The 4th International Conference on Engineering Mechanics and Automation (ICEMA-4)
Hanoi, August 25÷26, 2016

Extremum Seeking Control based MPPT for photovoltaic array under uniform and non-uniform irradiances

Van Manh Hoang, Ngoc Viet Nguyen, Manh Thang Pham

Faculty of Mechanics and Automation, University of Engineering and Technology

Abstract

In order to extract the maximum power from photovoltaic (PV) array, the maximum power point tracking (MPPT) technology has always been applied in PV systems. The Perturb and Observe (P&O) and Incremental Conductance (INC) methods are the most popular and widely used under the constant irradiance. However, the changes of the environmental parameters, such as cloud cover or the building block, will lead to the radiation change and then have a direct effect on the location of Maximum Power Point (MPP). In order to carry out MPPT in PV array under Partial Shading Conditions (PSCs), a method based on Extremum Seeking Control (ESC) is applied to determine the optimal value of a reference current in the PV system. The proposed ESC approach for the Global Maximum Power Point Tracking (GMPPT) in this work uses a series combination of a High Pass Filter (HPF) and two Low Pass Filters (LPFs). These three filters act as two Band Pass Filters (BPFs) and let a specific frequency of input power which includes the derivative of PV with respect to its voltage pass through. This auto-tuning strategy was developed to maximize the PV array output power through the regulation of the voltage input to the DC-DC boost converter in order to lead the PV array steady-state to a stable oscillation behavior around the Global Maximum Power Point (GMPP). The performance of the proposed ESC algorithm is evaluated by comparing it with the conventional ESC and modified P&O method in terms of tracking speed and accuracy by utilizing MATLAB SIMULINK. The simulation results demonstrate that the tracking capability of the proposed ESC algorithm is superior to that of the conventional ESC and modified P&O algorithm, particularly under low radiance and sudden mutation irradiance conditions.

Key Words: Boost converter; Extremum Seeking Control; Maximum Power Point Tracking (MPPT); Partial Shading Conditions (PSCs); Photovoltaic (PV) system.

I. Introduction

The target for 2030 of power generation from Photovoltaic (PV) array in total power generation was set in arrange of 7-17% for different countries [1]. The main obstacles to increase this ratio are the installation cost energy efficiency [2]. it is necessary to optimize the performance of PV systems through the operation of conversion systems to increase the output efficiency of the overall system operating. The output voltage and current of PV is a nonlinear function of panel temperature, radiation and loading conditions. The MPP can change under different conditions. There is various maximum power point tracking methods (MPPT) for getting maximum power from PV panels. As PV power generation arrays become more popular in urban buildings, the surrounding tall buildings and trees may produce shadow on PV panels during the day [3]. Consequently, al PV energy available must be harvested from the PV array operating under Partially Shaded Conditions (PSCs) or high dynamic variations of the irradiance profile [1]. Under Partial Shading Conditions (PSCs), the current-voltage and power-voltage characteristic curves will appear multiple peaks, and using MPPT strategies to track real MPP becomes a difficult task. Thus, a Global Maximum Power Point Tracking (GMPPT) algorithm must to be used instead of MPPT algorithm. The objective of GMPPT method is to track the Global Maximum Power Point (GMPP) not the Local MPPs (LMPPs) of the PV pattern usually generated during of a sunny-cloudy day [4]. Thus, in last decade this challenging subject was in attention of the researchers and over one hundred GMPPT algorithms were proposed [3][5]. The GMPPT algorithms were classified in firmware-based and hardware architecture-based algorithms [5].

The firmware-based GMPPT strategies operate in two stages. The GMPPT is located in the first stage using a search based on different methods [5]. For instance, the Fuzzy Logic Controller (FLC) proposed in [6] for tracking the MPP could be easily developed based on extended rules' base for locating the GMPP as well. The optimization algorithms inspired from nature such as Glowworm Swarm Optimization (GSO) and Particle Swarm Optimization (PSO) algorithms are successfully applied for locating the GMPP [7].

The GMPP is tracked accurately in the second stage using a popular MPPT strategy. the discrete-time implementation of the Ripple Correlation Control (RCC) is shown in [8]. Precise MPP estimation using P-V curve geometry is shown in [9], but the dynamic of the irradiance profile and the environmental noise are not considered in robustness evaluation. Experimental tests of open-loop MPPT strategies are presented in [10] for direct method proposed. A comparative study on of Open Circuit Voltage method [11] in comparison with the dP/dV feedback control method is performed in [12].

