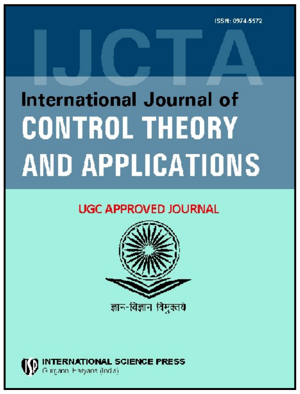


International Journal of Control Theory and Applications

ISSN : 0974-5572

Volume 10 • Number 34 • 2017

MPPT Performance Analysis using an Online Measurement Method with an Outdoor Monitoring

AHMED AZI Alaeddine[1], SAIGAA Djamel[2] and DRIF Mahmoud[2]

[1] *Department of Electrical Engineering, University of Biskra-Algeria, E-mail: alaelectro@hotmail.com*
[2] *Department of Electronics, University of M'sila-Algeria, E-mail: saigaa_dj@yahoo.fr; mhd.drif@gmail.com*

Abstract: This paper is intended to contribute to the conceptual design of an electronic helping tool to analyze the performance of maximum power point tracking systems(MPPT). Indeed, the MPPT is a device ensuring the connection between the PV generator and the rest of the PV conversion chain in order to extract and transfer the maximum of the electric power. In this work, we present a new method in analyzing MPPT performance witch the principle is based on the comparison of the maximum power(Pmp) that can be generated by the PVG and the power transferred to the DC load by the MPPT system. The measurement of these powers is realized outdoor with an online mode; i.e., the PV conversion chain is maintained in operation. The Pmp value obtained by measuring the couple (Isc, Voc). In this paper we will present the hardware implementation of the proposed technique. The measurement of climatic parameters such as, solar radiation and cell temperature are not taken into account, which characterizes the peculiarity of this method.

Keywords: PVG, Maximum power, MPPT, Online measurement, Analysis.

1. INTRODUCTION

The conventional electricity generation outcome from the hard consumption of fossil fuel sources, and causes an environmental problems. Photovoltaic panels and wind generators are the commonly used now as renewable power solutions[1]. Nowadays, solar energy is the most abundant and inexhaustible renewable energy resource. In a minute, the sun can provide energy that is needed by the world in a minute, the sun can provide energy that is needed by the world in a year and in a day, it can provide energy more than that of the world's required consumption for 27 years [2]. In fact, the production of this energy is nonlinear and it varies according to the temperature and solar radiation [3]. This nonlinear behavior is translated by a nonlinear output characteristics I-V curves of PV. Therefore, the maximum power can be provided at one point. Targeting this point by extraction of the maximum power from the PVG require maximum power point tracking controller(MPPT)[4]. A lot of research work revolves around the MPPT techniques have been intervening in the development of these systems, we can cite in general the most used techniques such as: Hill Climbing method according to [5]-[8], the Perturb and Observe (P&O) method used in [9]-[22], the Incremental Conductance (INC) cited in [23]-[30], the Neural Network, the Fuzzy Logic, Particle Swarm Optimization (PSO) and the Genetic Algorithms which are called the artificial intelligence methods and witch they are cited in [31]-[45].

In the last years, researchers and practitioners in PV systems have presented a comparative analysis of MPPT techniques [49]. In this paper we focused on the analysis of MPPT performance by adopting a new developed method based on an online measurement technique with an outdoor monitoring.

Otherwise, MPPT performance is important to system designers who are guaranteeing a certain system performance and need to know all of the system losses as well as to system operators who want to ensure that their system is operating per its specifications [50].

The identified methods to measure MPPT performance are mentioned in Table 1 divided into Laboratory (Indoor) and field (Outdoor) measurement.

Table 1
Overview on : MPPT Measurement Methods [50]
MPPT Measurement Methods

Laboratory (Indoor)	*Field (Outdoor)*
Assessment under static conditions	Switching between MPPT and I-V tracer
Assessment under dynamic conditions	Using a calibrated reference module
Assessment of energetic efficiency	Sampling MPPT input at high speed
Further tests	Using manual mode to obtain I-V curve
	Analysing monitoring data

The Laboratory measurement (Indoor) are made using a PV array simulator that generates DC power with the I-V curve characteristic under a variety of conditions and it must not interact with the MPPT [50].

