Maximum Power Point Tracking of a Network-Connected Photovoltaic System Based on Gravity Search Algorithm and Fuzzy Logic Controller

M. Hossein Mehraban Jahromi[1,*], Hossein Dehghani Tafti[2], S. Mehdi Hosseini[3], Ahvand Jalali[4] and Mehran Keivanimehr[5]

[1]Department of Electrical Engineering, Islamic Azad University, Neyriz branch, Neyriz, Iran; [2]University of New South Wales, Sydney, Australia; [3]Department of Electrical Engineering, Islamic Azad University, Science and Reserch, Tehran, Iran; [4]Universitu of Melbourne, Melbourne, Australia and [5]Department of Electrical Engineering, University of Kashan, Kashan, Iran

Abstract: This paper presents a novel hybrid approach based on fuzzy logic controller and gravity search algorithm to track the global maximum power point of a network-connected photovoltaic system in partially shaded conditions. One of the most critical issues in this context, which has been neglected in previous studies, is the consideration of speed and accuracy at the same time. Hence, this paper uses a boost converter with a fuzzy logic controller to increase the model's accuracy. Also, the speed of the method is increased by utilizing the gravity search algorithm. Finally, maximum power is subjected to a power network via a three-phase multi-level inverter. Simulation results show the proposed method's performance and accuracy in tracking the PV system's maximum power point with high-speed responses in partial and variable shadow conditions.

Keyword: Maximum Power Point Tracking, Photovoltaic System, Fuzzy Logic controller, Gravity Search algorithm.

1. INTRODUCTION

Photovoltaic systems are the most popular, suitable, and ideal types of Distributed Energy Resources (DER) and Distributed Generation Systems. These systems are not economical in large-scale power stations due to variations in environmental factors, such as radiation and temperature, and the impossibility of constructing spaces for very high voltage transmission systems [1, 2]. Generated power of a photovoltaic panel is entirely dependent on solar radiation on its surface. The amount of radiation received by the PV panel depends on various factors such as geographical location, radiation time, season, local climate, and radiation angle [3, 4]. Computational modeling of photovoltaic systems and using the systems' simulations are necessary because of the system implementation's high costs. According to recent studies, appropriate solar cell modeling in accordance with a real panel and its datasheet is the essential part of the simulation section. Besides, to use the solar energy source more effectively, control methods should be used to track optimum operation point under continuous changes of environmental conditions. These methods are known as Maximum Power Point Tracking (MPPT). MPPT is a control technique of Power Converters that presents excellent results on photovoltaic chains [5, 6]. This technique makes PV systems work around the maximum power point by matching the load impedance to the source impedance [7]. MPPT techniques are crucial for each solar system, despite having non-linear characteristics.

In this algorithm, at first current and voltage of the PV array are measured and delivered to the MPPT block to gain maximum powerpoint in a specific operating cycle. Then MPPT matches the voltage and current of this point with the converter. The MPP is not fixed steadily and varies with changes in temperature and radiation levels. Due to this dynamic, the controller should track MPP by updating the converter's duration at any time. Controllers that are quicker in MPPT tracking can demonstrate better results. Due to the introduction of a large number of MPPT methods, they can be classified into two group based on their difficulty: traditional methods such as Perturb and Observe(P&O), Incremental Conductance (IncCond), Look-Up Table, Constant Voltage and Short-Current Pulse methods, and advanced ones such as methods based on fuzzy algorithms and neural cells. The simplest MPPT control method is the Constant Voltage (CV) algorithm. It assumes that insulation and temperature variations are insignificant on the MPP voltage and that the constant reference voltage, VREF, is an adequate approximation of the real MPP. Because of this Connivance, the operating point is not precisely the MPP [8, 9]. The Short-Current Pulse (SC) method assumes a reference current, IREF, and apply

*Address correspondence to this author at the Department of Electrical Engineering Islamic Azad University, Neyriz Branch, Neyriz, Iran; E-mail: hmehraban82@gmail.com

E-ISSN: 2410-2199/20

its measurement to the power converter controller to achieve the MPP [10]. The IncCond algorithm is based on the following equation holds at the MPP [10]:

$$\left(\frac{dI_{PV}}{dV_{PV}}\right)+\left(\frac{I_{PV}}{V_{PV}}\right)=0 \tag{1}$$

This method is based on the fact that the slope of the P-V curve of the PV array is zero at the MPP point. It has been introduced for extreme environmental conditions variations [11] where IPV and VPV are the PV array current and voltage, respectively. This algorithm decrements or increments the PV array voltage VPV to track a new MPP. It offers a good performance under rapidly changing atmospheric conditions. P&O Method has the most repetition in researches and is utilized wildly in commercial products. It operates by periodically incrementing or decrementing (perturbing) the array terminal voltage and comparing the PV output power with that of the previous perturbation cycle. The P&O algorithm's main problem is that the array terminal voltage is perturbed every MPPT cycle; therefore, when the MPP is reached, the output power oscillates around the maximum point, reducing the generable power by the PV system. So this algorithm works more effectively in stable or slowly-varying atmospheric conditions but gets away from MPP under rapidly changing atmospheric conditions [12, 13]. In the Look-Up Table method, at first maximum power point of a PV system for every atmospheric condition is calculated and stored in MPPT memory. During operation, corresponding to the work environment, MPPs are called from memory and used. In this method, a PI controller tunes the duty cycle for the converter. Output signals of the PI controller, in other words, errors, will be zeros when the current and power of PV are equal to IMPP and Pmax, respectively. Every change in radiation level and system load creates confusion in the tuning system, so the PI controller must restore the system to the optimal operation point. This method's disadvantage is that it requires large memory for storing all possible data [14, 15]. To compare MPPT methods, we can study every technique's power response to radiation level variations. P&O, Look-Up Table, and IncCond methods refer to reference voltage then consider changes in the systems' output power; it is obvious that P&O and IncCond methods can be more effective in comparison with the Look-Up Table method in nominal voltage tracking. However, there are significant differences between these two methods and their accuracy. P&O steady-state error for all radiation levels is approximately equal, while this error for the IncCond method in a specific radiation level is much less than the other radiation levels.

On the other hand, it can be seen that the output power will decree by increasing the system temperature. Also, the Look-Up Table method cannot follow MPP and its changes. Around 25°C, the IncCond method shows a good approximation of input, but in higher temperatures, the steady-state error of this method will increase. The P&O method has the same steady-state error in all temperatures, and it means that we can fix this error in all temperature and radiation levels by set gains of the PI controller [16-19]. This article presents a reliable model of complex solar system simulations (especially solar cells). Also, the main challenges of the MPPT process (famous types) are discussed. After that, an optimized method based on gravity law and using a Fuzzy boost converter will be introduced. And finally, simulation results of the proposed system will be presented.

2. SYSTEM CONFIGURATION:

Photovoltaic systems, composed of interconnected components, can be used in energy generation for one or a set of loads by determined demands in off-grid and on-grid mode. In on-grid systems, the inverter circuit controls the active and reactive power based on network requirements. In contrast, in off-grid systems(island mode) inverter tunes the frequency and voltage parameters of consuming instruments and keeps them at desired level [20]. Now on-grid style is a pervasive utilization of these systems in practice. It allows consumers to supply their energy without environmental destruction [21]. If a PV system is used by another power source such as a wind turbine or diesel generator, it is considered a hybrid system. Control of Photovoltaic systems is not limited to local controls (such as inverter and battery control). For on-grid systems, a central control unit can support the system in critical loads. A general block diagram of an experimental PV system is shown in Figure **1**.