The main disadvantages of these methods are related to oscillations around the MPP and their blocking in one of the LMPPs rather than finding of the GMPP [5]. The generated PV power increases with about 45% if a MPPT algorithm is used on a PV array during a sunny day, but the PV systems with MPPT controller became ineffective if the shading coefficient is over to 30% [13]. The use of GMPPT algorithm instead of a MPPT algorithm can solve this issue of a PV array under PSCs.

In this paper, a new MPPT strategy for PV array under uniform irradiance and PSCs is presented. The operating principle takes advantage of the conditions for recognition of global MPP. In addition, the proposed MPP tracker does not add any extra complexity compared to the classical ones. However, it increases significantly the efficiency of the PV system under PSCs. To evaluate the performance of the algorithm, the proposed ESC-based GMPPT method is implemented on a DC-DC boost converter, and its performance is compared with that of the traditional ESC algorithm.

The information on the PV under uniform irradiance and PSCs and boost is presented in Section II. The proposed algorithm is discussed in Section III. The simulation of MPPT using SIMULINK and discussion of the results are shown in Section IV. Finally, the conclusion is presented in Section V.

II. Photovoltaic (PV) system model and DC-DC boost converter

1. PV array model under uniform conditions

A PV module is used to convert light

energy to electric energy. A PV-based system can be independently used for streetlights, water pumps, and grid connected systems [14]. The smallest unit of a PV module is the solar cells that are connected in series. The equivalent circuit of a solar cell is shown in Figure 1, where R_s and R_{sh} are the series and shunt resistances, respectively. Shunt resistance can be assumed to be infinite because the efficiency of a solar cell is not sensitive to its variations; that is, the circuit is an open circuit. The nonlinear current-voltage characteristics of a solar cell can be described by equation (1):

$$I = I_{ph} - I_s \left\{ exp\left[\frac{q(V+R_S I)}{akT}\right] - 1 \right\} - \frac{V+R_S I}{R_{sh}} \qquad (1)$$

where I and V are the output current and voltage of the solar cell, respectively; I_{ph} and I_s are the photocurrent and saturation current, respectively; $k = 1.38\, x\, 10^{-23}$ $(\boldsymbol{J/K})$ and $q = 1.6\, x\, 10^{-19}$ $(\boldsymbol{C})$ are Boltzmann's constant and the elementary charge, respectively; a is the ideal coefficient of p-n junction; T is the initial temperature of PV array $(\boldsymbol{K})$.

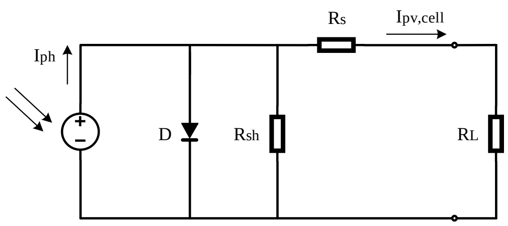


Figure 1. Equivalent circuit of a PV cell.

To produce higher current and voltage, modules are connected as a PV array in different configurations; each configuration has certain advantages and disadvantages. In this work, the modules are connected in a series in string to produce higher current; then, these strings are connected in parallel to produce higher voltage. When any PSCs of the PV system occurs due to the presence of the obstacles such as trees, clouds or tall buildings, the reducing current in the module reduces the current of the string and consequently reduces the total power of the array. To solve these problems, the bypass diodes are connected in parallel to each module. However, by installing these bypass diodes, multiple peak power points are created for the PV system. Among these peak powers, one point has the highest power, which is called the GMPP, and the other points are LMPPs.

2. *Mathematical model of PV array under uniform and partial shading conditions*

In the series-parallel configuration, as shown in Figure 2, the modules are connected in series as strings, and then, multiple strings are connected in parallel. The voltage V_M and current I_M of a PV module formed by $N_S\, x\, N_P$ solar cells are defined as follows:

$$I_M = N_P I, I_{scM} = N_P I_{SC} \qquad (2)$$

$$V_{ocM} = N_S V_{OC}, V_M = N_S V \qquad (3)$$

where N_S and N_P are the number of cells connected in series and parallel, respectively. The subscript M denotes a module, and subscripts without M denote an individual solar cell. As shown in Figure 2, if N_{SM} presents the number of modules connected in a string and N_{MP} represents the number of strings connected in parallel in a PV array, the output voltage and the current of the PV array under uniform conditions can be presented as follows [15][16]:

$$I_A = N_{PM} I_M, I_{scA} = N_{PM} I_{scM} \qquad (4)$$

$$V_A = N_{SM} V_M, V_{ocA} = N_{SM} V_{ocM} \qquad (5)$$

$$R_{SA} = \frac{N_{SM}}{N_{PM}} R_{SM} \qquad (6)$$

where R_{SM} and R_{SA} are the total resistance of the PV module and array, respectively. The output current of a PV array under uniform conditions can be presented as follows, the subscripts A and M denote "Array" and "Module", respectively:

$$I_A = I_{scM} - \frac{N_{PM} I_{scM}}{exp\left\{\frac{qV_{ocM}}{N_S kT}\right\}\left\{exp\left[\frac{q(V_A + R_{SA} I_A)}{akTN_S N_{SM}}\right] - 1\right\}} \qquad (7)$$

By using equation (7), the $I - V$ and $P - V$ characteristics of a PV array under uniform conditions is obtained. To analyze the behavior of the proposed GMPP algorithm, the $I-V$ and $P-V$ curves of a PV array under PSCs are required. By referring back to Figure 2, X denotes the string number and N_{DX} denotes the number of shaded modules in the Xth string. Under uniform conditions, N_{DX} is zero. Under PSCs, the related equations can be expressed as follows:

$$I_A = \sum_{X=1}^{N_{PM}} I_{AX} \tag{8}$$

$$I_{scA} = \sum_{X=1}^{N_{PM}} I_{scAX} \tag{9}$$

$$V_{AX} = (N_{SM} - N_{DX})V_M \tag{10}$$

$$V_{ocAX} = (N_{SM} - N_{DX})V_{ocM} \tag{11}$$

$$R_{SAX} = (N_{SM} - N_{DX})R_{SM} \tag{12}$$

where I_A and I_{scA} are the output current and the short-circuit current of the PV array under PSCs, respectively. V_{AX} and V_{ocAX} denote the output and open-circuit voltage in the Xth string, respectively, and R_{SAX} denotes the resistance in the Xth string.

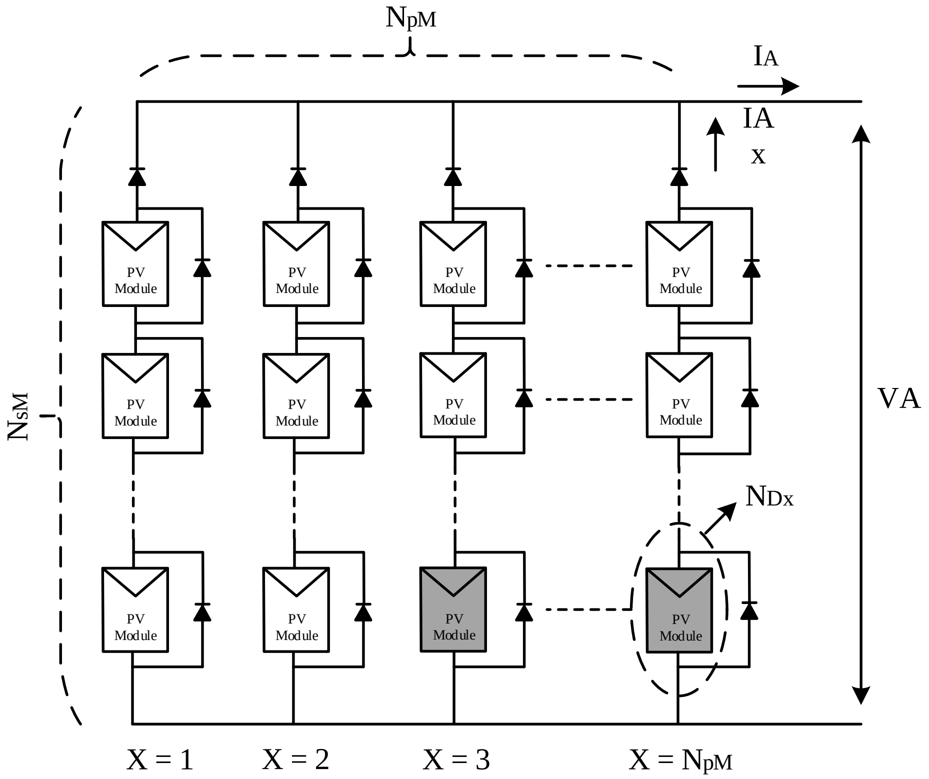


Figure 2. Series-parallel (SP) configuration of PV array.

