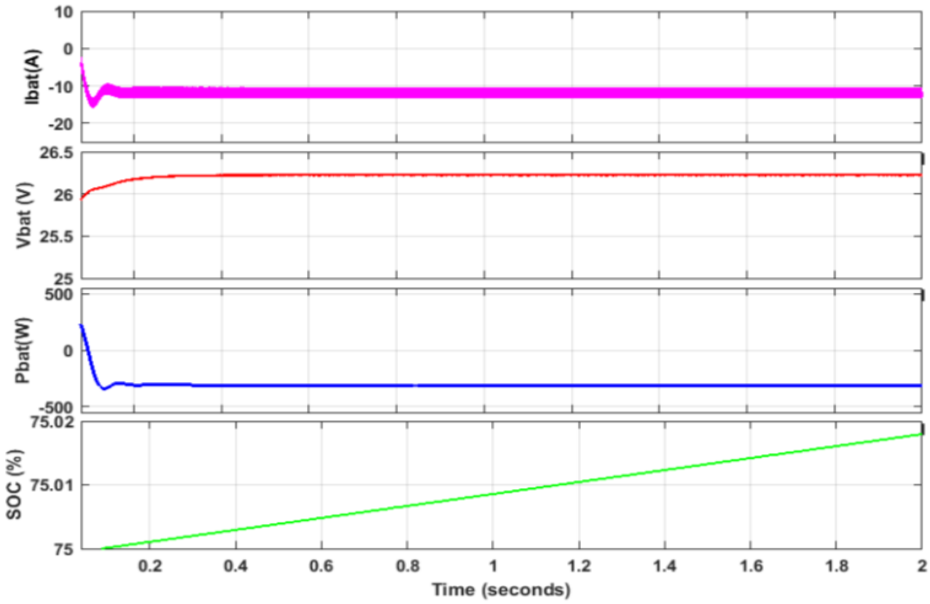


Figure.3.10. Battery current, voltage, power and SoC.

3.7.2. Under variable irradiance condition

Under fast variations of irradiance (Figure.3.11) and with accordance to Figure 3.12, it can be observed that the load power is kept at the same level thanks to the MA, whereas the battery power varies to compensate the mismatching of the delivered power from the PV array, meanwhile, maintaining the load level.

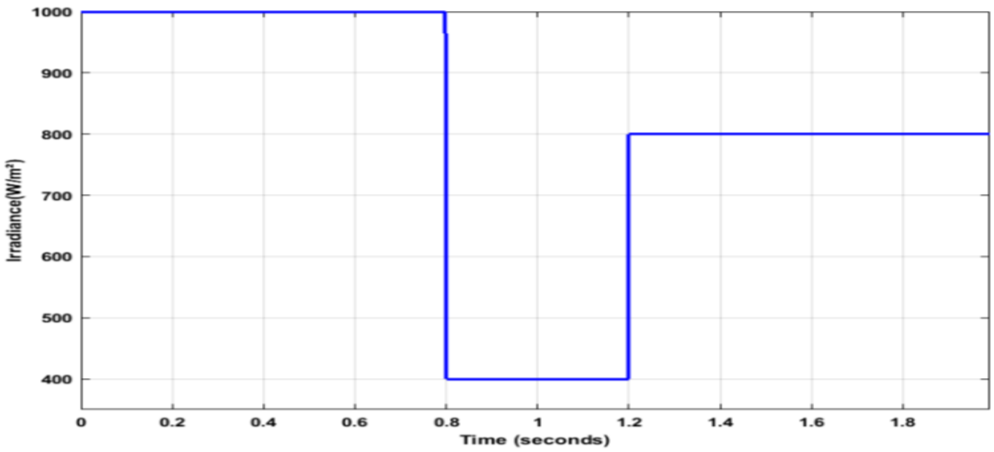


Figure 3.11. Variations of irradiance levels

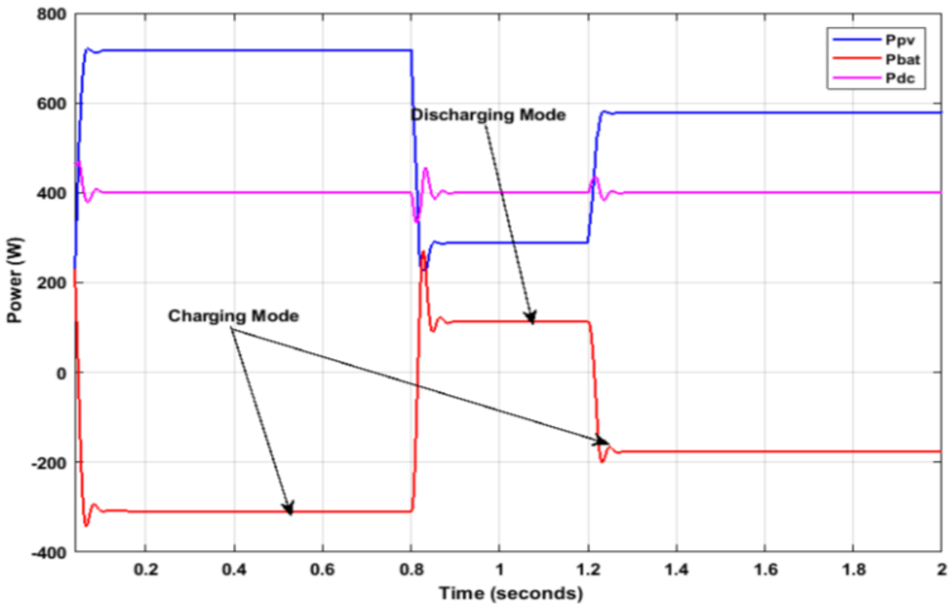


Figure 3.12 PVG, battery and load power under varying irradiance levels

3.7.3. Under Partial shading conditions

The aptitude of the proposed MA to preserve both voltage and current at the load level makes it very helpful under PSCs. Figure.3.13 shows that the HC-PSO can effectively track the global maximum, with optimized output power. According to these results, low distortions are shown on the load power, while the battery discharges to firstly, compensate for the lack of power, and secondly, keep the DC power at load level.

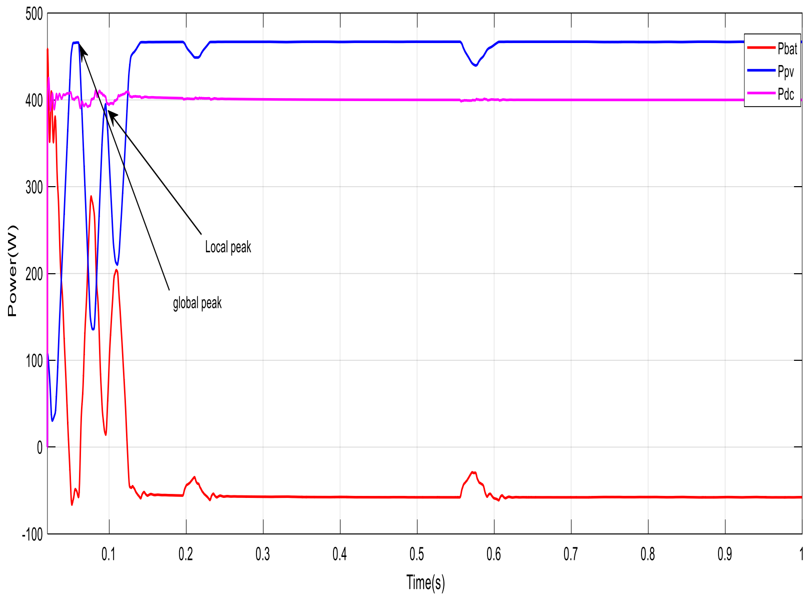


Figure 3.13 battery, PV and load power under PSCs

3.7.4. Comparisons analysis

To show the effectiveness of the proposed system, simulation under variable irradiance levels Figure.3.14, indicates that the developed strategy outperforms the HC algorithm [29], and improves its ability in term of rapidity, tracking precision with a considerable decrease in the oscillation amount, and hence it tracks the exact MPP while HC keeps a value approximated to the MPP as shown in Figure 3.14 summarized in Table 3.2.

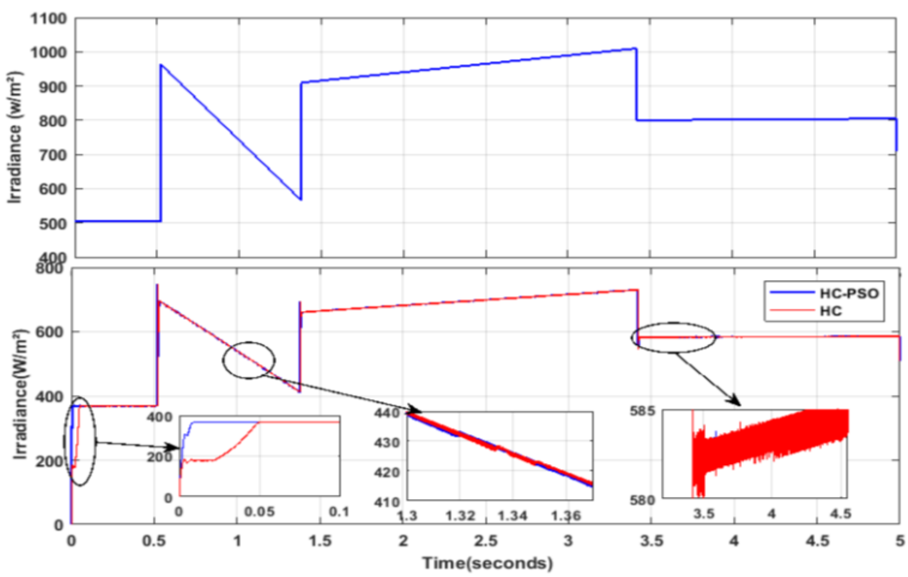


Figure 3.14 Power using HC and HC-PSO under uniform irradiance conditions

Table 3.2 Comparison of the HC-PSO method and conventional HC MPPT method

	HC-PSO	HC [29]
Tracking under partial shading	Yes	Not possible
execution time	Very fast	Slow
Efficiency under uniform irradiance	99.5%	86.2%
Oscillation amount	Low	High
Dynamic performance	Good	Poor

3.8. Conclusion

Proper management and control of power electronic interfaces under different weather conditions is essential for a practical micro-grid. In this chapter, the interaction between PV generation and load power management based on HC-PSO control has been investigated. The HC-PSO control has been adopted to maximize the power flow of the PV/Battery stand-alone DC-MG system under PSC. While the bidirectional control is employed to keep the DC-Power at load profile through the proposed MA and double PI control loops. The proposed MA has been tested, using MATLAB/SIMULINK software.

Thanks to the used MA , the power quality has been improved by maintaining excellent precision with minimum complexity and high performance. Comparisons to HC control have been performed, and all obtained results show the effectiveness and the robustness of the proposed MA and HC-PSO in controlling MGs.

The next chapter will focus on the improvement of the current inner loop control for the power electronic interfaces to mitigate the problems associated with power quality such as harmonics and power loss in a standalone double stage MG, and manage the power flow to load under varying studied circumstances. To this end, a Fuzzy controller is modified to extract the maximum power from the PVGs and control the inner current loops of both bidirectional converter interfacing the battery to DC-Link and the H-bridge inverter.