Power electronic converters must deliver power appropriately and efficiently to the user. These features are needed in PV systems to convert DC voltage to the desired scale, convert from DC to AC or vice versa [22]. Furthermore, these converters control the battery charge and discharge in systems based on batteries. So converters are used in all types of PV systems. DC to DC converters are divided into three basic topologies named BUCK, BOOST, and BUCK-BOOST. In PV systems, the BUCK converter, due to the simplicity and

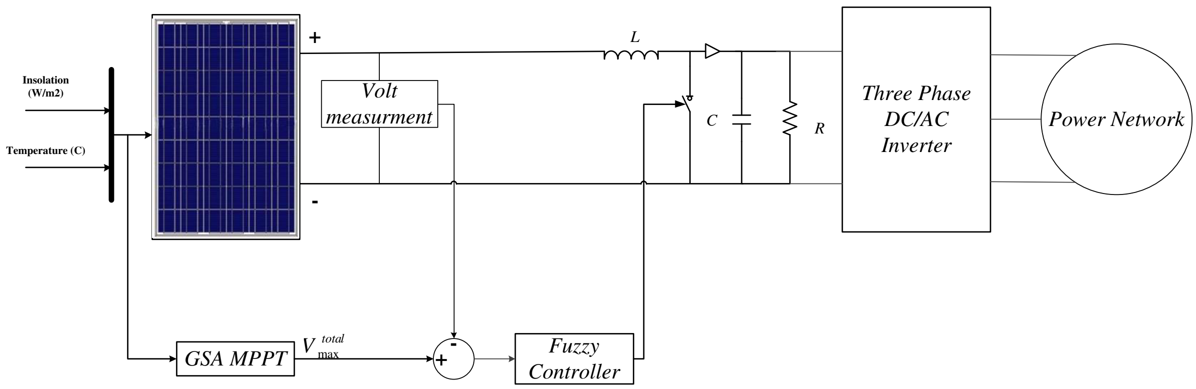

Figure 1: Block diagram of experimental PV system [20].

high efficiency, plays an important role [23]. BOOST converter increases the voltage to the desired level. This converter is generally used in its classic form due to voltage stress, low flexibility, and low error tolerance. It is also not appropriate for voltage control in solar array tracking [24-26]. BUCK-BOOST converter can increase or decrease output voltage and is used in PV systems to operate in maximum power point [27]. Inverters convert direct current to alternating current in single-phase or multi-phase form. Improvements in Power electronic converters technology to merge Distributed Energy Resources (DERs) with the network or in island mode in microgrids leads to improve abilities of this converter on many issues related to the system[28, 29].

3. PHOTOVOLTAIC CELL MODELING

PV cell model is the most important part of each PV system simulation. It is desired that the simulated model has the most similarity to a real PV cell's physic-cal behavior. So it must match the V-I characteristic in all operating conditions. To simplify the behavior of a real photovoltaic cell, we used a cell model with a single diode. This model is shown in Figure **2** [30].

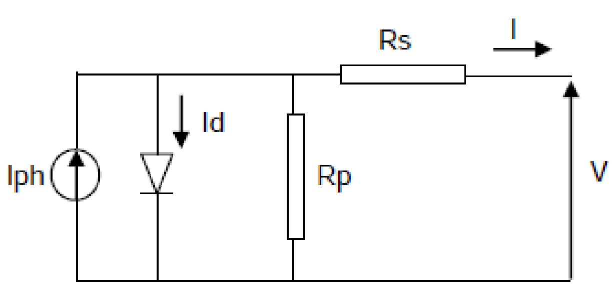

Figure 2: Practical equivalent circuit of a real solar cell [36].

The practical equivalent circuit has following parameters:

- Temperature dependency has been modeled by a diode with reversed saturation current Id.
- Temperature dependency of radiation has been modeled by a current source Iph.
- Shunt resistance R_P, in parallel with the diode, corresponds to leakage current to the ground. R_P effect increases when operation point is in area of current source
- Series resistance Rs (internal losses) gives a more accurate shape between the maximum power point and the open-circuit voltage. It has more effect when the operation point is in the area of the voltage source.

This model can be described by the following equation:

$$I = I_{ph} - I_{sat}\left[\exp\left(\frac{V + R_s I}{aV_t}\right)\right] - \frac{V + R_s I}{R_P} \quad (2)$$

Where I_{sat} is the reverse saturation current of the diode, a is a non-ideality factor of the p-n junction, $V_t = \frac{q}{kT}$, I, and V are the output current and output voltage of the PV cell [31]. This model has been simulated using the Matlab/Simulink. . I–V and P–V characteristic curves can be seen in Figure **3**.

In designing a fast and reliable PV system, using an efficient, fast, and accurate simulation model is necessary. Besides, information obtained from simulation like analysis of PV systems' characteristics under particular or unusual circumstances and weather conditions, such as partial shade or rapid radiation or temperature changes, can be valuable [38]. The most popular model is the electrical equivalent circuit that will include both linear and nonlinear components. Many models have been proposed, like the elementary diode model, Rs and Rp models, two and three diode models [31-33].

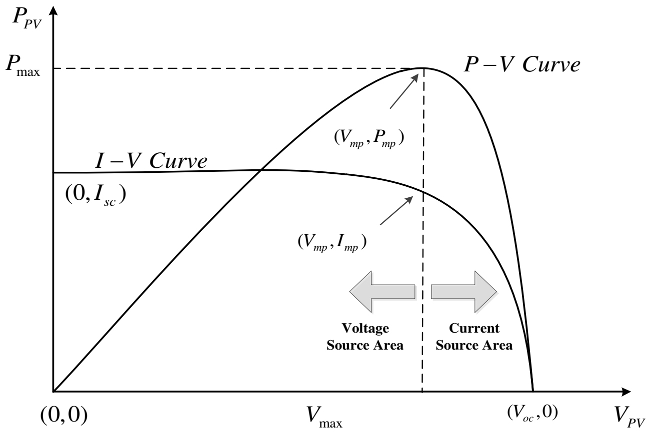

Figure 3: I–V and P–V characteristic curves.

4. PROBLEM STATEMENT AND SOLUTION PROCEDURE

In PV systems, the MPPT process plays a vital role in increasing the system's output power. Using novel methods with appropriate speed and minimum error can improve the process. The main sections of the PV system which can be useful in this issue are the DC-DC converter and MPPT control unit. An optimized control unit can improve the MPP detection process such that select a closer point to MPP based on novel algorithms faster. The purpose of the converter improvement is to use effective and fast algorithms in tracking MPP, which is detected by the control unit. So in this paper, a novel optimized method based on the law of gravity to detect MPP and a fuzzy boost converter is proposed to track this point rapidly.