3. *DC-DC boost converter*

The boost converter is a switch mode power supply that is used to increase the voltage output. As shown in Figure 3, the ideal topology of the boost converter is composed of an inductor, capacitor, power switch and diode.

The voltage conversion ratio can be defined as follows [17]:

$$M(D) = \frac{V_o}{V_g} = \frac{1}{1-D} \tag{13}$$

where V_o and V_g are the output and input voltage of the boost converter, respectively, and D is the duty cycle, which is defined as the ratio of the turn-on duration to the switching time period.

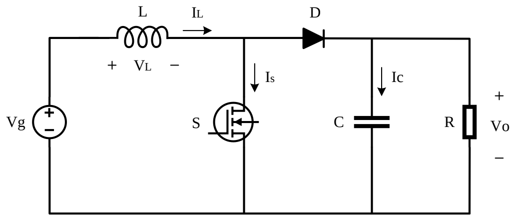


Figure 3. Topology of boost converter

III. An Extremum Seeking Control for GMPPT under PSCs

1. *A classical ESC model for MPPT*

Extremum Seeking Control (ESC) is a control method applicable to static nonlinear plants that have a local minimum or maximum, where the nonlinear function is unknown. Hence, it can be used as an MPPT algorithm in PV applications [18][19]. The algorithm employs the injection of a small perturbation signal called the *dither* signal ($\alpha sin(\omega t)$) with a relatively high frequency to an estimate of the optimal input (V^*) as shown in Figure 4.

Where P^* denotes the optimal power, and $\tilde{V}$ represents the estimate of the optimal voltage that gets updated to approach the MPP. The PV power will have a sinusoidal component with the same frequency of the *dither* signal that is extracted through a High Pass Filter (HPF). Due to the nature of the *P-V* characteristics, this sinusoidal component is either in phase with the *dither* signal if the voltage is less than the MPP or out of phase if the voltage is larger than the MPP. Multiplying the resulting sinusoid with the *dither* signal yields a shifted sinusoid with a positive or negative DC component if the multiplied signals are in phase or out of phase, respectively. This DC component that is extracted through a Low Pass Filter (LPF) represents a signal proportional to the gradient of the PV power. It is integrated and multiplied by a gradient update gain (K) such that the voltage estimate asymptotically approaches the MPP. The design of ESC parameters is generally a tuning process rather than an analytical design since the nonlinear objective function is unknown [20]. Different factors need to be considered in the tuning process such as the required speed of the ESC, the plant dynamics, and the sensitivity to noise.

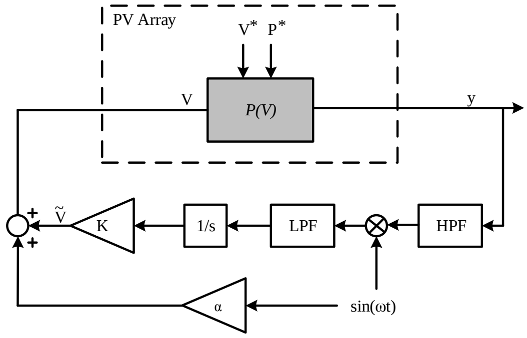


Figure 4. Classical ESC diagram

2. *Proposed ESC-Based Method*

Although the classical ESC method is advantageous over global-scan methods in terms of convergence speed, it still requires significant time to converge at each LMPPs and at each turning point. The proposed method aims to eliminate the need to converge at all MPPs and still be able to locate the voltage of the global MPP. The algorithm proposed in this paper is shown in Figure 5. In this proposed ESC, the probing signal filtered by the BPF2 (the series connection of HPF and LPF2) is a smooth approximation of the absolute value. Note that the HPF, LPF1 and LPF2 are of first order type in this study and the search speed is proportional with the k_1 loop gain.

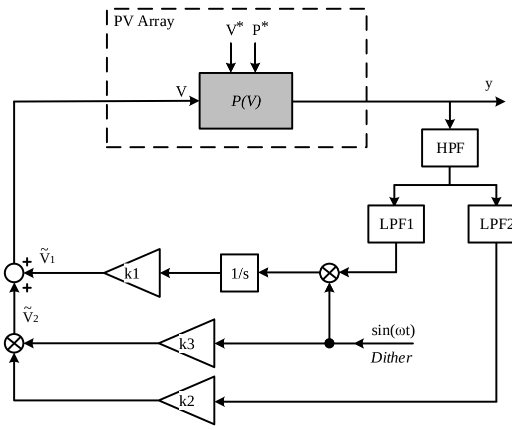


Figure 5. Proposed ESC diagram.