CHAPTER 4 Single phase double-stage standalone Photovoltaic Micro-Grid

4.1. Overview

The previous chapter proposed management of a PV-Battery MG feeding a DC load, where, a PSO technique is improved and incorporated to control the interfaced boost converter and deal with different variations that occur in weather conditions and during PSCs. This standalone PV system is generally adopted in rural and isolated areas, to satisfy the electricity requirement, besides, to draw maximum allowable power from the PV array, and to manage and ensure the continuity of service. However, the major drawback is that in most of the time, the loads used in MG installation are AC-loads which means that the electricity needed to feed them should be AC. Accordingly, the present chapter developed and analyzed a management algorithm for double stage PV-Battery MG. To this end, an improved Fuzzy MPPT is used to track the maximum power from the PV generator. Moreover, battery storage is linked to the DC inverter side through a bidirectional converter which is controlled through a PI outer voltage loop and a fuzzy inner current loop. Furthermore, the use of single-phase H-bridge inverter has lower electromagnetic interference that made it adequate for low voltage and power generation to get sinusoidal voltage and current in order to feed AC-loads. To this end, fuzzy and PWM controllers are combined to regulate the inverter switches commutations (ON-OFF), hence, an improved management algorithm is applied to fulfil the following objectives:

- The enhancement of the extracted power from the PVGs;
- Maintain the DC-Voltage to ensure the continuity of the power flow to the load;

- Guarantee the efficiency and quality of load power and minimize the THD value.

4.2. Standalone PV system without storage device

4.2.1. System configuration

Figure 4.1. represents the block diagram of a two-stage standalone PV system. The first stage is composed of a boost DC-DC converter associated to its PWM generator and a conventional P&O MPPT. The boost converter is responsible of stepping up the output voltage of the PV array. Whereas, P&O MPPT aims to appropriately track the PV array's MPP. The second stage, which is a single-phase inverter controlled by two control loops has been cascaded with the first stage, so that an AC voltage results. The inverter's output current and voltage pass through a second order low-pass LC filter which consists of a series inductor and a parallel capacitor as shown in Figure 4.1. The LC filter has been chosen thanks to its advantages, which are: its simplicity and ability of mitigating the output waveform's higher harmonic components

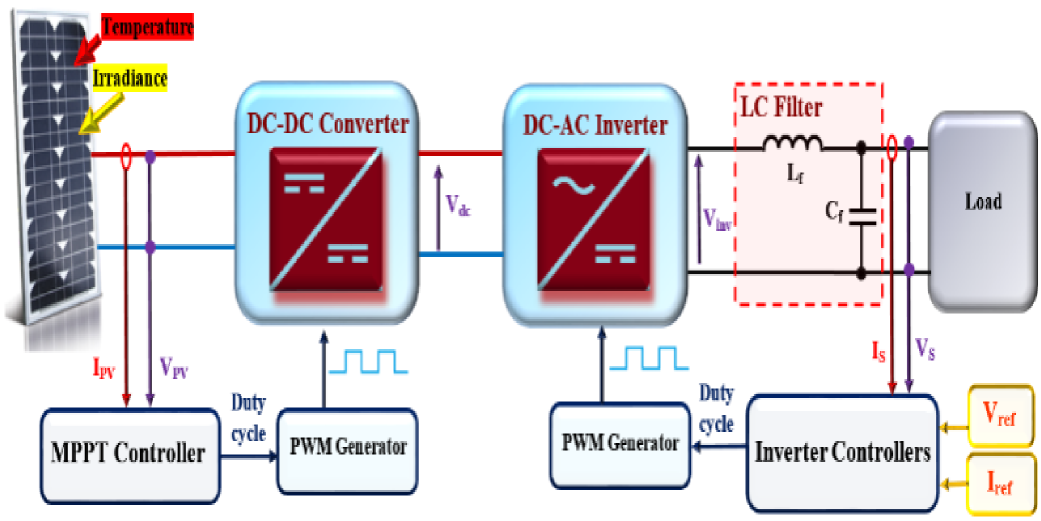


Figure 4.1.The two-stage standalone PV system block diagram

The designed system assumes that it can function without any interaction with the grid to fulfill local load demand. The power circuit topology includes an LC-filter as an interface between the inverter and AC-load with unipolar switching. In fact, the LC filter is employed to mitigate switching ripples.

4.2.2. Installation design

The design of the installation components is very important to optimize and ensure a high quality of the delivered power with relatively low loss and distortions.

4.2.2.1. DC-DC Stage Design

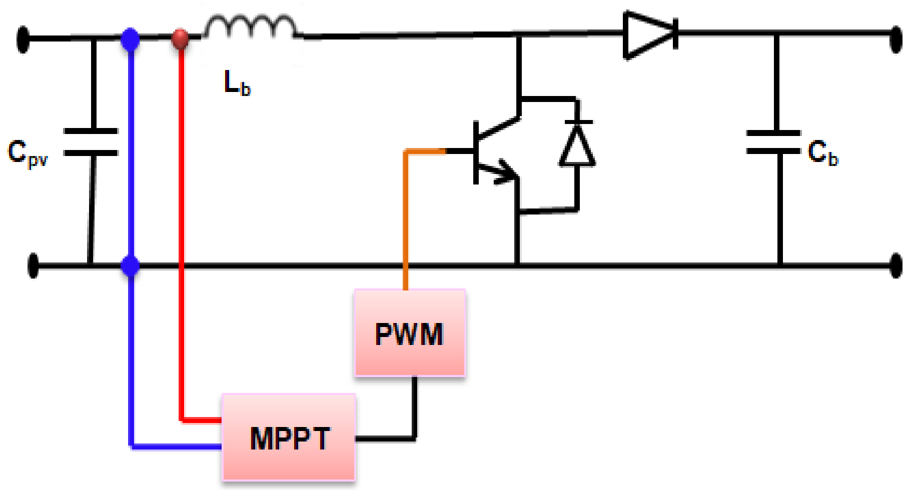


Figure.4.2. DC-DC boost converter + MPPT control

A boost DC-DC converter (shown in Figure 4.2) aims to generate the regulated DC output voltage higher than the input voltage. It is composed of a diode along with an inductor (L_b) and a capacitor (C_b).The output capacitor (C_b) has the objective of enhancing the DC output voltage stability, and therefore, reducing the effect of fluctuation on the AC output [93][95].The switching frequency (f_s) of the power electronics-switching device (i.e., it could be MOSFET or IGBT) is chosen equal to 20 kHz. The minimum value of the inductor (L_{bmin}) and the output capacitor (C_{bmin})are computed using the following equations

$$C_{b\min} = \frac{V_{pv} D}{\Delta V_{pv} f_s R} \tag{4.1}$$

$$L_{b\min} = \frac{V_{dc} D}{\Delta V_L f_s} \tag{4.2}$$

Where $\Delta V_{pv}$is the voltage ripple across the PV array, the ratio($\Delta V_{pv}/V_{pv}$) is around 0.001, V_{dc} is the DC-link voltage, ΔI_L is the inductor ripple current and R is the load resistor.

Finally, the duty cycle (D) of the boost converter is obtained by the following relationship

$$\frac{V_{dc}}{V_{pv}} = \frac{1}{1-D} \tag{4.3}$$

4.2.2.2. DC-AC Stage Design

The high power quality achievement is essential for a stable operation of PV systems; It could be fulfilled through the well design of the filters and controllers. To this end, a second order LC filter has been implemented at the inverter AC-side to attenuate harmonics caused by the switching frequency, maximize the stability of the system, and minimize the energy loss when transmitting power to the load.

The transfer function of the system is given as [36]

$$G(s) = \frac{V_s}{V_{inv}} \frac{V_s}{L_f C_f f_s s^2 + \frac{L_f}{R} s + 1} \tag{4.4}$$

Where V_s is the voltage measured at the output of the LC filter, V_{inv} is the voltage measured at the output of the inverter, L_f is the filter's inductor, C_f is the filter's capacitor and R is the load resistor.

The filter inductance is calculated as follows:

$$L_f = \frac{V_{dc}}{8 \Delta I_{max} f_s} \tag{4.5}$$

Where, V_{dc} is the DC-link voltage, f_s is the switching frequency of the inverter and ΔI_{max} is the maximum current ripple, its value has been chosen 10% of the maximum available current I_{max} ($\Delta I_{max} = 0.01 \times I_{max}$).

The resonance frequency (f_r) of the inverter can be obtained by the following relationship:

$$f_r = \frac{1}{2\pi\sqrt{L_f C_f}} \tag{4.6}$$

To avoid the resonance effect, generally, the value of f_r is taken below than 1/10 value of switching frequency (f_s) of the inverter ($f_r \leq f_s/10$).The filter capacitance is calculated by the equation below

$$C_f = \frac{1}{(2\pi f_r)^2 L_f} \tag{4.7}$$

4.2.3. Control design

The voltage controller produces the inner current reference by comparing the actual load voltage with a reference sinusoidal waveform, which is then passed through a PI inner current control loop to provide Sinusoidal pulse width modulation (SPWM) to control the inverter where the switching device of the same leg operates complementarily.

4.3. Storage device and management integration

The configuration shown in Figure.4.1 presents an adequate solution to feed remote loads. Therefore, the intermittent nature of the solar requires the inclusion of storage devices to provide the required energy during low production or night. Hence, the use of a management algorithm is necessary to control the power flow all over the installation. Figure 4.3 presents the proposed structure with the management strategy.

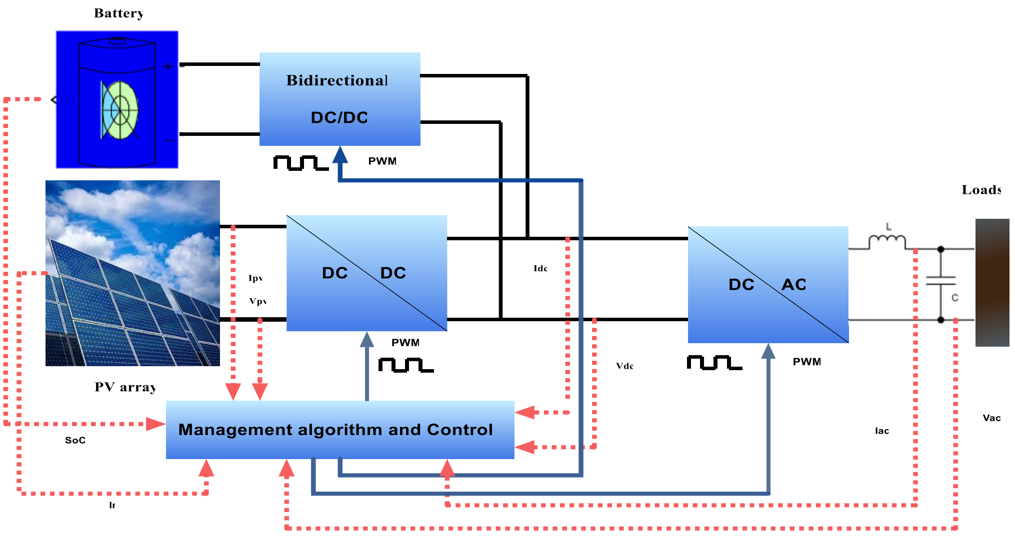


Figure.4.3 The standalone double stage PV-MG.

4.3.1. Control design

Enhanced controllers and sophisticated installation help on improving the power quality and benefit from the free solar energy. Hence, the management will ensure the continuity and security of energy among the installation. So, the use of intelligent and improved fuzzy-MPPT aids on automatically achieving maximum power under any weather condition.