4.1. Optimization Method

In this section, a novel optimization algorithm based on the law of gravity will be introduce [34]. In the proposed algorithm, agents are considered as objects and their performance is measured by their masses. All these objects attract each other by the gravity force, and this force causes a global movement of all objects towards the objects with heavier masses. Hence, masses cooperate using a direct form of communication through gravitational force. The heavy masses – which correspond to good solutions – move more slowly than lighter ones; this guarantees the exploitation step of the algorithm.

In GSA, each mass (agent) has four specifications: position, inertial mass, active gravitational mass, and passive gravitational mass. The position of the mass corresponds to a solution of the problem, and its gravitational and inertial masses are determined using a fitness function.

In other words, each mass presents a solution, and the algorithm is navigated by properly adjusting the gravitational and inertia masses. By lapse of time, we expect that masses be attracted by the heaviest mass. This mass will present an optimum solution in the search space. The GSA could be considered as an isolated system of masses. It is like a small artificial world of masses obeying the Newtonian laws of gravitation and motion. More precisely, masses obey the following laws:

Law of gravity: each particle attracts every other particle and the gravitational force between two particles is directly proportional to the product of their masses and inversely proportional to the distance between them, R. We use here R instead of R2, be-cause according to our experiment results, R provides better results than R2 in all experimental cases.

Law of motion: the current velocity of any mass is equal to the sum of the fraction of its previous velocity and the variation in the velocity. Variation in the velocity or acceleration of any mass is equal to the force acted on the system g divided by mass of inertia.

Now, consider a system with N agents (masses). We define the position of the ith agent by:

$$X_i = (X_i^1, \ldots X_i^d, \ldots X_i^n) \quad ,for \quad i = 1,2,\ldots,N \tag{3}$$

Where x_{di} presents the position of i_{th} agent in the d_{th} dimension.

At a specific time ‘t’, we define the force acting on mass ‘i’ from mass ‘j’ as following:

$$F_{ij}^d(t) = G(t)\frac{M_{aj}(t) \times M_{Pi}(t)}{R_{ij}(t)+\varepsilon}(x_j^d(t) - x_i^d(t)) \tag{4}$$

where Maj is the active gravitational mass related to agent j, Mpi is the passive gravitational mass related to agent i, G(t) is gravitational constant at time t, e is a small constant, and Rij(t) is the Euclidian distance between two agents i and j:

$$R_{ij}(t) = \left\| X_i(t), X_j(t) \right\|_2 \tag{5}$$

To give a stochastic characteristic to our algorithm, we suppose that the total force that acts on agent i in a dimension d be a randomly weighted sum of dth components of the forces exerted from other agents:

$$F_i^d(t) = \sum_{j=1, j\neq i}^{N} rand_j(t) F_{ij}^d(t) \tag{6}$$

where randj is a random number in the interval [0, 1].

Hence, by the law of motio n, the acceleration of the agent i at time t, and in direction dth, adi

ðtÞ, is given as follows:

$$a_i^d(t) = \frac{F_i^d(t)}{M_{ii(t)}} \tag{7}$$

Where Mii is the inertial mass of ith agent.

Furthermore, the next velocity of an agent is considered as a fraction of its current velocity added to its acceleration.

Therefore, its position and its velocity could be calculated as follows:

$$V_i^d(t+1) = rand_i \times V_i^d(t) + a_i^d(t) \times t \tag{8}$$

$$X_i^d(t+1) = x_i^d(t) + V_i^d(t+1) \times t \tag{9}$$

$$G(t) = G(G_{0,t}) \tag{10}$$

5. FUZZY BOOST CONVERTER

The fuzzy boost converter is used to convert the three-phase ac voltages to a dc voltage that is used to supply the dc load and energize the battery. The fuzzy logic converter has found many applications in the past decade. This is so largely because the fuzzy boost converter has the capability to control non-linear, uncertain system even in the case where no mathematical model is available for the control system. There are four important elements in the fuzzy logic control system structure, which are the identification of input and outputs, membership functions, fuzzification method, and inference method. Details of the fuzzy logic controller system structure have been shown in Figure **4**.

As can be seen in Fig. (**4**), The fuzzy logic converter consists of two parts: a three-phase full-bridge diode rectifier that rectifies the generator output voltages and a dc-dc converter that controls the output dc voltage of the rectifier. The dc-dc converter is used to convert the diode rectifier output voltage into a regulated dc voltage against load and input voltage variations. It also reduces the ac voltage ripple on the dc output voltage below the required level and provides isolation between the input source and the load [35]. The dc-dc converter is controlled by a fuzzy logic controller, which stabilizes and regulates the output dc voltage at 110V. The schematic of the dc-dc converter and the PID controller is shown in Fig. (**5**). All of the diode rectifier, dc-dc converter, and fuzzy logic controller is implemented and modeled in the Simulink environment.

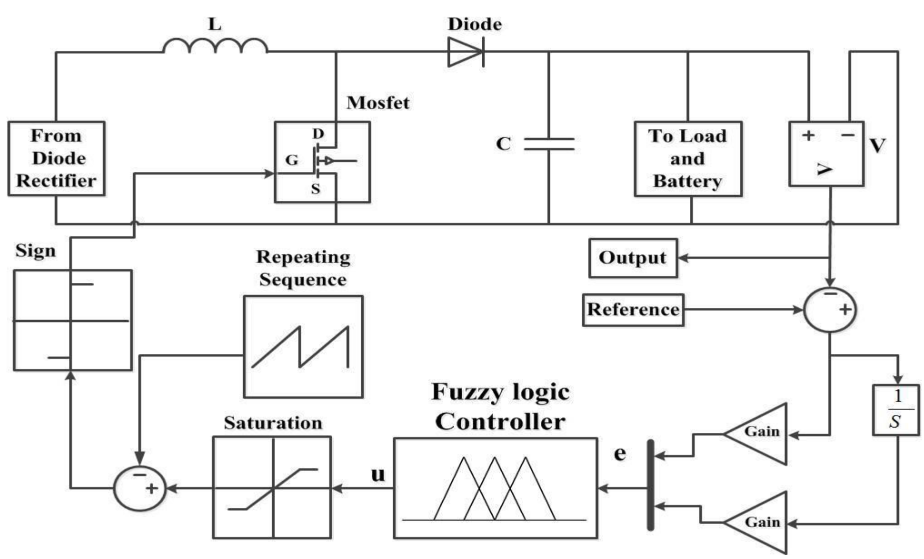

Figure 4: The dc-dc Converter with fuzzy logic Controller.

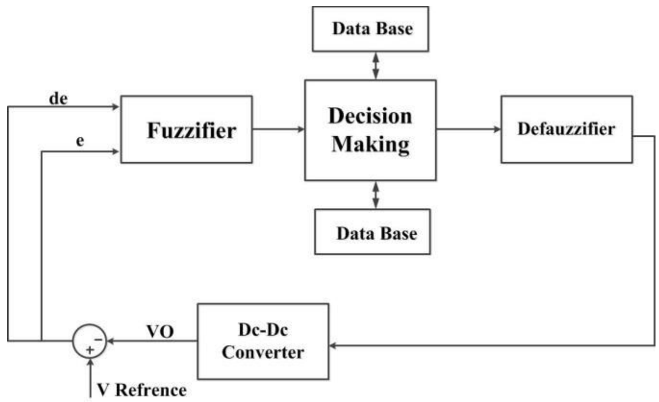

Figure 5: Block Diagram of Fuzzy Logic Controller.