The following values are used in simulation for the parameters of proposed ESC scheme:

1. The dither frequency is $f_d = 100\ Hz$;
2. The dither amplitude is set to 1;
3. The cut-off frequency of the HPF: $f_h = \beta_h . f_d$, where $\beta_{l1} = 0.3$;
4. The cut-off frequency of the LPF1: $f_{l1} = \beta_{l1} f_d$, where $\beta_{l1} = 3.5$ in order to increase the dither persistence on the control loop;
5. The cut-off frequency of the LPF2: $f_{l2} = \beta_{l1} f_d$, where $\beta_{l2} = 1.5$ in order to approximate the first harmonic;
6. The minimum amplitude of dither is set to $A_m = 0.005$ in order to obtain a very low ripple on the probing signal during the stationary phases;
7. The normalization gain: $k_N = 1/y_{max}$, where $y_{max} = 2000$ is a value in the range estimated for the maximum values of the nonlinear map;
8. The gain $k_2 = 10.5$;
9. The gain $k_1 = \gamma_{sd} \omega$, where $\gamma_{sd} = 3$.
10. The gain $k_3 = 1.5$;

IV. Simulation and result discussion

In this paper, simulation works are performed using MATLAB Simulink to investigate the operation of the modified ESC algorithm under PSCs. The considered PV array is based Ultra SQ85-P PV modules connected in the series-parallel configuration with four strings, and in each string, five modules are connected in series. The main specifications of the module are presented in Table 1, based on the manufacturer's data sheet. The modified ESC is implemented in the system as shown in Figure. 6, which includes a PV array, a boost converter, and an MPPT controller.

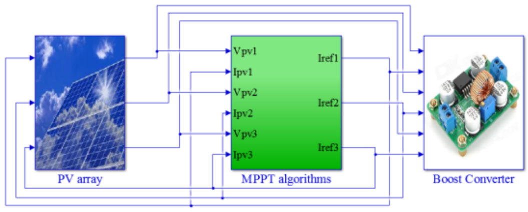


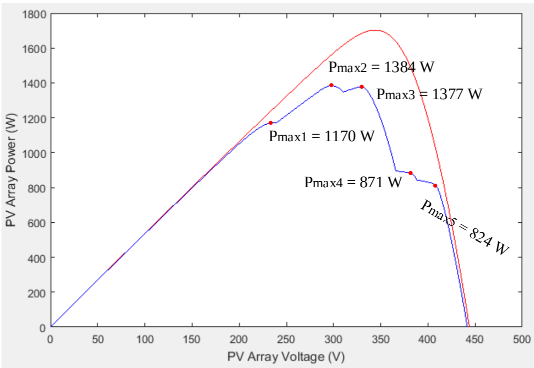
Figure 6. Configuration of system

Table 1. Specifications of Solar SQ85-P at 1000 W/m^2 and 25 ^{o}C.

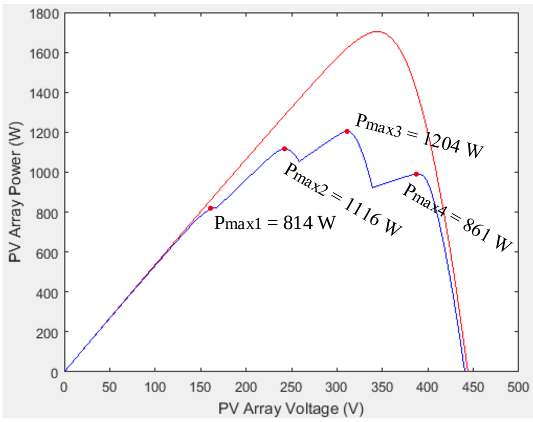
Parameters	Values
Power in maximum point, P_{MPP}; [W]	85
Voltage in maximum point, V_{MPP}; [V]	17.2
Current in maximum point, I_{MPP}; [A]	4.95
Open circuit voltage, V_{oc}; [V]	22.2
Short circuit current, I_{sc}; [A]	5.45
Temperature coefficient of V_{oc}; [mV/^{o}C]	- 64.5
Temperature coefficient of I_{sc}; [mA/^{o}C]	1.4
Number of cells per module	36

To evaluate the operation of the proposed algorithm, the scenarios of shadowing which are shown in Figure 7a,b are considered for the simulation. Specifically, in Figure 7a, three strings have shaded modules, where the numbers of shaded modules in the strings are different. Meanwhile, in Figure 7b, three strings have shaded modules, but the numbers of shaded modules in two strings are the same; thus, the numbers of peak power points are different.