4.3.1.1. MPPT design

The fuzzy control shows its efficiency in improving the stability of the PV system under non-linearities. Besides, conventional techniques have high oscillations, slow response time, and dependence on the system's initial conditions [30] [43]. Accordingly, an improved fuzzy logic control based MPPT is applied to enhance the MPP extraction and to overcome the drawbacks of the conventional techniques. It is important to know that the fuzzy control inputs are the error and the variation in the error. As well, the basic rules are defined within the range of [-1 1]. Accordingly, it is essential to normalize the inputs into the interval of [-1 1]. These numerical values are transferred to linguistic variables using the fuzzification stage. The scaling factors of these inputs are G_e and G_{ce}, respectively; also named normalized gains are introduced at the input side of the FLC. Then, fuzzy inference using a min-max operator is applied. The defuzzification stage based on the center of the area is then used to get a numerical output variable which is also defined within the range of [-1 1] as in Figure 4.4. The obtained value is multiplied by scaling gain G_d (denormalization gain). The design of these gains (i.e.,G_e,G_{ce} and G_d) is based on the behavior of the system. Basically, a big G_e value increases the system speed but an exceeding big value leads to an overshoot. However, a small value leads to a slower system and influences the performance and steady-state precision of the system. On the other hand, a smaller G_{ce} value enhances the response time. However, a very small G_{ce} will lead to overshoot and vibration [52] [54]. The described Fuzzy process is schematized in the Figure 4.5 bellow:

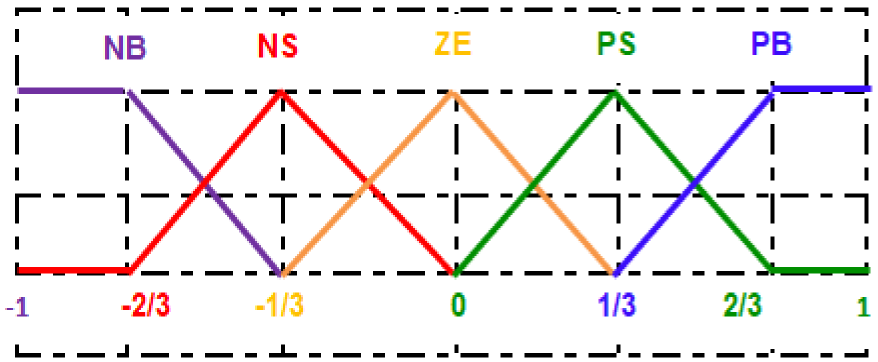


Figure 4.4.Membership functions used for inputs and output of the fuzzy controller

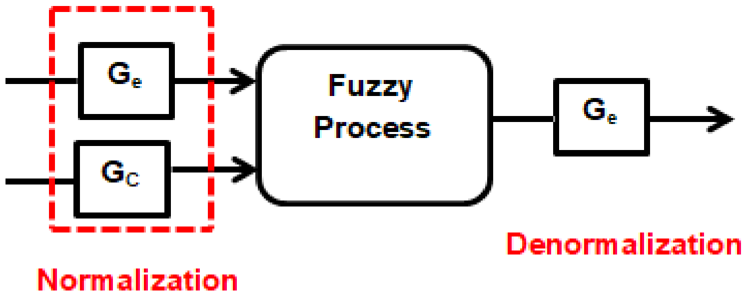


Figure 4.5. The used Fuzzy control

The fuzzy rules are divided into five fuzzy sets (PB, PS, ZE, NS, and NB) for both inputs and output variables. Control intervals are considered and done by the control rule database shown in Table 4.1. The reasoning of this method is based on the series “if-and-then” rules.

Table 4.1 the used fuzzy rules.

e(k) / de(k)	NB	NS	ZE	PS	PB
ZE	NB	NB	NM	NS	ZE
NS	NB	NM	NS	ZE	PS
ZE	NM	NS	ZE	PS	PM
PS	NS	ZE	PS	PM	PB
PB	ZE	PS	PM	PB	PB

The output of the fuzzy control which is the instantaneous duty cycle D(k) is obtained through the centre of area defuzzification technique. This method is based on the weighted mean calculation for the fuzzy region as:

$$D(k) = \frac{\sum_{i=1}^{i=k} (D_i \times \mu D_i)}{\sum_{i=1}^{i=k} \mu(\Delta D_i)} \qquad (4.8)$$

where $\mu(D_i)$ is membership value obtained through the combined membership function associated with each rule.

The improved fuzzy-MPPT is based on calculating the rated power and the variation on the rated power to obtain the duty cycle variations, which is adjusted to the switching boost converter. The proposed system SIMULINK scheme associated with the management algorithm is given in Figure.4.6 bellow. And can be interpreted as follows :

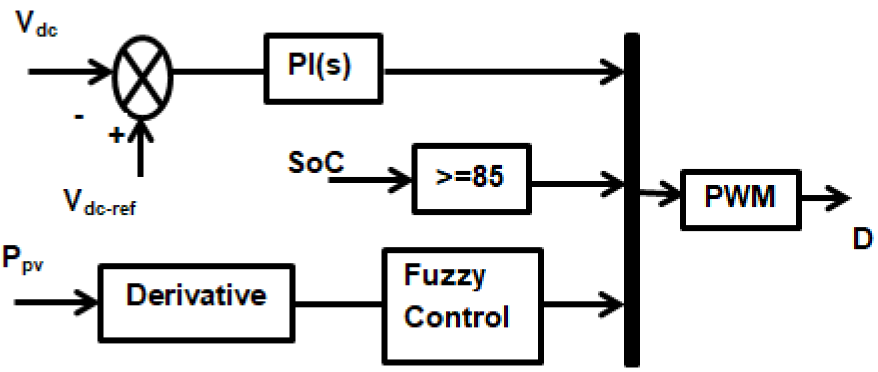


Figure.4.6 Proposed MPPT control associated with the management algorithm.

First, the PV power is calculated as

$$P_{pv}(k) = V_{pv}(k) \times I_{pv}(k) \qquad (4.9)$$

where $P_{PV}(k)$, $V_{pv}(k)$, and $I_{pv}(k)$ are the PV array output power, voltage and current at the instant k, respectively. So, the variation of the power $dP_{pv}(k)$ is calculated as

$$dP_{pv}(k) = P_{pv}(k) - P_{pv}(k-1) \qquad (4.10)$$

Then, the error e(k) and the error variation de(k) which are the fuzzy inputs variables can be calculated as:

$$e(k) = dP_{pv}(k) \times dP_{pv}(k-1) \qquad (4.11)$$

$$de(k) = e(k) - e(k-1) \qquad (4.12)$$

The applied fuzzy rules are depicted in Table 4.1, the output of the fuzzy control is the duty cycle variations, and then, the boost converter duty cycle is adjusted respecting the management algorithm procedure.

The PI controller is used to control the boost converter during constant voltage flow control. The PI transfer function is given as

$$G(s) = K_p + -\frac{K_i}{s} \tag{4.13}$$

Where k_p is the proportional gain and k_i is the integral gain which must be designed respecting stability margins of the system.

4.3.1.2. Bidirectional converter control

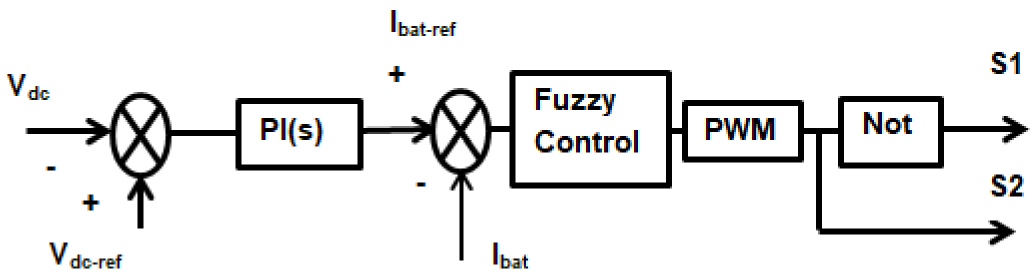


Figure 4.7 Proposed bidirectional converter control scheme.

The buck-boost converter interfacing battery to the DC inverter side regulates the injected power.The control is shown in Figure 4.7. It is composed of two loops:

- An outer PI control loop that maintains the DC-link voltage and generates the battery current reference;
- An inner fuzzy current control loop that allows the selection of an adequate switching signal value for the bidirectional converter switches at a frequency of 5KHz. The inputs of the fuzzy control are the error between the battery current and reference current generated by the PI DC-Voltage control loop, and the rated error as :

$$e_b(k) = i_{bref}(k) - i_b(k) \tag{4.14}$$

$$de_b(k) = e_b(k) - e_b(k-1) \tag{4.15}$$

where $e_b(k)$, $de_b(k)$ are the error and the variation of error, respectively, whereas, $i_b(k)$,$i_{bref}(k)$ are the battery's current and the reference current, respectively.

The applied fuzzy rules are the same as in the fuzzy-MPPT shown in Table 4.1.

4.3.1.3. Inverter control

An LC filter is used to link the inverter to the load. The transfer function can be expressed as in Equation.4.4.

The frequency and voltage regulation ensures the stability of the MG. Therefore, the current control allows the maximum power transfer to load.

The main objective of the proposed control scheme is to preserve power at the load level. The fuzzy control receives the variations of the current error ($e_i(k)$) and the rated error ($de_i(k)$). Their equations are defined as:

$$e_i(k) = i_{iref}(k) - i_i(k) \quad (4.16)$$

$$de_i(k) = e_i(k) - e_i(k-1) \quad (4.17)$$

While the output of the fuzzy control is the variation on the duty ratio, which is in turn adjusted to the inverter switches through a PWM process. The fuzzy control based rules are given in Table.4.1, and the control scheme is depicted in Figure 4.8.

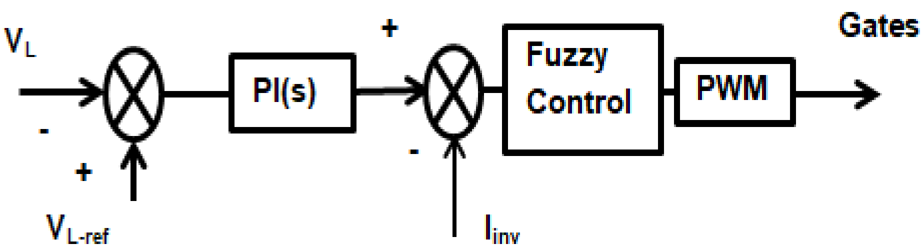


Figure4.8. Inverter control scheme.

4.4. Results and discussions

The simulation of the proposed control has been carried out using MATLAB software. This PV array is composed of two strings; each one is composed of two series connected PV modules to get a total maximum power of 0.7 Kw. The specifications of the used controllers and system are given in Table 4.2 and Table 4.3, respectively.