5.1. Identification of input and output's Parameters

This step is done to identify the key inputs that affect the system performance and to ensure that the output voltage matches the reference voltage. The inputs of the fuzzy controller are:

1. The voltage error (e) (reference voltage subtracted from actual voltage).

2. The change of the voltage error(de) (previous error subtracted from current error) over the sample period.

5.2. Membership functions

A fuzzy set must be defined for each input and output variable, as can be seen in Fig. (**6-8**). There are five fuzzy subsets: PB (Positive Big), PS (Positive Small), ZE (zero), NS (Negative Small), NB (Negative Big) has been chosen for input variable error (e) and change of error (de). The Triangular and trapezoidal shapes have been adopted for the membership functions; the value of each input and output variable is normalized in [-1,1] by using suitable scale factors.

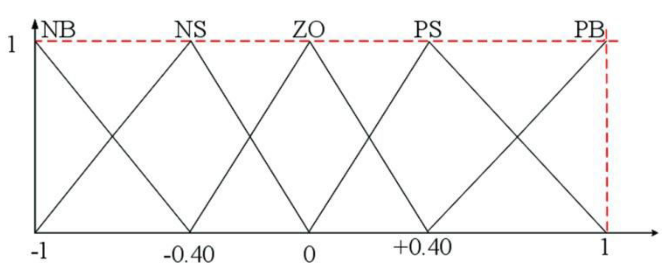

Figure 6: The Membership Function plots of error.

5.3. Fuzzification Methode

Fuzzification is the process of making a crisp quantity fuzzy. Before this process is taken into action, the definition of the linguistic variables and terms is needed. Linguistic variables are the input or output variables of the system whose values are words or sentences from a natural language instead of numerical values. A linguistic variable is generally decomposed into the asset of linguistic terms. Next, to map the non-fuzzy input or crisp input data in fuzzy linguistic terms, membership functions are used in quantifying a linguistic term.

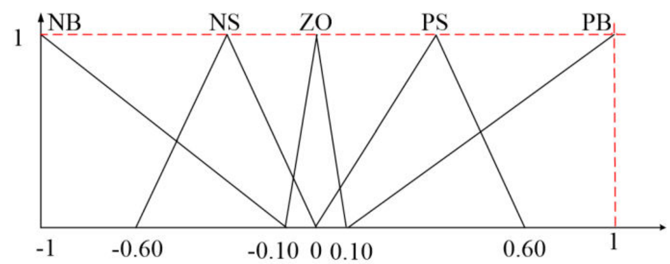

Figure 7: The Membership Function plots of change error.

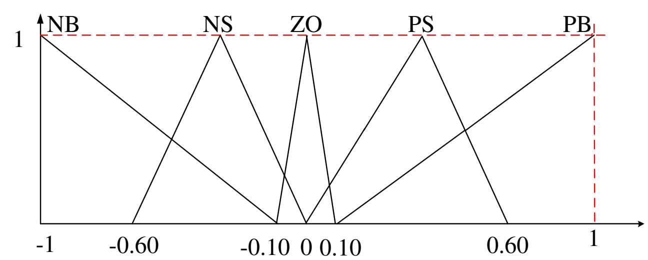

Figure 8: The Membership Function plots of duty ratio.

5.4. Fuzzy Logic Rules

Fuzzy control rules are obtained from the analysis of the system behavior. In their formulation, it must be considered that using different control laws depending on the operating conditions can significantly improve the converter performances in terms of dynamic response and robustness.

First, when the output voltage is far from the setpoint, i.e., error (e) is PB or NB, the corrective action done by the controller must be strong, i.e., duty cycle close to zero or one in order to have the dynamic response as fast as possible, obviously taking into account current limit specifications.

Second, when output voltage error approaches zero, i.e., error (e) is NS, ZE, PS, the current error should be properly taken into account similarly to current-mode control to ensure stability around the working point. Finally, when the current approaches the limit value, appropriate rules must be introduced in order to perform the current limit action while preventing large overshoots.

These fuzzy control rules for error and change of error can be referred to the rules that are shown in Table **1**.

Table 1: Table Rules for Error and Change Error

de \ e	NB	NS	ZO	PS	PE
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

6. CONNECTED NETWORK INVERTER

The inverter is used to convert DC to AC. There are many design considerations in the development of three-phase inverters for connected network photovoltaic systems. Since large photovoltaic systems in 5kW to 1MW range are becoming more common, increasing the importance of three-phase network connected inverters to the photovoltaic industry. Each inverter is a combination of a switching and control unit. The basic inverter control schemes are divided into two categories: current control and voltage control. In a grid-connected PV system (on-grid), the inverter operates by current control mode. The inverter is supplied by a DC link capacitor interconnected to the PV power system via a DC-DC converter combined with a Maximum Power Point Tracking (MPPT) controller[6]. A basic scheme of a three-phase connected network inverter is shown in Figure **9**.

7. SIMULATION RESULTS

In this section, to test and validate the proposed optimized method, simulation results are presented in two scenarios; uniform temperature - radiation conditions and variable temperature - partial shadow conditions. PV cell characteristics which are utilized in this paper are presented in Table **2**.

Table 2: PV Cell Array Characteristics in 25°C

$\alpha = 0.002086[A / C^{\circ}]$	Current-Temperature Coefficient
$\beta = 0.0779[V / C^{\circ}]$	Voltage-Temperature Coefficient
$I_s = 0.5 \times 10^{-4}[A]$	Reverse saturation current
$I_{SC} = 2.926[A]$	Short circuit current
$R_S = 0.0277[\Omega]$	Cell resistance
$\lambda = 20.41[V^{-1}]$	Cell material coefficient

7. UNIFORM TEMPERATURE - RADIATION CONDITIONS

In this scenario, PV cell is assumed uniform, which is used in two conditions. At first, the radiation level and

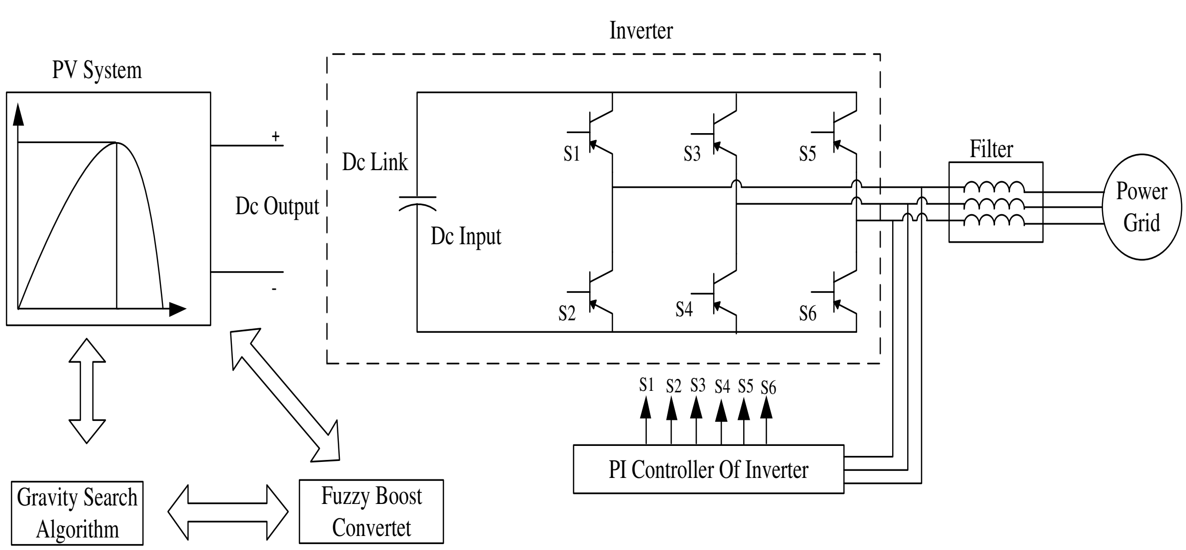

Figure 9: Structure of three phases connected network inverter.

temperature for this cell are constant. In this condition, the radiation level and temperature are 800 W/m2 and 27 °C, respectively. As shown in Figure **10**, MMP will be 214 W and the control unit can track this point excellently.