The field measurements (Outdoor) was made in this work using five methods as [50];

- Switching between MPPT and I-V tracer.
- Using a calibrated reference module.
- Sampling MPPT input at high speed.
- Using manual mode to obtain I-V curve data.
- Analyzing monitoring data.

Therefore, a new method of performance analysis is presented in this paper which is based on an online field measurement.

(A) Basic unit of photovoltaic generator

The electrical equivalent circuit representing the static behavior of real PV cell which is modeled by a current source in parallel with a diode, a shunt resistance and a series resistance [50]. This simplified model allows us to model the behavior of the electrical power source from the PV array.

(B) The principle of seeking the maximum power point

The principle of these commands is to search the maximum power point (MPP) while ensuring perfect adaptation between the PVG and the load to transfer maximum power to the rest og the PV conversion chain.

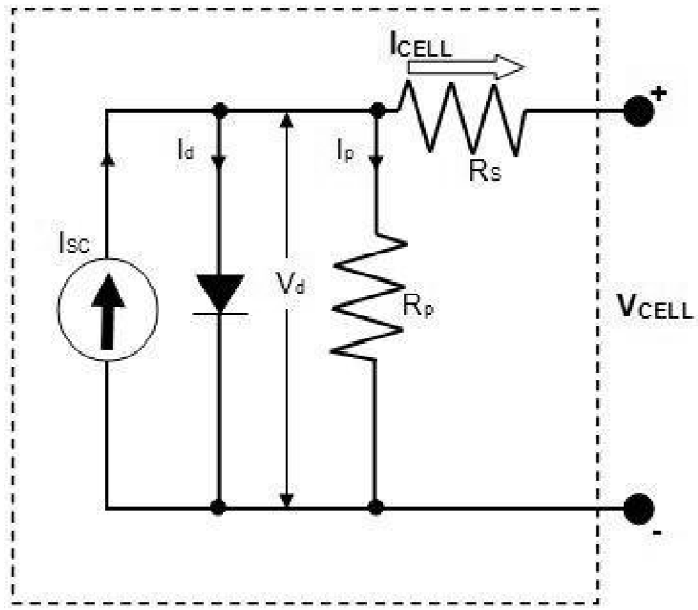


Figure 1: Equivalent circuit model of PV cell

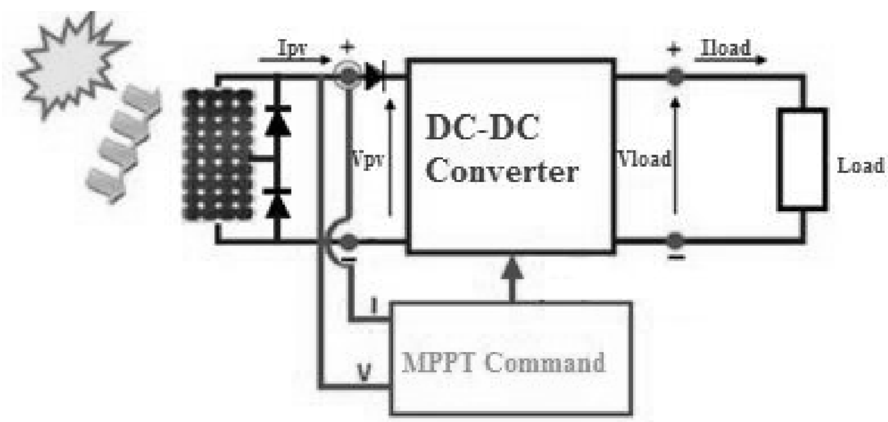


Figure 2: Elementary photovoltaic conversion chain

For instance, we often encounter the problem of optimizing the outcome of the PVG, which must be provided by the MPPT. It should be noted that there is little research according to the performance analysis of these systems (MPPT) few of them are mentioned below [50]. The purpose is this paper is the proposal of a new analysis method which provides a performance parameter in real time (in online mode) where the PV conversion chain is operating outdoor.