To evaluate the operation of the proposed algorithm, the scenarios of shadowing which are shown in Figure 7a,b are considered for the simulation. Specifically, in Figure 7a, three strings have shaded modules, where the numbers of shaded modules in the strings are different. Meanwhile, in Figure 7b, three strings have shaded modules, but the numbers of shaded modules in two strings are the same; thus, the numbers of peak power points are different.



(a)



(b)

Figure 7. P-V curves for **(a)** first scenario of shadowing and **(b)** second scenario of shadowing

To further evaluate the performance of the modified ESC strategy, the simulation for the scenarios depicted in Figure 7 have been done in MATLAB/Simulink, which involves three systems (S_1, S_2 and S_3). In the first system (S_1), the modified ESC method is implemented. In the second system (S_2), the conventional ESC is used. In the third system (S_3), modified P&O is used to find the GMPP under PSCs. The simulation results for the considered systems are summarized in Table 2, which has some abbreviations that are defined as follows:

1. SOP: Status of strategy operation;
2. T_{GMPP}: the GMPP reaching time (s);
3. P_{avg_uni}: the average MPP value in uniform condition (W);
4. P_{avg_PSCs}: the average MPP value under PSCs (W);
5. P_{ripp_uni}: the oscillation in power in uniform condition (W);
6. P_{ripp_PSCs}: the oscillation in power under PSCs (W).

In Figure 8, the simulation results for the scenario depicted in Figure 7a are shown. We can be seen that S_3 fails to find the GMPP, and a LMPP with a value of 1167.6 W is detected. For S_1 and S_2, where modified and conventional ESC are implemented, respectively, the GMPP is obtained correctly. However, by comparing both, S_2 can clearly find the GMPP in less time. As shown in Table 2, T_{GMPP} for S_1 and S_2 are 2.1 and 1.5 s, respectively. Moreover, the oscillation in power decreases significantly for S_1, which the oscillation values for S_1 and S_2 are 0.2 and 0.8 W, respectively, when the GMPP is obtained (P_{ripp_ESC}). In comparing the modified ESC method (S_1) with S_2 in terms of oscillation in power in uniform condition (P_{ripp_uni}), S_1 decreases the oscillation value significantly, and the values for S_1 and S_2 are 0.2 and 1.1 W, respectively.