Another condition is tested to verify the speed of the proposed method in this scenario in which temperature and radiation are changed according to Figure **11-a**, **11-b**. As seen in Figure **11-c**, the proposed optimized method tracks MPP immediately with radiation and temperature changes.

7.1. Variable Temperature - Partial Shadow Conditions

In this scenario, to simulate partial shadow conditions, the PV cell has been divided into three

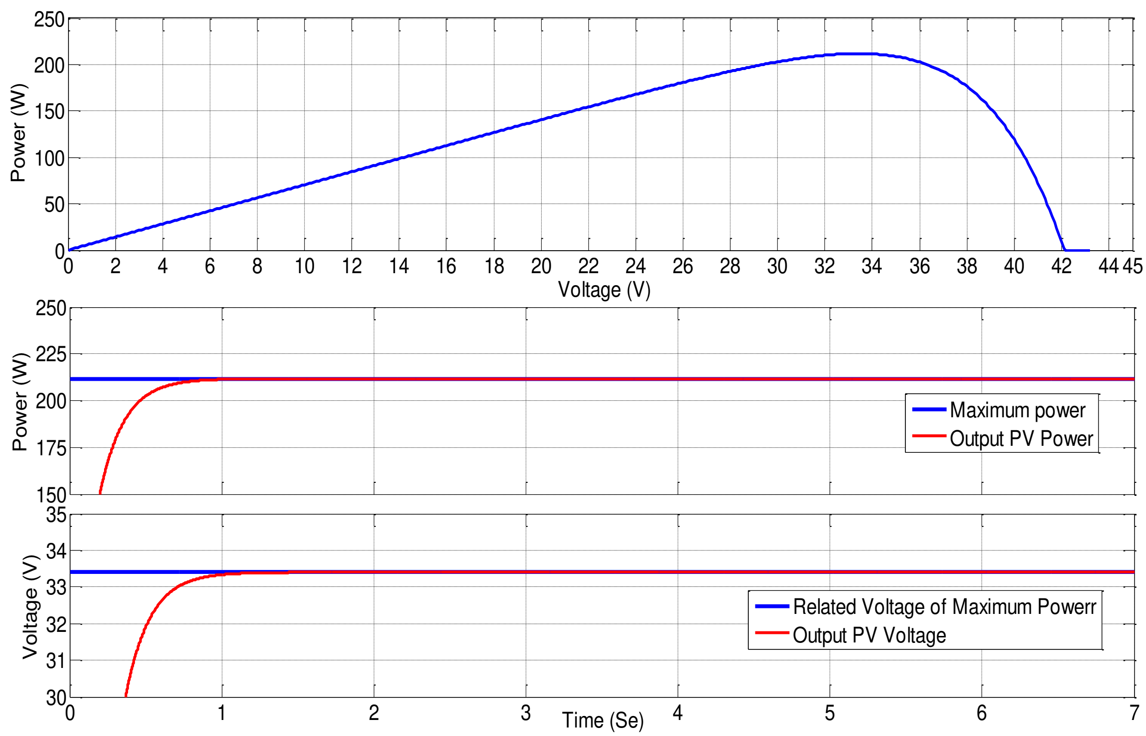

Figure 10: MPP tracking and its voltage in constant condition for first scenario.

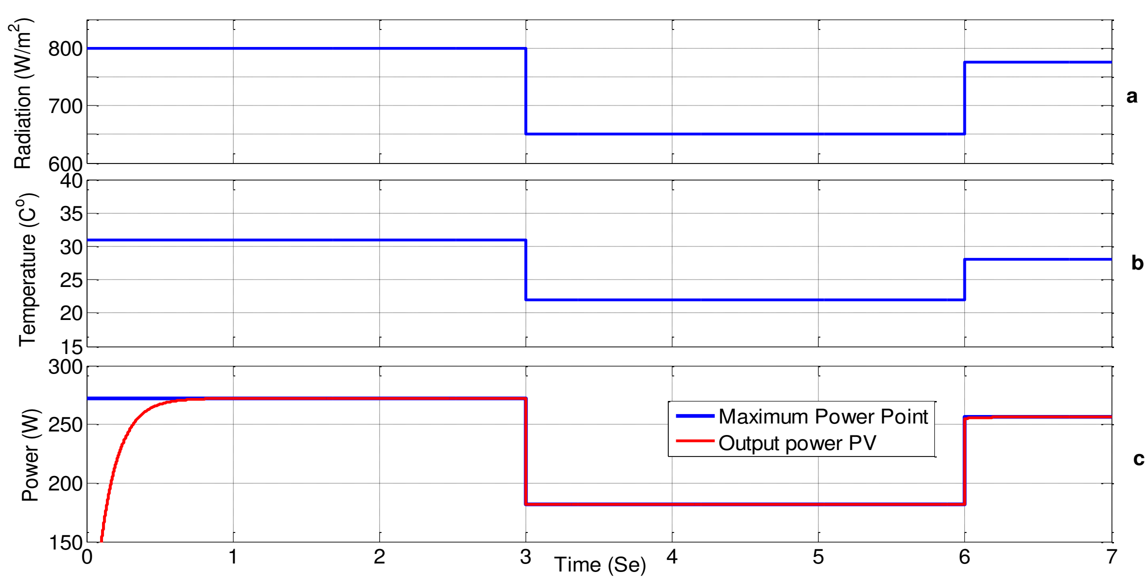

Figure 11: MPP tracking and its voltage in variable condition for first scenario.

sections with different radiation levels, and each of these sections has a different temperature. The aim is to evaluate the proposed method's potential to track MPP in variable conditions that are close to reality.

Radiation level and temperature for the first section of PV array are 1000 W/m2 and 30 °C ,respectively. These parameters for second section are assumed 850 W/m2 and 28 °C and for third section are 750 W/m2 and 25 °C which can be seen in Figure **12**.

As seen in Figure **13**, proposed optimization method can follow MPP and its voltage carefully in less than 0.2 seconds and tracking curve is approximately match on target curve.