Table 4.2. Control parameters

Parameter	symbol	Value
Constant Voltage controller	K_p	0.63
	K_i	6.4
dc-Voltage controller	K_{pb}	22
	K_{ib}	500
Load voltage controller	K_{pl}	60
	K_{il}	650

Table 4.3. Micro-Grid parameters

	Symbol	Parameter	Value
PV Module	P_{MPP}	Maximum power	482.8 W
	V_{MPP}	Voltage at P_{max}	34 V
	I_{MPP}	Current at P_{max}	14.2 A
DC-DC Converter	C_{PV}	Boost inductance	100μf
	L_b	PV capacitor	3 mH
	f_s	Switching frequency	5K Hz
Battery	L_{bat}	Battery inductance	0.3mH
	C	Rated Capacity	28Ah
	V_{bat}	Battery voltage	48V
	V_{dc}	DC voltage	70 V
	C_{dc}	DC-Link Capacitor	330 μf
	f_s	Switching frequency	5 kHz
AC side	L_f	Filter inductor	3mH
	C_f	Filter capacitor	10μf
	Fs	Switching frequency	5 KHz
	R	Resistive load	20ohm

4.4.1. Test under STD

The system is first analysed under Standard Test Condition(i.e., STC; 1 kW/m² at 25 °C). The waveforms of the inverter load current and voltage current and load voltage are illustrated in Figure 4.9 a and b, respectively. The results show that the waveforms are purely sinusoidal. On the other hand, the analysis of inverter output current and load voltage demonstrates that they are both in phase as in Figure 4.9.c, keeping a unite power factor.

Moreover, the THD analysis shows a value of 0.1032% for both the load voltage and load current, indicating that they are under the acceptable **IEEE std_519** limits.

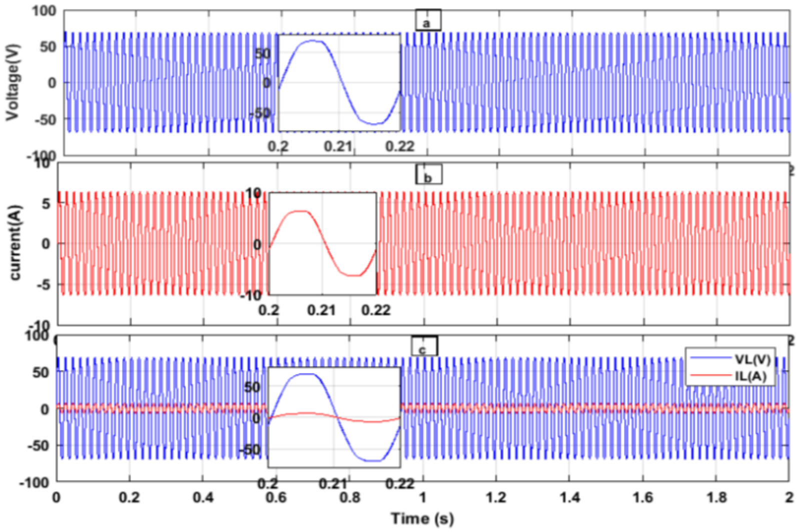


Figure.4.9. a.inverter output current. b.load voltage. c. analysis of inverter output current and load voltage

The amounts of both active and reactive powers are visualized in Figure 4.10. At steady-state, the active power is delivered to load while the reactive power is kept equal to zero, ensuring a high power quality level.

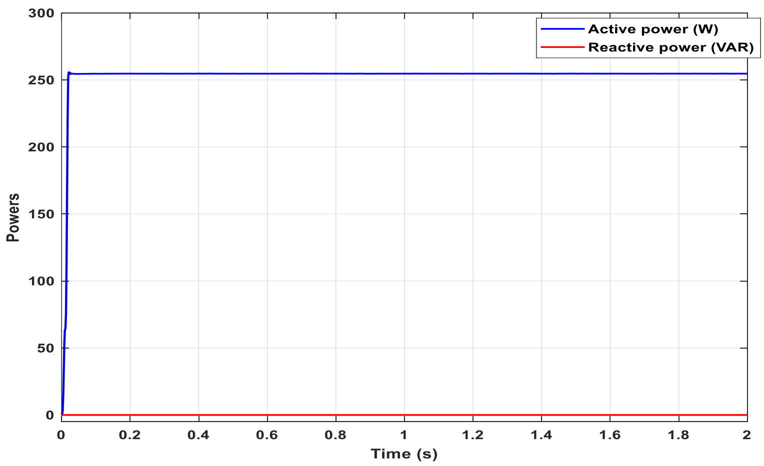


Figure 4.10. Load active and reactive powers.

4.4.2. Test under time varying irradiance level

After that, the system is tested used time varying irradiance level, therefore, a change in irradiance from 1KW/m² to 0.5KW/m² is applied at t=1s. The battery storage charges and discharges compensating the power lack and keeping the DC-voltage at its reference level which is equal to 70V, as illustrated in Figure 4.11.

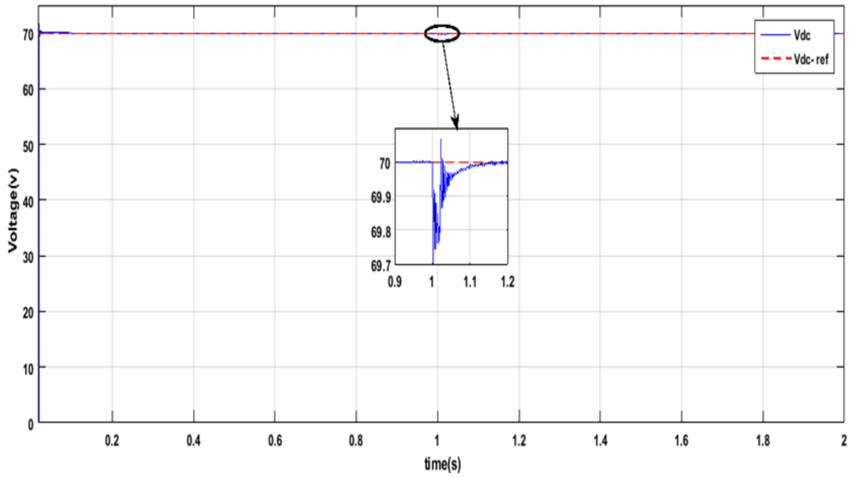


Figure 4.11.DC-link voltage and its reference under time varying irradiance level.

Small perturbations are shown in the delivered load power as in Figure 4.12, the battery discharges to compensate the required power by the load. Also, the THD analysis of both voltage and current signals show a value of 0.15% which is always under the acceptable **IEEE std_519** limits.

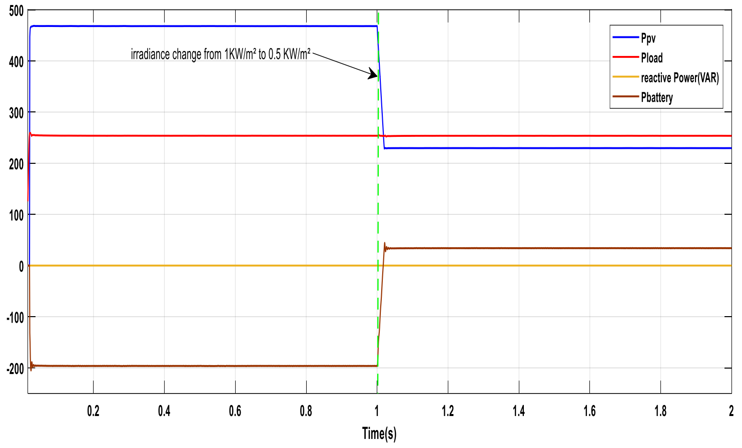


Figure4.12. PV Power, battery power and load power under time varying irradiance level.

4.4.3. Comparison analysis

For further validation of the proposed approach, Table.4.4 illustrates the comparisons between the proposed system and the based scheme without the management algorithm.

Table 4.4.Comparaison analysis

	System without battery and MA	Proposed system
Response time	Medium	Fast
THD (%)	0.33%	0.1032%
Steady state error	High	Low
Cost	Low	Medium
Application of management algorithm	No	Yes
Use of storage device	No	Yes
Validation under varying irradiance condition	No	Yes

In view of that, high improvement is shown in the power quality, efficiency and THD level using the proposed strategy with only 0.1032% THD value compared to 0.33% using the control scheme without battery and MA. This latter does not contain any management algorithm or analysis under fast varying conditions. Thus, the use of battery storage can increase the reliability of the system and satisfy the load energy demand during a lack of production. However, the costs will increase.

4.5. Conclusion

The chapter developed a new management algorithm that can handle the problem of power quality and variable irradiance levels in low voltage applications. The management strategy is associated with an improved controller's loops through the integration of a fuzzy logic controller. First, the fuzzy-MPPT technique used the second power derivation to locate and extract the exact MPP. Then, the improved inner current loops for both bidirectional converter and the H-bridge single-phase inverter has successfully facilitated the control process and improved the power quality (unit power factor, low THD value) respecting the international standards ***IEEE std_519 limits***. The complete system was implemented in MATLAB/SIMULINK platform. Comparisons to the system without the Management strategy show that the proposed one has more robustness, accuracy, fast response and efficiency.

The planned system with the management strategy can be used as a reference for more improvement in DC-PV-Battery MG on one hand, and on the other hand, the fuzzy controller can be effectively applied to further improvements under the PV installation due to its features.

Accordingly, the next chapter will deal with an improved Fuzzy incremental conductance based MPPT technique for grid-connected system and study its performance and effect in improving the power quality under the grid-connected system.

CHAPTER 5 Improved Fuzzy-Inc-Cond for grid connected PV system

5.1. Overview

To ensure the energy quality in rural areas and improve the monitoring process of the DC-MG, the previous chapter handled the control of the energy delivered to load thanks to the fuzzy logic theory. Accordingly, in this chapter, the Fuzzy Logic Control (FLC) proposed in the previous study is combined with the one famous MPPT known as Incremental Conductance (Inc-Cond) for improving the performance and quality of the generated power in grid-connected mode.

The investigated PV system is composed of PVG, DC-DC converter controlled by the proposed Hybrid FL-Inc-Cond MPPT, H-Bridge DC-AC inverter associated with the electrical grid through an L-filter and controlled by VOC strategy using the classical PI technique. The whole system is implemented in MATLAB/SIMULINK software.

The desired objectives to be achieved by the proposed Hybrid FL-Inc-Cond MPPT are:

- Achieving the MPP under different weather conditions;
- Improving the response time to achieve the MPP, and minimizing losses under fast variations of irradiance;
- Enhancing the power quality by decreasing ripples in the output current and voltage, hence, transferring maximum power to the grid;
- Maximizing the tracking efficiency.

5.2. Grid Connected PV system

Figure 5.1 shows the proposed grid-connected PV system. It includes a PVG connected to the DC-link inverter side through a DC-DC boost converter. The switching device of this latter is controlled by means of the proposed Hybrid FL-

Inc-Cond MPPT. Then, the incorporation of the system to the grid is ensured through an H-bridge circuit topology, which is adequate for low voltage applications. L-filter is inserted at the inverter output to eliminate the high-frequency current ripples. A VOC strategy is employed to control the inverter switches states through the classical PI controller and to generate the switching signals through the Pulse Width Modulation (PWM) technique.