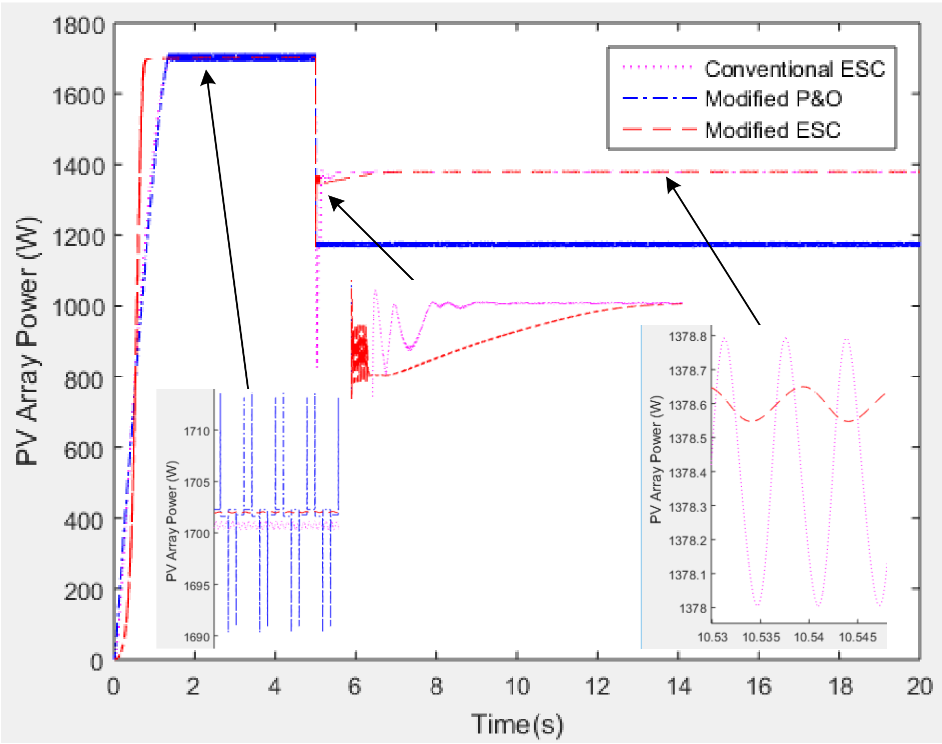


Figure 8. PV array output powers for the Figure 7a

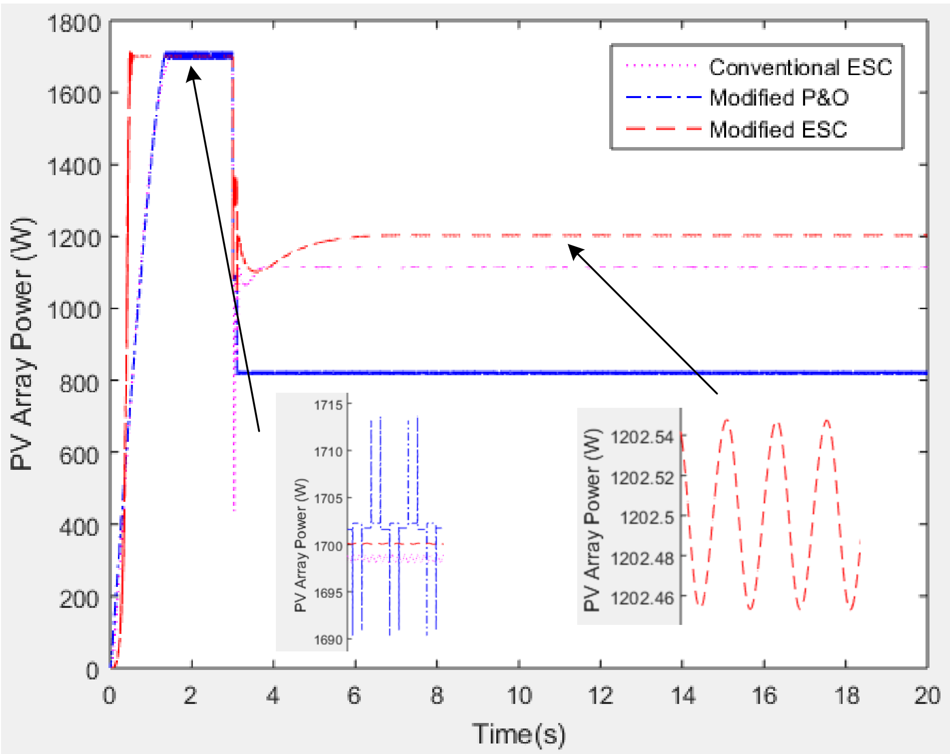


Figure 9. PV array output powers for of Figure 7b

Table 2. The simulation results for S_1, S_2 and S_3

System	Scenario	SOP	T_{GMPP}	P_{ave_uni}	P_{ave_PSC}	P_{ripp_uni}	P_{ripp_PSC}
S_1	7a	Successful	2.1	1702.3	1378.6	0.2	0.1
S_2	7a	Successful	1.5	1700.6	1378.1	1.1	0.8
S_3	7a	Failed	-	1702.1	-	11.9	-
S_1	7b	Successful	3.3	1702.3	1202.5	0.1	0.1
S_2	7b	Failed	-	1700.6	-	-	-
S_3	7b	Failed	-	1702.1	-	-	-

V. Conclusion

Under PSCs in which multiple peak power points exist in the $P-V$ curve of a PV array, conventional methods cannot detect the GMPP. In recent years, researchers have developed different strategies to obtain the GMPP, but each of the techniques has drawbacks. In this paper, a new approach for tracking GMPP for PV array under PSCs and uniform irradiances is proposed. This method operates on the DC to DC converter based on proposed ESC method. Also, the paper compares proposed MPPT strategy with an approach based on conventional ESC. The MPPT circuits based on both approaches have been simulated with MATLAB Simulink. Therefore, based on the simulation results, it is concluded that the proposed algorithm can obtain the GMPP under PSCs in the minimum amount of time with high accuracy and the minimum oscillation in power, which leads to achieve the maximum available energy.

Acknowledgments

This work has been supported by VNU University of Engineering and Technology, under Project No. CN. 15.05

VI. References

[1] Y.-H. Liu, J.-H. Chen, and J.-W. Huang, “A review of maximum power point tracking techniques for use in partially shaded conditions,” *Renew. Sustain. Energy Rev.*, vol. 41, pp. 436–453, 2015.