Now to evaluate the speed and power of the proposed algorithm in partial shadow condition, radiation level and temperature of each section change separately according to Figure **14**. Figure 15 shows the power and speed of our method regarding the following

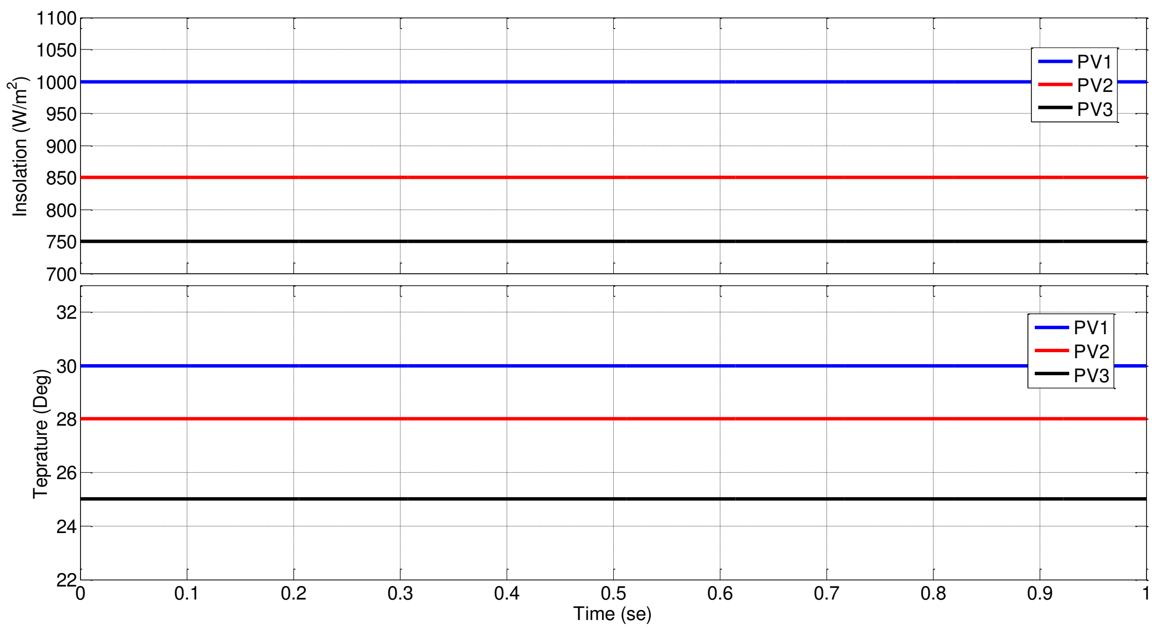

Figure 12: Radiation level and temperature for second scenario.

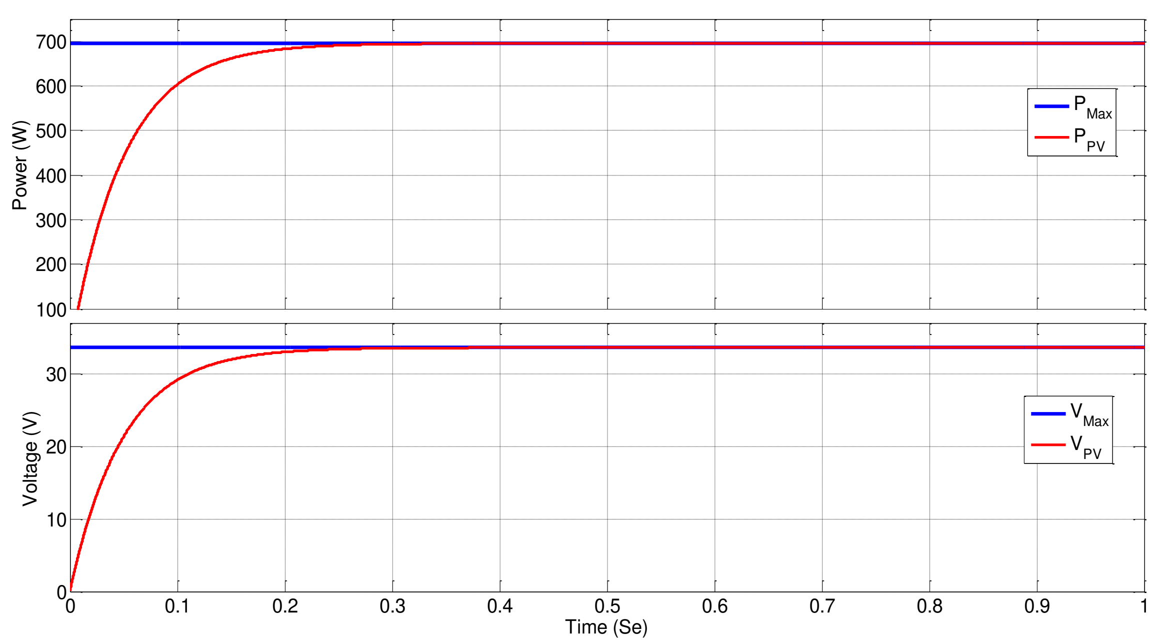

Figure 13: MPP tracking and its voltage in second scenario with constant conditions.

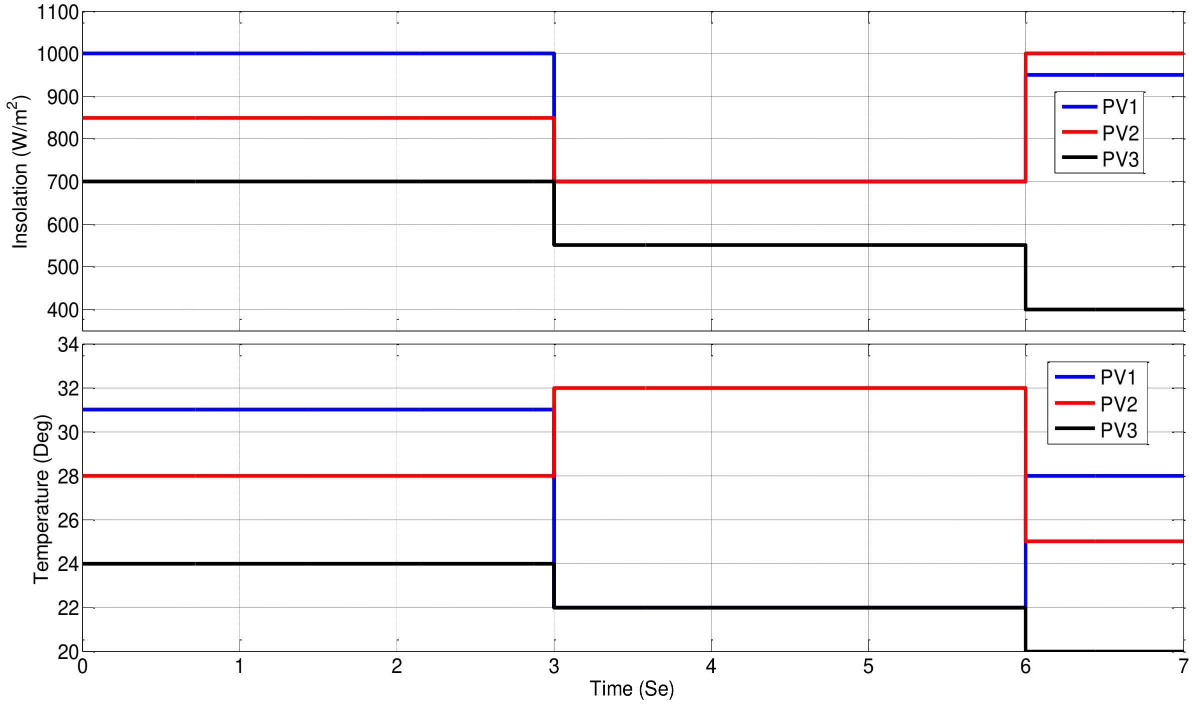

Figure 14: Radiation level and temperature changes for each section of PV cell in second scenario.