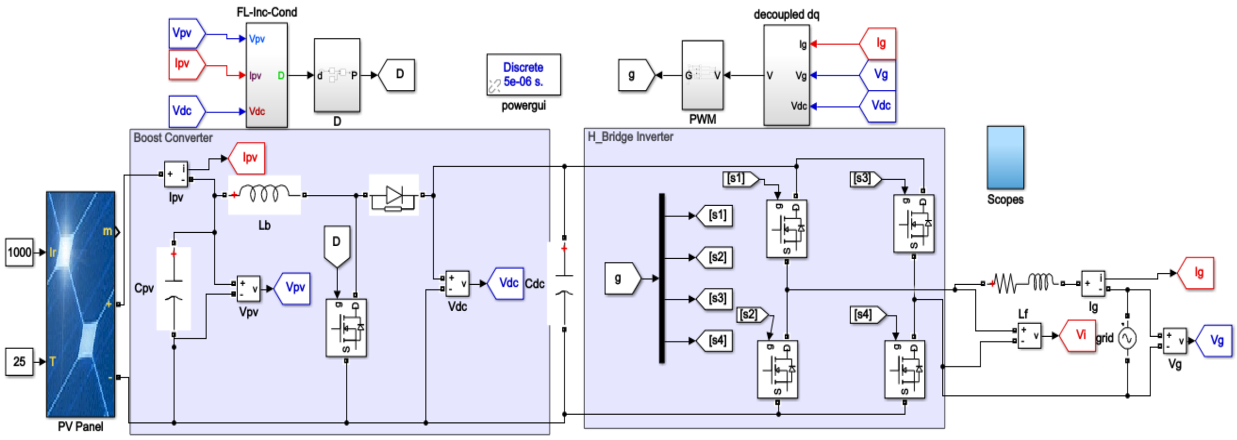


Figure 5.1. Grid connected PV system implementation in MATLAB/SIMULINK.

5.3 Power electronic interfaces design

5.3.1 Boost converter

A DC-DC boost converter is necessary to extract and transfer maximum generated power to the DC-link inverter side and boost the voltage to the desired value. The converter contains an inductor, capacitor and a power switch (MOSFET or IGBT) controlled by an MPPT algorithm.

According to the measured current and voltage at the PVG output side, the MPPT's control varies the duty cycle of the DC-DC converter to track the MPP, as well as, to successfully limit the high current and voltage ripples to obtain high-distributed power quality [76].

Consequently, the well-designed DC-DC boost converter is essential for achieving this goal. This can be done by determining the minimum values of PV output capacitor C_{pvmin}, boost inductor L_{bmin}, and boost capacitor C_{bmin} using the following relationships:

$$C_{pv\min} = \frac{\Delta I_L}{8\Delta V_{pv} f} \tag{5.1}$$

$$L_{b\min} = \frac{V_{pv} D}{2\Delta I_L f} \tag{5.2}$$

$$C_{b\min} = \frac{I_L (1-D) D}{8\Delta V_{pv} f} \tag{5.3}$$

where ΔI_L is the inductor ripple current and $\Delta V_{pv}$is the voltage ripple across the PVG. D is the duty cycle. I_L is the inductor current and *f* is the switching frequency.

5.3.2. H-Bridge inverter output L-filter design

The inverter output inductor (L_f) minimizes the current ripples (ΔI_{Lfrip}) caused by the switching frequency (f_{sw}) of the inverter. Frequently, a ripple of 20% is chosen in the inverter output current to select the L_{fmin}, ΔI_{lfrip} can be expressed as [136][146] :

$$\Delta I_{lfrip/\max} = \frac{V_{dc} T_s}{4L_f} \tag{5.4}$$

The minimum inverter inductor(L_{fmin}) can be obtained as [132]:

$$L_{f\min} = \frac{V_{dc}}{4 f_{sw} \Delta I_{ifrip}} \tag{5.5}$$

It is important to note that, the DC-DC converter and the H-bridge inverter are assumed to have the same switching frequency value ($f=f_{sw}$)to offer a high dynamic response of the system.

5.4. Control design

5.4.1. Proposed Fuzzy-Inc-Cond

In order to maximize power harvested from the PVG and enhancing its efficiency, the design of an appropriate MPPT is necessary. Accordingly, an advanced hybrid FL-Inc-Cond MPPT is proposed by combining FLC and Inc-Cond control techniques. The flowchart of the proposed algorithm is illustrated in Figure 5.2.

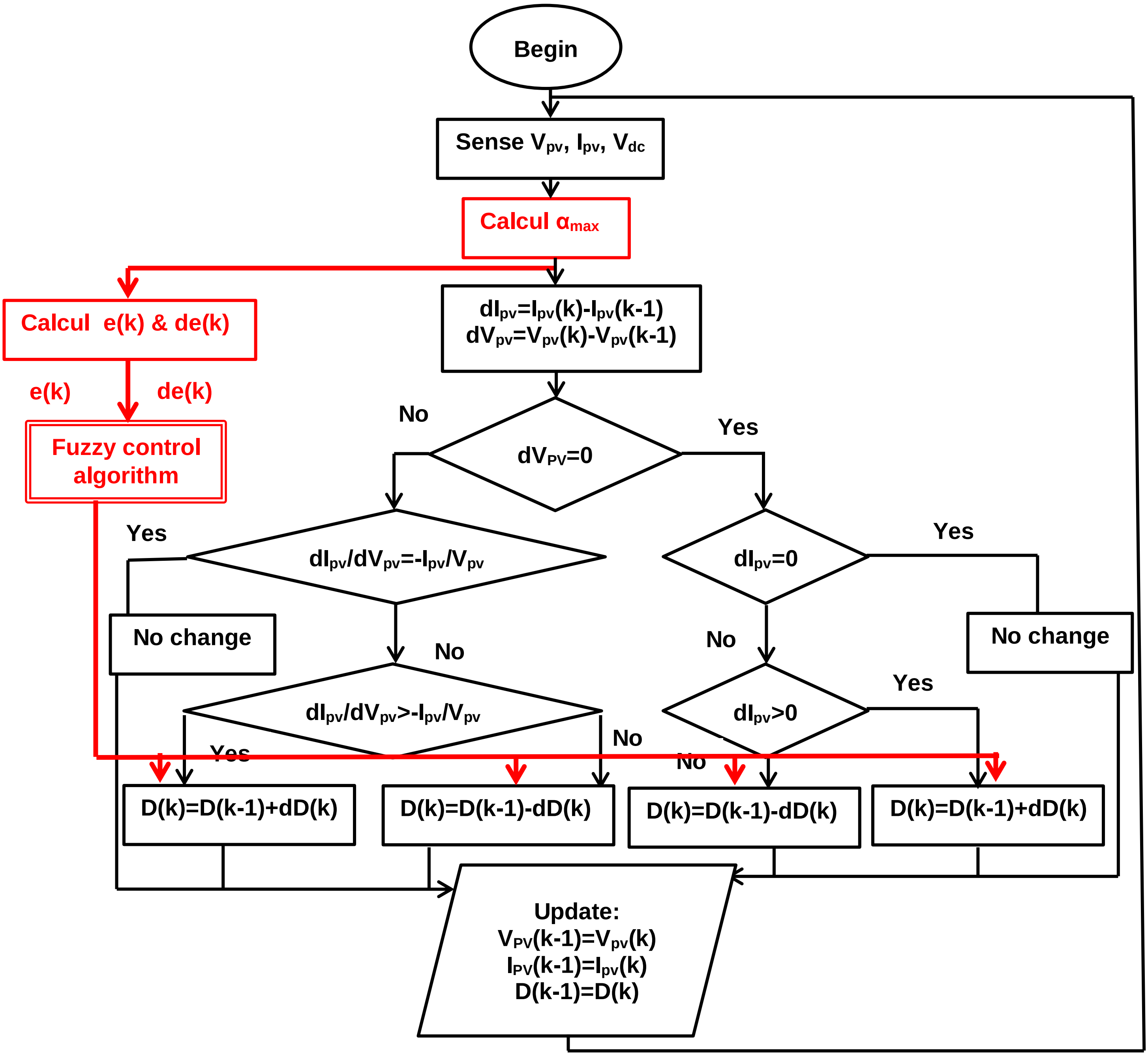


Figure 5.2.The proposed MPPT algorithm flowchart

At first, the algorithm acquires the PV voltage and current (V_{pv} and I_{pv}, respectively), as well as the load voltage (V_{dc}) in order to calculate α_{max} using the Equation. 5.8.

α_{max} is employed as a scaling factor to the FLC input. It represents the ratio between the maximum load voltage (V_{dcmax}) and maximum PV voltage (V_{mpp}). The voltage transfer function of the boost converter is written as [22] [87]:

$$\frac{V_{dc}}{V_{pv}} = \frac{I_{pv}}{I_{dc}} = \frac{1}{1-D} = \alpha \tag{5.6}$$

where V_{pv} and V_{dc} are the PV voltage and load voltage, respectively; I_{pv} and I_{dc} are the PV current and load current, respectively.

D_{max} is selected by employing the maximum PV Voltage (V_{mpp}), maximum power (P_{mpp}) and the resistive load value (R_{load}) according to the following relation

$$D_{\max} = 1 - \frac{V_{mpp}}{\sqrt{P_{mpp} * R_{load}}} \tag{5.7}$$

The value of α_{max} used in the proposed method is computed by considering Equation.5.6 and Equation.5.7 as follows

$$\alpha_{\max} = \frac{1}{1-D_{\max}} \tag{5.8}$$

By obtaining α_{max}, the ratio of the output and input voltage of the boost converter can be expressed using an adaptive α_{max} value as:

$$e(k) = \frac{dV_{dc}(k)}{\alpha_{\max} \times dV_{pv}(k)} \tag{5.9}$$

The variation in the error $E(k)$ can be expressed as

$$de(k) = e(k) - e(k-1) \tag{5.10}$$

Equation.5.9 and Equation.5.10 are used as inputs of the fuzzy system. When the values of e(k) and de(k) are small (i.e. the instantaneous power is approaching the MPP), a small value of dD should be selected by the FLC. However, in the case where e(k) and de(k) are large, a large value of dD should be selected.

e(k) and de(k) are the inputs of the FLC and dD is the output. The input variables are divided into five membership functions: NB, NS, ZE, PS and PB. Therefore, the resulting numbers of rules are 25 processed by the Mamdani fuzzy inference system (with max-min). Table 5.1 recapitulates the used fuzzy rules.

Table.5.1 Fuzzy rules

E(k) / de(k)	NB	NS	ZE	PS	PB
ZE	NB	NB	NM	NS	ZE
NS	NB	NM	NS	ZE	PS
ZE	NM	NS	ZE	PS	PM
PS	NS	ZE	PS	PM	PB
PB	ZE	PS	PM	PB	PB

The defuzzification stage uses seven membership functions (NB: negative big, NS: negative small, NM: negative medium, ZE: zero, PS: positive small, PM: positive medium PB: positive big) alongside the centre of gravity technique for calculating the appropriate step size dD:

$$dD = \frac{\sum_{i}^{n} \mu(D_i) D_i}{\sum_{i}^{n} \mu(D_i)} \tag{5.11}$$

where dD is the control signal provided by the FLC and D_i is the centre of the max-min composition in the output membership functions. The shape of the FLC membership functions are shown in Figure 5.3.