[2] M. Marzband, A. Sumper, J. L. Domínguez-García, and R. Gumara-Ferret, “Experimental validation of a real time energy management system for microgrids in islanded mode using a local day-ahead electricity market and MINLP,” *Energy Convers. Manag.*, vol. 76, pp. 314–322, 2013.

[3] S. Agrawal and A. Tiwari, “Experimental validation of glazed hybrid micro-channel solar cell thermal tile,” *Sol. Energy*, vol. 85, no. 11, pp. 3046–3056, 2011.

[4] M. García, J. M. Maruri, L. Marroyo, E. Lorenzo, and M. Pérez, “Partial shadowing, MPPT performance and inverter configurations: observations at tracking PV plants,” *Prog. Photovolt Res. Appl.*, vol. 15, no. November 2007, pp. 529–536, 2008.

[5] K. Ishaque and Z. Salam, “A review of maximum power point tracking

techniques of PV system for uniform insolation and partial shading condition," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 475–488, 2013.

[6] A. Messai, A. Mellit, P. A. Massi, A. Guessoum, and H. Mekki, "FPGA-based implementation of a fuzzy controller (MPPT) for photovoltaic module," *Energy Convers. Manag.*, vol. 52, no. 7, pp. 2695–2704, 2011.

[7] L. L. Jiang, D. L. Maskell, and J. C. Patra, "A novel ant colony optimization-based maximum power point tracking for photovoltaic systems under partially shaded conditions," *Energy Build.*, vol. 58, pp. 227–236, 2013.

[8] J. W. Kimball, P. T. Krein, J. W. Kimball, and P. T. Krein, "Discrete-time ripple correlation control for maximum power point tracking Discrete-Time Ripple Correlation Control for Maximum Power Point Tracking," vol. 23, no. 5, pp. 2353–2362, 2008.

[9] G. Kumar, M. B. Trivedi, and A. K. Panchal, "Innovative and precise MPP estimation using P-V curve geometry for photovoltaics," *Appl. Energy*, vol. 138, pp. 640–647, 2015.

[10] G. W. Hart, H. M. Branz, and C. H. Cox, "Experimental tests of open loop maximum-power-point tracking techniques," *Sol. Cells*, vol. 13, pp. 185 – 195, 1984.

[11] B. Subudhi and R. Pradhan, "A Comparative Study on Maximum Power Point Tracking Techniques for Photovoltaic Power Systems," *Sustain. Energy, IEEE Trans.*, vol. 4, no. 1, pp. 89–98, 2013.

[12] M. A. G. De Brito, L. Galotto, L. P. Sampaio, G. De Azevedo Melo, and C. A. Canesin, "Evaluation of the main MPPT techniques for photovoltaic applications," *IEEE Trans. Ind. Electron.*, vol. 60, no. 3, pp. 1156–1167, 2013.

[13] A. Orioli and A. Di Gangi, "Review of the energy and economic parameters involved in the effectiveness of grid-connected PV systems installed in multi-storey buildings," *Appl. Energy*, vol. 113, pp. 955–969, 2014.

[14] M. Simulink and S. S. Mohammed, "Simulation and Analysis of Stand-alone Photovoltaic System with Boost Converter using MATLAB/Simulink," pp. 814–821, 2014.

[15] Y. H. Ji, J. G. Kim, S. H. Park, J. H. Kim, and C. Y. Won, "C-language based PV array simulation technique considering effects of partial shading," *Proc. IEEE Int. Conf. Ind. Technol.*, no. 1, 2009.

[16] N. Gokmen, E. Karatepe, F. Ugranli, and S. Silvestre, "Voltage band based global MPPT controller for photovoltaic systems," *Sol. Energy*, vol. 98, no. PC, pp. 322–334, 2013.

[17] P. Mohan, *Fundamentals of*. 2005.

[18] R. Leyva, C. Alonso, I. Queinnec, a Cid-Pastor, D. Lagrange, and L. Martinez-Salamero, "MPPT of photovoltaic systems using extremum-seeking control," *Ieee Trans. Aerosp. Electron. Syst.*, vol. 42, no. 1, pp. 249–258, 2006.

[19] X. Li, Y. Y. Li, and J. E. Seem, "Maximum Power Point Tracking for Photovoltaic System Using Adaptive Extremum Seeking Control," *Ieee Trans. Control Syst. Technol.*, vol. 21, no. 6, pp. 2315–2322, 2013.

[20] Y. Y. A. Chang and S. J. Moura, "Air Flow Control in Fuel Cell Systems: An Extremum Seeking Approach," *2009 Am. Control Conf. Vols 1-9*, pp. 1052–1059, 2009.