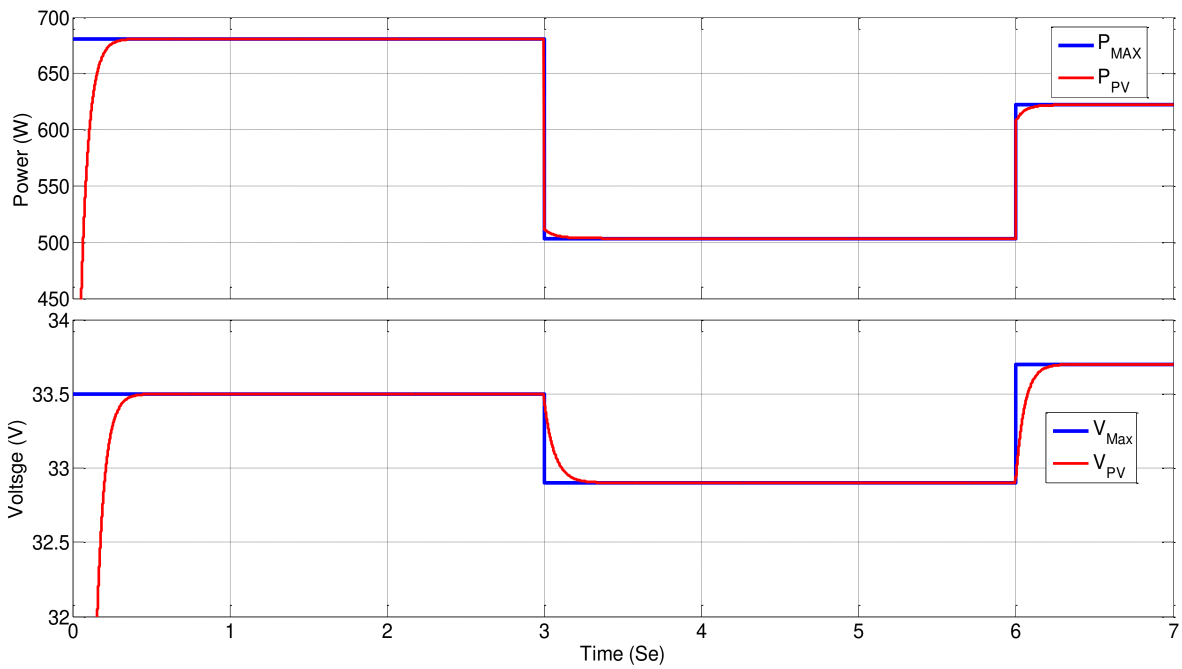

Figure 15: MPP tracking and its voltage with variable conditions in second scenario.

MPP, which has been defined by the optimization method in the control unit.

8. CONCLUSION

Solar energy generation faces many challenges such as changes in environmental conditions, rapid load changes, technical limitations of MPPT methods, etc., which forces the authors of this paper to utilize more appropriate methods. In this paper, a novel hybrid approach based on gravity search algorithm and the fuzzy logic controller is presented to track maximum power point of PV system when it is connected to a power network in partially shadow condition. The approaches improve the speed and efficiency of the

MPPT process in PV systems. An optimization algorithm based on the law of gravity in the MPP detection unit can detect MPP of each PV cell accurately, and fuzzy boost converters in the MPP tracking unit follow this point rapidly. Simulation results present excellent behavior of the proposed optimized method in defining and tracking MPP in two scenarios by uniform and partial shadow radiation conditions.

REFRENCES

[1] I. PVPS, "Trends in photovoltaic applications. Survey report of selected IEA countries betw een 1992 and 2011," *Report IEA-PVPS T1–21,* 2012.

[2] A. H. Arianfar, M. H. M. Jahromi, M. Mosalanejad, and B. Dehghan, "Design and modeling remote monitoring system for a solar pow er plant," in *2009 Second International Conference on Computer and Electrical Engineering*, 2009, pp. 81-86. https://doi.org/10.1109/ICCEE.2009.163

[3] L. Philipson, "Distributed and dispersed generation: addressing the spectrum of consumer needs," in *Power Engineering Society Summer Meeting, 2000. IEEE*, 2000, pp. 1663-1665.

[4] M. H. Mehrabanjahromi, H. Gharehchahi, and A. R. Khosravi, "Modelling and simulation of a hybrid controller for solar thermal generation," 2013.

[5] S. Srikanth, "A Three Phase Multi Level Converter For grid Connected PV System," International Journal of Pow er Electronics and Drive Systems, vol. 5, p. 71, 2014. https://doi.org/10.11591/ijpeds.v5i1.6156

[6] M.H Mehraban jahromi, S, Soleymani, B Mozafari, "Optimal allocation of inverter connected DGs: An objective function to minimize deterioration of transient stability of pow er system" International Journal of Electrical Pow er & Energy Systems, Elsevier 2020. https://doi.org/10.1016/j.ijepes.2020.106267

[7] A. F. Murtaza, H. A. Sher, M. Chiaberge, D. Boero, M. De Giuseppe, and K. E. Addow eesh, "Comparative analysis of maximum pow er point tracking techniques for PV applications," in Multi Topic Conference (INMIC), 2013 16th International, 2013, pp. 83-88. https://doi.org/10.1109/INMIC.2013.6731329

[8] P. Srivastava, P. Gupta, and A. Singh, "Critical Factors Affecting Efficiency of Maximum Pow er Point Tracking in Solar Cells," SAMRIDDHI: A Journal of Physical Sciences, Engineering and Technology, vol. 7, 2015. https://doi.org/10.18090/samriddhi.v7i1.4465

[9] M. H. Mehraban. Jahromi, B. Dehghan, A. M. Jahromi, and S. F. Zarei, "Design and modeling control system for a solar pow er plant," in 2009 Second International Conference on Computer and Electrical Engineering, 2009, pp. 27-31. https://doi.org/10.1109/ICCEE.2009.158

[10] N. Femia, D. Granozio, G. Petrone, G. Spagnuolo, and M. Vitelli, "Optimized one-cycle control in photovoltaic grid connected applications," IEEE Transactions on Aerospace and Electronic Systems, vol. 42, pp. 954-972, 2006. https://doi.org/10.1109/TAES.2006.248205

[11] F. Liu, S. Duan, F. Liu, B. Liu, and Y. Kang, "A variable step size INC MPPT method for PV systems," IEEE Transactions on industrial electronics, vol. 55, pp. 2622-2628, 2008. https://doi.org/10.1109/TIE.2008.920550

[12] P. Singh, D. Palw alia, A. Gupta, and P. Kumar, "Comparison of Photovoltaic Array Maximum Pow er Point Tracking Techniques," International Advanced Research Journal in Science, Engineering and Technology, vol. 2, 2015.