The duty cycle is incremented or decremented by dDthrough carrying out the FLC rules. An accurate duty cycle D is obtained by combining FLC and Inc-Cond MPPT. Variations of the PV voltage (dV_{pv}) and the PV current (dI_{pv}) are calculated as follows

$$dV_{pv}(k) = V_{pv}(k) - V_{pv}(k-1) \tag{5.12}$$

$$dI_{pv}(k) = I_{pv}(k) - I_{pv}(k-1) \tag{5.13}$$

- If dV_{pv} is equal to zero, the variation of PV current (dI_{pv}) is calculated. If dI_{pv} is equal zero, it means that the MPP is achieved and the old value of the duty cycle D(k-1) is kept. If dI_{pv} is higher or lower than zero, the duty cycle D is incremented or decremented, respectively, by a step size dD.
- If dV_{pv} is different from zero, the instantaneous conductance ($\frac{dI_{pv}(k)}{dV_{pv}(k)}$) and the incremental conductance ($\frac{I_{pv}(k)}{V_{pv}(k)}$) are calculated and compared. If no change is detected, D(k-1) is kept. However, if ($\frac{dI_{pv}(k)}{dV_{pv}(k)}$)>-($\frac{I_{pv}(k)}{V_{pv}(k)}$) the duty

cycle is incremented by a step size (dD).Otherwise, the duty cycle is decremented.

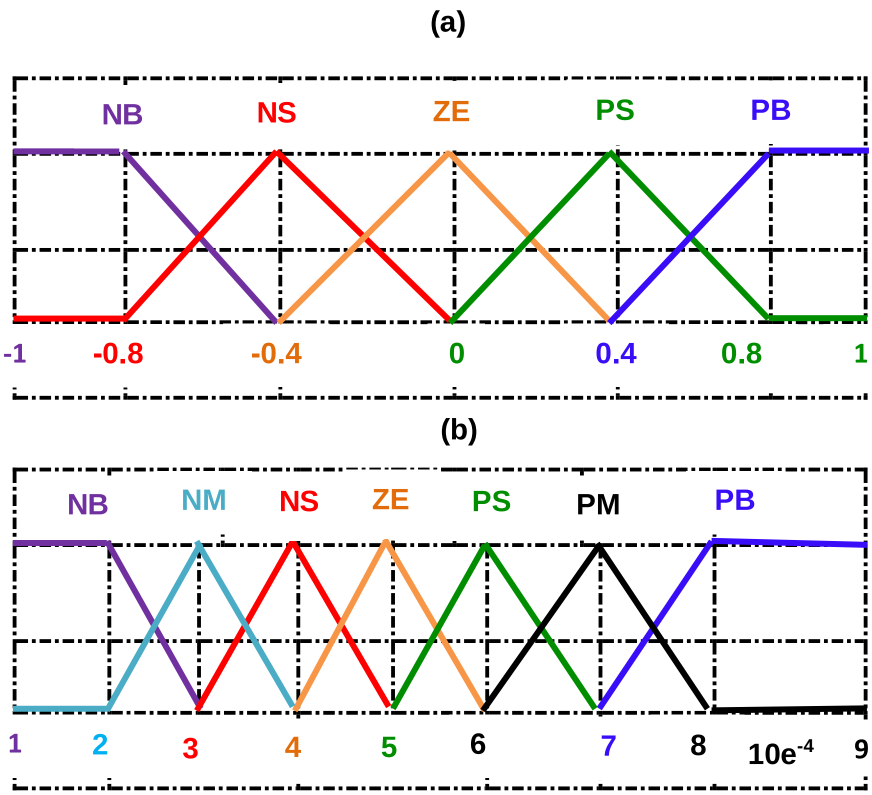


Figure 5.3. Membership functions: (a) Input of FLC: E and dE (b) Output of FLC: dD

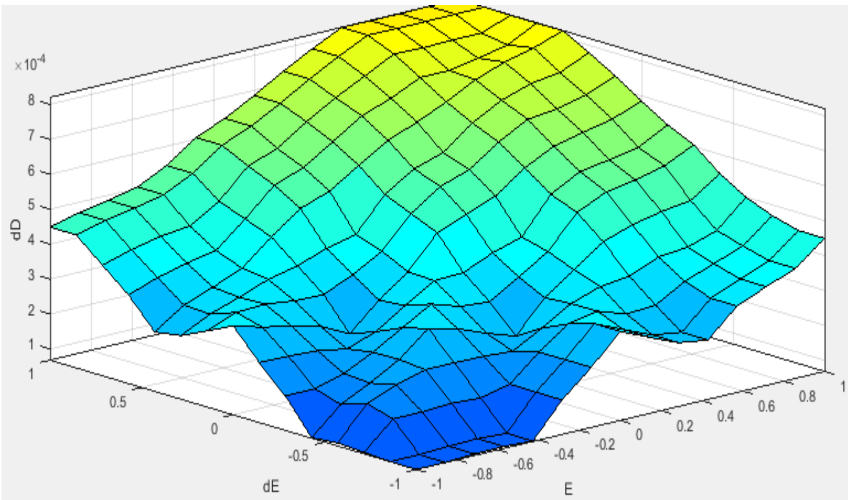


Figure.5.4. Surface viewer for FLC

5.4.2. Inverter side control

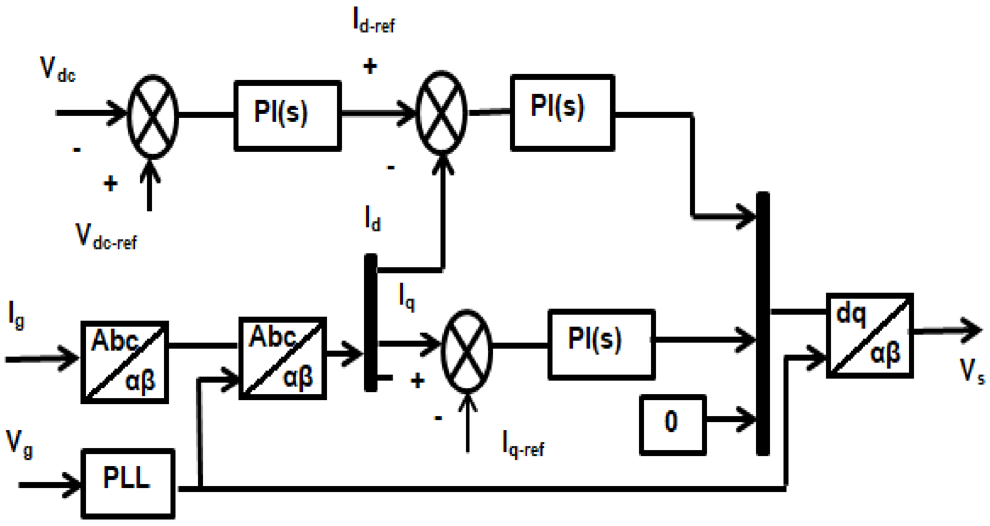


Figure. 5.5. VOC H-bridge inverter control

VOC aims at orienting the current vector regarding the line voltage vector through active and reactive current control [135] .

In the VOC, the grid is considered as a virtual electrical machine. Thus, the inductor (L) and resistor (r) of the filter are equivalent to stator parameters. Whereas, the grid voltage is considered as the induced voltage in the virtual electric machine. In this case, the current and voltage at PCC must be aligned beside the α-axis. Whereas, the main purpose of the β -axis is to ensure the synchronous reference frame transformation [101][105].

The differential equation in the α-β coordinate can be obtained as follows:

$$V_{\alpha\beta} = rI_{\alpha\beta} + L\frac{I_d}{dt} + V_g \tag{5.14}$$

Where $I_{\alpha\beta}$ is the coordinate grid current, $V_{\alpha\beta}$ is the coordinate inverter voltage, and V_g is the grid voltage.

The transformation of the Equation.5.14 to a synchronous reference frame (I_d, I_q) is expressed as:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = L \begin{bmatrix} \frac{dI_d}{dt} \\ \frac{dI_q}{dt} \end{bmatrix} + \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} V_{gd} \\ I_{gd} \end{bmatrix} \quad (5.15)$$

V_d, V_q, I_d, I_q are the direct and quadrature voltages and currents, respectively.

The transfer function of I_d and I_q is presented in Equation.5.16 and schematized in Figure.5.6.

$$\frac{I_{(d/q)}}{I_{(d/q)ref}} = \frac{k_P(k_i s + 1)}{k_i s(sT_i + 1)(sL_f + r_{lf})} \quad (5.16)$$

Where k_p, $k_i$are the proportional and integral gains, T_i is a simple time of the PWM modulation.

The direct (V_d) and quadrature (V_q) voltages commands are obtained from the I_d and I_q control loops. Then $V_{\alpha\beta}$ coordinate are created, where, V_α delivers the reference signal of the modulation algorithm to get PWM inverter signals. Whereas, the V_β signal is not required.

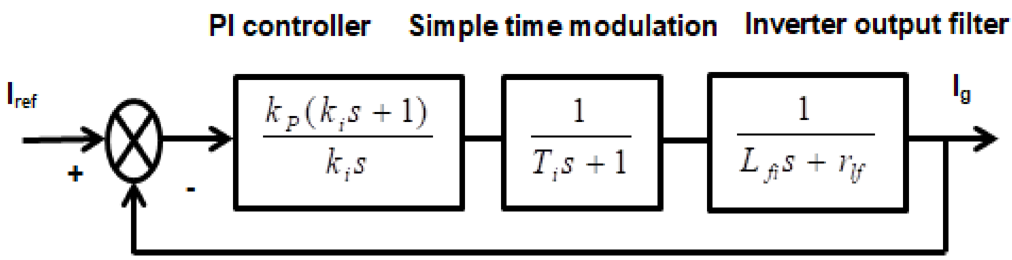


Figure 5.6.Current control loop.

The standard second-order transfer function is defined as

$$G(s) = \frac{k_P w_n^2}{s^2 + 2\zeta w_n^2 s + w_n^2} \quad (5.17)$$

Where$\omega_n = \sqrt{\frac{k_i}{L_f}}$,$\zeta = \frac{k_P + r}{2\sqrt{k_i L_f}}$

ω_n, ζ , L_f and r are natural frequency ,damping ratio of the system, inductor filter and resistor, respectively.

Comparing Equation.5.16 and Equation.5.17, we get the current control gains as:

$$K_p = 2\zeta w_n L_f - r \tag{5.18}$$

$$K_i = w_n L_f \tag{5.19}$$

Obviously, the design of gains defined by the equations must guarantee the stability margins and the dynamic performance.

5.5. Simulation Results

This section is devoted to evaluating the performance of the proposed MPPT. To this end, analyses of many performance indices at different operating conditions, as well as, comparisons with conventional P&O and Inc-Cond for grid-connected mode are carried out. Firstly, the proposed MPPT is evaluated under Standard Test Condition (STC; 1 kW/m² at 25 °C). Secondly, tests under fast varying irradiance conditions are carried out. Finally, a comparison to conventional P&O, Inc-Cond is performed to validate the proposed technique. The MATLAB/SIMULINK software has been employed for implementing the PV system, as shown in Figure.5.1. The simulation parameters are presented in Table.5.2.

Table.5.2. The implemented system parameter settings

	Symbol	Parameter	Value
PV Module	P_{MPP}	Maximum power	334.905 W
	V_{MPP}	Voltage at P_{max}	41.5 V
	I_{MPP}	Current at P_{max}	8.07 A
DC-DC Converter	C_{PV}	PV capacitor	110µf
	L_b	Boost inductance	3 mH
	C_{dc}	DC-Link Capacitor	3300 µf
	f_{sw}	Switching frequency	20KHz
AC side	L_f	Filter inductor	3mH
	r_f	Filer resistor	0.01ohm
	V_g	Grid voltage	220V
	f_{sw}	Switching frequency	20 KHz

5.5.1. Test under STC (1kW/m² at 25°C)

Figure 5.7 shows the measured current, voltage, and power I_{pv}, V_{pv}, and P_{pv}, respectively under STC. Short transient time has been obtained by the proposed MPPT, which is around 30ms.Throughout this operation condition, the instantaneous PV power (P_{pv}) has been maintained at 334 W in steady state, which is the desired maximum power that must be obtained at STC (Figure 5.7.c).As can be seen from Figure 5.7.a. and b, the instantaneous voltage (V_{pv}) and current (I_{pv})are around their maximum values, which are 41.5 V, 8.07 A, respectively.