[13] F. Shabania and M. M. Jahromi, "Identification of Oil Cycle in the case of parabolic trough Solar Pow er Plant," in IEEE, 39th North American Pow er Symposium (NAPS 2007), pp. 197-204.

[14] B. Subudhi and R. Pradhan, "A comparative study on maximum pow er point tracking techniques for photovoltaic pow er systems," IEEE Transactions on Sustainable Energy, vol. 4, pp. 89-98, 2013. https://doi.org/10.1109/TSTE.2012.2202294

[15] P.-C. Chen, P.-Y. Chen, Y.-H. Liu, J.-H. Chen, and Y.-F. Luo, "A comparative study on maximum pow er point tracking techniques for photovoltaic generation systems operating under fast changing environments," Solar Energy, vol. 119, pp. 261-276, 2015. https://doi.org/10.1016/j.solener.2015.07.006

[16] B. Bendib, H. Belmili, and F. Krim, "A survey of the most used MPPT methods: Conventional and advanced algorithms applied for photovoltaic systems," Renew able and Sustainable Energy Review s, vol. 45, pp. 637-648, 2015. https://doi.org/10.1016/j.rser.2015.02.009

[17] J. M. Enrique, J. M. Andújar, E. Durán, and M. A. Martínez, "Maximum pow er point tracker based on maximum pow er point resistance modeling," Progress in Photovoltaics: Research and Applications, vol. 23, pp. 1940-1955, 2015. https://doi.org/10.1002/pip.2620

[18] M. Hosenuzzaman, N. Rahim, J. Selvaraj, M. Hasanuzzaman, A. Malek, and A. Nahar, "Global prospects, progress, policies, and environmental impact of solar photovoltaic pow er generation," Renew able and Sustainable Energy Review s, vol. 41, pp. 284-297, 2015. https://doi.org/10.1016/j.rser.2014.08.046

[19] J. M. Guerrero, P. C. Loh, T.-L. Lee, and M. Chandorkar, "Advanced control architectures for intelligent microgrids-Part II: Pow er quality, energy storage, and AC/DC microgrids," IEEE Transactions on Industrial Electronics, vol. 60, pp. 1263-1270, 2013. https://doi.org/10.1109/TIE.2012.2196889

[20] R. K. Akikur, R. Saidur, H. W. Ping, and K. R. Ullah, "Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: a review," Renew able and Sustainable Energy Review s, vol. 27, pp. 738-752, 2013. https://doi.org/10.1016/j.rser.2013.06.043

[21] Y. Bae, T.-K. Vu, and R.-Y. Kim, "Implemental control strategy for grid stabilization of grid-connected PV system based on German grid code in symmetrical low -to-medium voltage netw ork," IEEE Transactions on Energy Conversion, vol. 28, pp. 619-631, 2013. https://doi.org/10.1109/TEC.2013.2263885

[22] B. Tamimi, C. Cañizares, and K. Bhattacharya, "System stability impact of large-scale and distributed solar photovoltaic generation: The case of Ontario, Canada," IEEE Transactions on Sustainable Energy, vol. 4, pp. 680-688, 2013. https://doi.org/10.1109/TSTE.2012.2235151

[23] K. Ishaque and Z. Salam, "A review of maximum pow er point tracking techniques of PV system for uniform insolation and partial shading condition," Renew able and Sustainable Energy Review s, vol. 19, pp. 475-488, 2013. https://doi.org/10.1016/j.rser.2012.11.032

[24] R. Enne, M. Nikolić, and H. Zimmermann, "Dynamic integrated MPP tracker in 0.35 μm CMOS," IEEE Transactions on Pow er Electronics, vol. 28, pp. 2886-2894, 2013. https://doi.org/10.1109/TPEL.2012.2213615

[25] M. K. Alam, F. Khan, and A. M. Imtiaz, "Optimization of subcell interconnection for multijunction solar cells using switching power converters," IEEE Transactions on Sustainable Energy, vol. 4, pp. 340-349, 2013. https://doi.org/10.1109/TSTE.2012.2223493

[26] K. Gunaseelan, "Grid-Connected Boost-Half-Bridge Photovoltaic Micro inverter System Using Repetitive Current Control and Maximum Power Point Tracking," IJRCCT, vol. 3, pp. 596-603, 2014.

[27] M. A. Ramli, S. Twaha, K. Ishaque, and Y. A. Al-Turki, "A review on maximum power point tracking for photovoltaic systems with and without shading conditions," Renewable and Sustainable Energy Reviews, vol. 67, pp. 144-159, 2017. https://doi.org/10.1016/j.rser.2016.09.013

[28] G. K. Singh, "Solar power generation by PV (photovoltaic) technology: a review," Energy, vol. 53, pp. 1-13, 2013. https://doi.org/10.1016/j.energy.2013.02.057

[29] P. Caramia, G. Carpinelli, F. Mottola, and G. Russo, "An optimal control of distributed energy resources to improve the power quality and to reduce energy costs of a hybrid AC-DC microgrid," in Environment and Electrical Engineering (EEEIC), 2016 IEEE 16th International Conference on, 2016, pp. 1-7. https://doi.org/10.1109/EEEIC.2016.7555883

[30] S. Pattnaik, R. Dash, S. C. Swain, and P. Mohapatra, "Control of active and reactive power of a three phase grid connected photovoltaic system," in Circuit, Power and Computing Technologies (ICCPCT), 2016 International Conference on, 2016, pp. 1-6. https://doi.org/10.1109/ICCPCT.2016.7530227

[31] V. J. Chin, Z. Salam, and K. Ishaque, "An accurate modelling of the two-diode model of PV module using a hybrid solution based on differential evolution," Energy Conversion and Management, vol. 124, pp. 42-50, 2016. https://doi.org/10.1016/j.enconman.2016.06.076

[32] E. Gadjeva and M. Hristov, "Development of Temperature-Dependent SPICE Computer Models of Photovoltaic Cells," in Materials Science Forum, 2016, pp. 322-327. https://doi.org/10.4028/www.scientific.net/MSF.856.322

[33] A. Bouraiou, M. Hamouda, A. Chaker, M. Sadok, M. Mostefaoui, and S. Lachtar, "Modeling and simulation of photovoltaic module and array based on one and two diode model using Matlab/Simulink," Energy Procedia, vol. 74, pp. 864-877, 2015. https://doi.org/10.1016/j.egypro.2015.07.822

[34] E. Rashedi, H. Nezamabadi-Pour, and S. Saryazdi, "GSA: a gravitational search algorithm," Information sciences, vol. 179, pp. 2232-2248, 2009. https://doi.org/10.1016/j.ins.2009.03.004

[35] M. Veerachary, T. Senjyu, and K. Uezato, "Neural-network-based maximum-power-point tracking of coupled-inductor interleaved-boost-converter-supplied PV system using fuzzy controller," IEEE Transactions on Industrial Electronics, vol. 50, pp. 749-758, 2003. https://doi.org/10.1109/TIE.2003.814762

Received on 30-11-2020 Accepted on 20-12-2020 Published on 30-12-2020

DOI: http://dx.doi.org/10.31875/2410-2199.2020.07.6