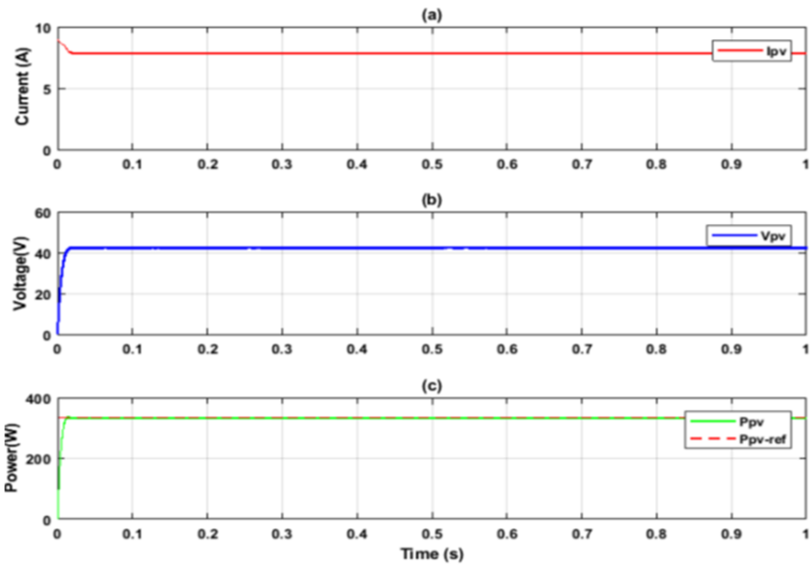


Figure 5.7.PV output (a) current, (b) voltage and (c) Power at STC (25°C & 1 kW/m²)

Figure 5.8.(a) shows the voltage at the inverter DC-side and its reference (V_{dc} and V_{dc_ref}) under STC. It can be noted that the DC voltage has been boosted to the desired level, which is 400V. Therefore, the proposed MPPT is capable of regulating the voltage and minimizing loss. Hence, the inverter output current waveform is purely sinusoidal and also well synchronized with the grid voltage as shown in Figure 5.8.(b). This permits the transfer of maximum power to the grid and ensures a unit power factor. Additionally, the analysis of the THD using MATLAB/SIMULINK POWERGUI for both voltage and current gives values of 0.02% and 1.16%, respectively; which conforms to that given by the **IEEE 519-standard**. The active power exported by the inverter is equal to DC-power while the reactive power rests equal to zero.

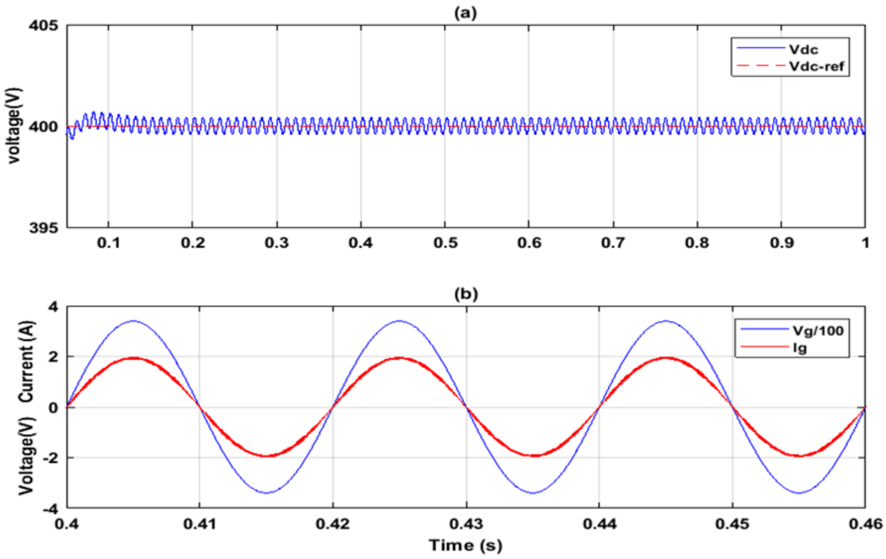


Figure 5.8.(a) DC-link Voltage, (b) PCC Voltage and current

5.5.2. Test under varying irradiance

Environmental conditions are time-varying. Therefore, checking the ability of the proposed MPPT in tracking the MPP under fast variations of irradiance is necessary. This has been accomplished by varying the irradiance many times within a few seconds. Four levels are considered in this test, which are 1kW/m², 0W/m², 0.5kW/m², and 0.9kW/m² MPPs, corresponding to the aforementioned irradiance levels are 334.53W, 0W, 166.2W, and 301.71W, respectively.

As can be seen from Figure 5.9, thanks to the proposed MPPT, the output PV voltage (V_{pv}) and current (I_{pv}) are kept around their maximum values V_{mpp} and I_{mpp}, respectively. This means that the instantaneous power of the PVG achieves the MPP (the red dashed line) for each level of irradiance (Figure 5.9. c).

High performance and stability are shown in the DC-link voltage which is kept around its reference (400V) under irradiance variations applied to the PV system (Figure 5.10). Furthermore, the inverter output current keeps a sinusoidal waveform with variable amplitude (Figure 5.11) staying in phase with the grid voltage. Small THD values are shown in both current and voltage, and the FFT analysis gives values of 1.16% and 0.01%, respectively.

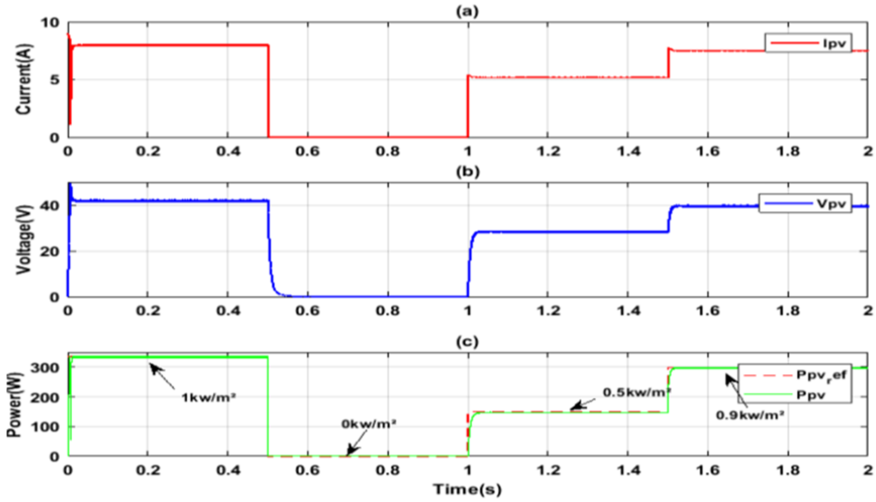


Figure 5.9.PV output (a), current (b) voltage and (c) Power under varying irradiance

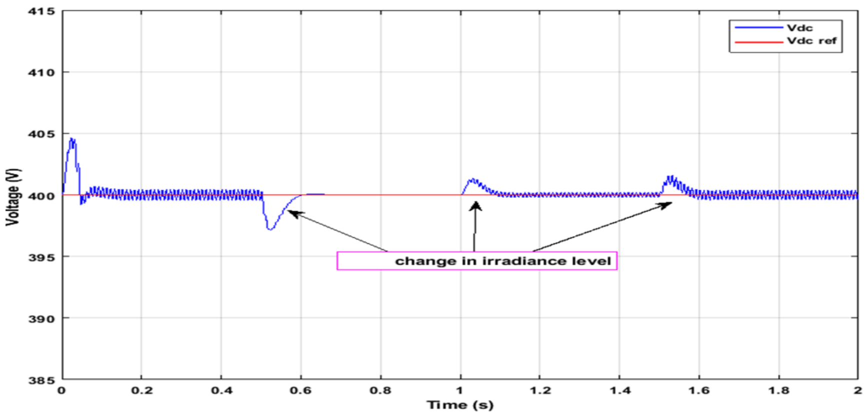


Figure 5.10. DC-link voltage (V_{dc}) under varying irradiance.

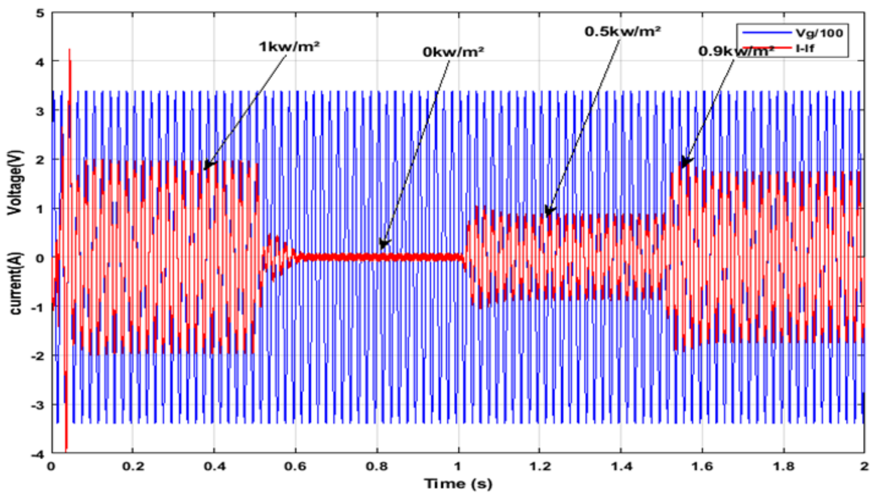


Figure 5.11. PCC Voltage and current under varying irradiance

5.5.3. Comparison with conventional P&O and Inc-Cond MPPTs

In this sub-section, further assessments of performance under fast variations of irradiance and temperature are carried out. To this end, two well-known MPPT methods, namely conventional P&O [32] and Inc-Cond [37] are employed in the present comparison. Results showing waveforms of the PV output power obtained by the proposed MPPT, P&O and Inc-Cond are depicted in Figure 5.12.

Table 5.3 presents a comparison in terms of convergence time, steady-state error, average power at 1kW/m², tracking efficiency, grid current THD and the error (P_{PV}-P_g) between the proposed MPPT, P&O and Inc-Cond. (where P_g presents the grid power)

As can be seen from Table 5.3, the numerical values of convergence time demonstrate superior tracking performance of the proposed MPPT (20 ms). Whereas, P&O and Inc-Cond take around 40.2 ms and 38.9 ms, respectively, to reach the MPP. P&O presents power ripple around the MPP and consequently, lower efficiency in tracking the MPP (around 97.04%), Compared to 98% for Inc-Cond. While the proposed method presents a high tracking efficiency of 99.07%.The power transmitted from the PVG to the grid under the control of the proposed MPPT has a low power loss (around 4 W) due to the control of both the PV voltage (V_{pv}) and the inverter DC-side voltage (V_{dc}), while the power loss using P&O and Inc-Cond is high (6.57W and 8.42 W, respectively).This leads to a low THD in current delivered at PCC 1.16% compared to 1.43% and 2.03% using Inc-Cond and P&O, respectively.

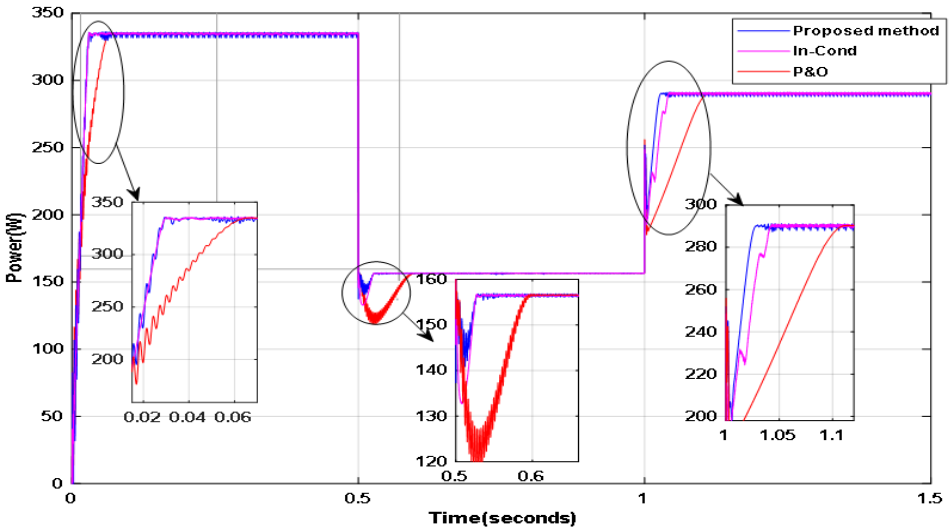


Figure 5.12. PV power extracted by P&O, Inc-Cond and the proposed MPPT under varying of irradiance

Table 5.3. P&O, Inc-Cond and the proposed MPPT Performances

MPPT Methods	T_r (ms)	Steady-state error (W)	Average power at 1000w/m²	Efficiency (%)	Grid current THD(%)	$\lvert P_{PV} - P_g \rvert$ (W)
P&O	40.2	9.9050	325W	97.04	2.03	8.42
Inc-Cond	38.9	5.6924	329.2116W	98.3	1.43	6.57
Proposed method	20	3.1106	331.7904W	99.07	1.16	4.31

5.6. Conclusion

This chapter covered the efficiency and power quality improvement of the grid-connected double stage PV system. To this end, a new contribution of Fuzzy-Inc-Cond is proposed, investigated, and compared to previously developed MPPTs techniques.

The fuzzy controller allows the automatic tuning of the Inc-Cond step size, in order to minimize the power loss between the generation and the grid side. Besides, results show the efficiency of the proposed strategy in minimizing the AC-current distortions (THD), ensuring unit power factor, improving speed convergence, stability, accuracy, and robustness of the system. Moreover, comparisons to the well-known MPPT techniques (P&O and Inc-Cond) showed that FLC-Inc-Cond can effectively deal with the problems meet when using the aforementioned strategies.

Accordingly, the next part of this work will focus on analysing the transition of the system between the grid-connected and islanded modes, Validate the FLC-Inc-Cond to large scale MG, adapt the algorithm to partial shading, and then validate it using hardware implementation.

GENERAL CONCLUSION AND PERSPECTIVES

Conclusion

Among the existing renewable energy sources, the Photovoltaic is the most promising applied technology for power generation in future smart grids. The major advantages of this technology are free cost access, abundant, inexhaustible, and environmentally friendly. The Micro-grid based PV generation is gaining popularity due to the absence of mechanical parts that produced noise during the production.

In this thesis, the power quality control and management of a low voltage DC-MG based on Photovoltaic and battery storage have been presented and analysed. It has been demonstrated that the use of intelligent and improved controllers had advantages in improving the behaviour of the MG with fast dynamics. The control design strategy needs a discrete-time model of the controlled variables to develop the equivalent control rules. Although in this work, only boost, buck-boost (bi-directional) converters and single-phase inverter has been considered, the developed approach could be treated for other kinds of power electronic devices.

The management of the standalone PV-Battery micro-grid through an improved HC-PSO based MPPT and CV-CC is integrated to control the battery charge and discharge process, and to maintain the DC-link voltage. It has been demonstrated that the MPPT using HC-PSO combined with the management strategy improved the efficiency and the quality of the delivered power. Whereas, the double loop of CV-CC Control which is fulfilled using conventional PI maintained the balance power at load level. The outer loop maintains the DC-voltage and adjusts the inner loop reference current in order to balance power accurately between battery and load side during the discharging mode (or CV mode). However, during CC mode the battery charges when its SoC and voltage are lower than their nominal values. The whole controller has been implemented and validated in MATLAB/SIMULINK. It is demonstrated by analysing the results that a suitable regulation of the DC-Link voltage is achieved using the management algorithm and under three different scenarios: standard conditions (1KW/m^2-25°C), varying weather conditions, and partial shading. Also, the results proved the effectiveness, high reliability, and efficiency of the proposed HC-PSO in dealing with such phenomena.

On the other hand, an improved management strategy is applied to a PV-Battery MG in a double-stage single phase inverter to ensure the management and to improve the quality of the power delivered to the load at the inverter AC-side. To this end, an improved Fuzzy MPPT is applied to extract maximum available power from the PVGs. Moreover, the fuzzy control is applied in the inner current control loops of both battery and inverter. Whereas, an analogue PI controller was implemented for the outer loops. An important improvement has been reached in the quality of both load current and voltage with reduced THD values. Moreover, appropriate DC-Link voltage regulation is achieved through the considered intelligent management technique.

Furthermore, to ensure the stability and the power quality of the grid-connected PV system, and to surmount the drawbacks of the existing P&O and Inc-Cond, an improved Fuzzy-Inc-Cond is developed. This algorithm is applied to automatically adjust the variations of the duty cycle investigating the relationship between DC-link voltage and PV voltage. Besides, the VOC is applied using PI controllers in the second stage and improved its performance in maintaining pure sinusoidal current and voltage curves which are in phase (ensure a unit power factor) with low THD values respecting the international standards such as **IEEE-1547** which is used to standardize the power quality of the local power injection.

Single-phase H-bridge inverters usually used to interconnect the low voltage micro-grid DC-side to AC-loads and the utility grid, so as to, guarantee that the power quality encounters grid standards. Simulations were performed on the MATLAB/SIMULINK platform to test the performance of the proposed Micro-grid. The modelling of PV array and module using MATLAB-Simulink is done. The discussion about the effects of various operating conditions on PV characteristics is presented where the results proved the high response time of the proposed controllers under steady-state and dynamic conditions, improved quality, reliability, efficiency, stability and performances of the different proposed controllers.

Perspectives

Future work directions derived from my thesis could be focused on:

- The validation of the designed controllers under different power quality problems incorporating during both operating modes of the MG : grid-connected and islanded modes;
- The inclusion of hybrid generation using different renewable and conventional micro-sources such as Wind, hydraulic, tied, fossil fuel;
- The integration of hybrid storage to perform the management and continuality of the energy delivered to load during day and night for long period , and enhance the lifetime of the storage devices;
- The Validation of the proposed controller experimentally using Dspace;
- The design and implementation of those prototypes in an FPGA-based control board;
- The enhancement of the economic benefits and management of the system at the investment layer and reduce the prices;
- The development of new controllers to improve the extraction, transfer and the optimization of the MG operating, so as to, achieve smart grid and to realize smart cities;
- The suggestion of new intelligent management strategies to deal with all the phenomena hinders the work of the MG;
- The Combination of the proposed DC-MG with the AC-MG and the integration of advanced controllers to manage and to ensure high power quality of the system.

APPENDICES

APPENDIX A: LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
AC	Alternative Current
ACO	Ant Colony Optimization
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
CC	Constant Current
CS	Cuckoo Search
CV	Constant voltage
DC	Direct Current
DE	Differential Evolution
DES	Distributed Energy Source
EMS	Energy Management System
FA	Firely Algorithm
FLC	Fuzzy Logic Control
FOCV	Fractional Open Circuit Voltage
FSCC	Fractional Short Circuit Current
HC	Hill Climbing
Inc-Cond	Incremental conductance
GA	Genetic Algorithm
GMPP	Global Maximum Power Point Tracking
LMPP	Local Maximum Power Point Tracking
MA	Management Algorithm
MG	Micro-Grid
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
P&O	Perturb and Observe
PCC	Point of Commune Coupling
PID	Proportional Integral Derivative

PV	Photovoltaic
PSC	Partial Shading Condition
PSO	Particle Swarm Optimization
PVG	Photovoltaic generator
PWM	Pulse Width Modulation
RCC	Ripple Correlation Control
SC	Soft Computing
SoC	State of Charge
SSO	Slap Swarm Optimization
STC	Standard Test Condition
T-S	Takagi-Sugeno

APPENDIX B: LIST OF SYMBOLS

IMPP	Current at Pmax [A]
Iph	PV cell light current [A]
Ipv	photovoltaic generator output current [A]
Isc	short circuit current [A]
k	Boltzmann's constant (1.38×10-23 [J/K])
n_p	number of PV cells connected together in parallel [ ]
n_s	number of PV cells connected together in series [ ]
P_{MPP}	Maximum power [W]
P_{pv}	photovoltaic generator output power [W]
q	Charge of an electron (1.602×10^{-19} [C])
R_p	PV cell shunt resistance [A]
R_s	PV cell series resistance [Ω]
T	PV cell temperature (in [Kelvins] or [Degrees celsius])
V_{MPP}	Voltage at Pmax [V]
V_{oc}	open circuit voltage [V]
V_{pv}	photovoltaic generator output voltage [V]
P	Active Power [W]
Q	Reactive Power [VAR]
S	Apparent Power [VA]
$\cos(\varphi)$	Power factor [ ]
I_{bat}	Battery Current [A]
I_{bat}^*	Reference battery Current [A]
SoC	State of Charge [%]
V_{dc}	DC-Link Voltage [V]
V_{dc}^*	DC-Link reference Voltage [V]
V_{bat}	Battery Voltage [V]
V_{bat}^*	Battery Reference Voltage [V]
SoC_0	Initial state of charge
L_{bat}	Battery current [mH]
R_{dc}	Output DC resistance [Ω]
C_{dc}	Output capacity [µf]
f_S	Switching Frequency [KHz]
f_n	Nominal frequency [Hz]
C	Rated Battery Capacity [Ah]
P_{dc}	DC Load power [W]
η	Efficiency [%]
f_r	Resonance frequency [Hz]
V_s	voltage measured at the output of the LC filter [V]
V_{inv}	voltage measured at the output of the inverter [V]
L_f	the filter's inductance [mH]
C_f	the filter's capacitor [µf]
R	The load resistance [Ω]
$I_{\alpha\beta}$	The coordinate grid current [A]
$V_{\alpha\beta}$	The coordinate inverter voltage [V]

V_g	The grid voltage.[V]
V_d	The direct Voltage [V]
V_q	The quadrature voltage [V]
I_d	The direct current [A]
I_q	The quadrature current [A]
I_g	The grid current [A]
ω_n	Natural frequency [rad/s]
ζ	Damping ratio
w	Inertia weight
C_1	Personal learning coefficient
C_2	Global learning coefficient
r_1, r_2	Random quantities

PUBLICATIONS AND CONFERENCES

Publication

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