2. CONCEPT AND PRINCIPLE OF THE PROPOSED MPPT PERFORMANCE ANALYSIS TECHNIQUE

The occurrence of an abnormality is seen as variation of the MPPT performance to reach the maximum power point for instant weather compared to a reference value for the same conditions cited. The analysis concept in this paper is to detect these variations to distinguish those resulting from failures of those resulting from normal behavior, to decide whether these changes are actually significant compared to the uncertainties on the model and the reference and noise on the measured data.

(A) Principle of the proposed technique

A system called MPPT-PA (Maximum Power Point Tracking Performance Analyzer) will measure the values of the two powers by comparing component namely: the maximum power of PVG calculated by the MPPT (Pmp) and the DC output power delivered to the load (Pload). These measurements are outcomes by physically interconnecting the MPPT-PA system between the PVG and the MPPT for one side (far Upstream) and between the MPPT and load for the other side (far Downstream).

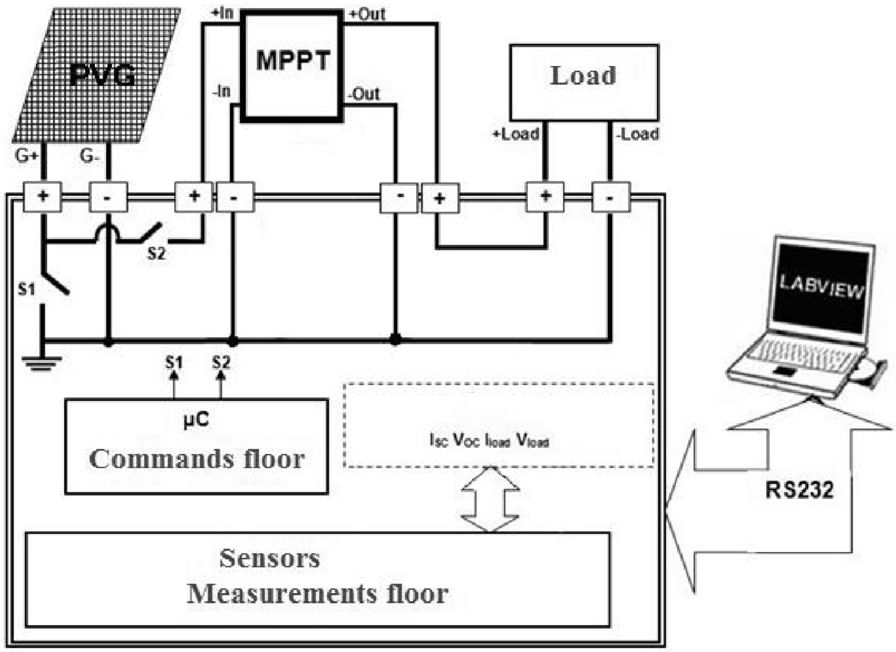


Figure 3: Block diagram of MPPT-PA system

(B) Maximum power reference (Pmp)

The maximum power reference (Pmp) is the maximum power that can be delivered by the PVG in an instant weather conditions. This power is the result of the arithmetic product of the maximum current (Imp) and the maximum voltage (Vmp) as:

$$Pmp = Imp * Vmp \tag{1}$$

with:

$$Imp = k_i * Isc \tag{2}$$

$$Vmp = k_v * Voc \tag{3}$$

(C) Choice of multipliers k_i and k_v

It has been verified experimentally that there is a dependency between the short circuit current (Isc) and the maximum current that can deliver a PVG (Imp), and for the open circuit voltage (Voc) and the PVG maximum voltage that can apply under certain climatic conditions [51].

k_i and k_v respectively represents the slopes of two straight curves. k_i and k_v are called respectively a current factor and a voltage factor and they are respectively equal to 0.86 and 0.71 [51]. By analogy, we can also define the product (k_i * k_v) by the form factor of PVG as:

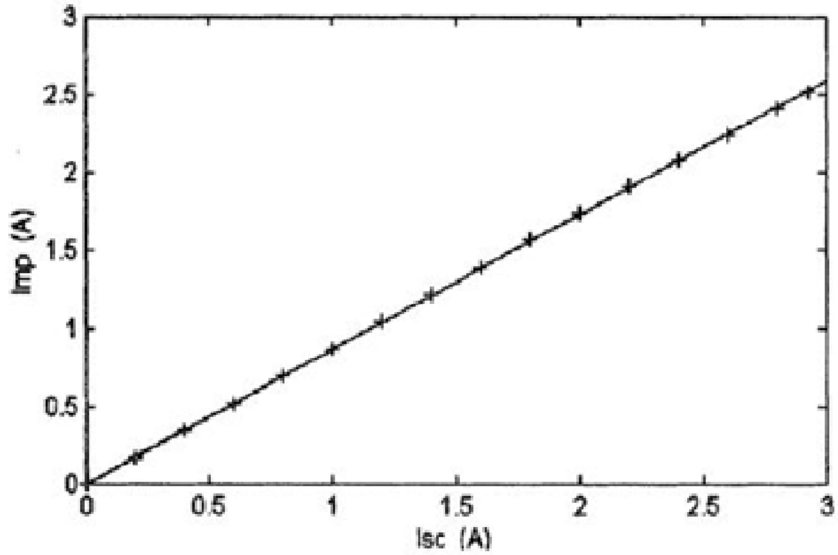


Figure 4: Dependence between "the current corresponding to maximum power" and "short circuit current" for an OFFC panel [51]

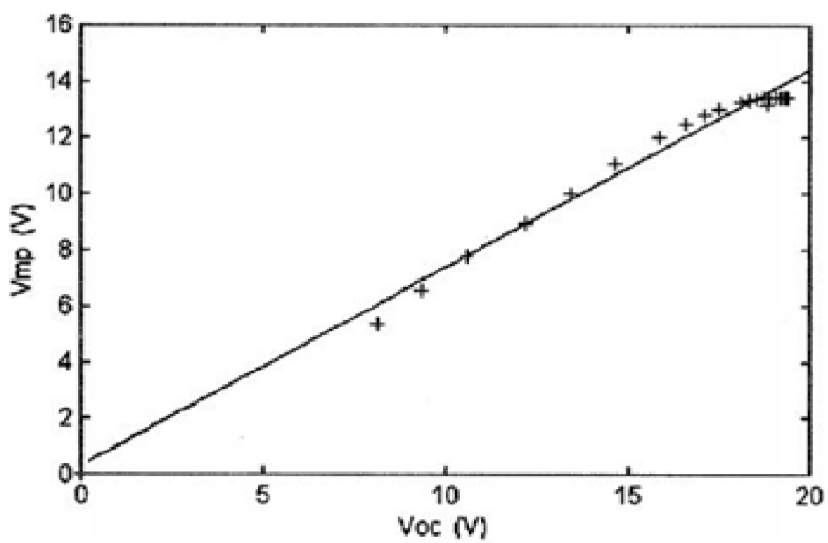


Figure 5: Dependence between "the voltage corresponding to the maximum power" and "open circuit voltage "for an OFFC panel [51]

$$FF = (Pmp / Isc * Voc) = k_i * k_v \tag{4}$$

(D) Output power delivered by MPPT

We called it Pload and it is the result of the arithmetic product of the current (Iload) and voltage (Vload) as:

$$\text{Pload} = \text{Iload} * \text{Vload} \tag{5}$$

(E) Performance factor

The performance factor (PF) is quite different from the energy efficiency of the MPPT. In fact, it is the ratio of the power extracted from the Pload and the maximum power that can generate the PVG (Pmp), under the same climatic conditions.

$$PF = (Pload\ /\ Pmp) * 100 \quad (6)$$

(F) Principle of the online measurement method

The principle of the proposed method resolves the sampling of the short-circuit current Isc and the open circuit voltage Voc in a Tsw period without a permanent disconnection of the MPPT from the PV conversion chain. Simply disconnect this MPPT during this period Tsw to take the open circuit voltage Voc then short-circuit the PVG to pick up the short-circuit current Isc then reconnect the MPPT to the PVG.

Given the temperature and radiation (two slow phenomena), these two main parameters that will modify the characteristic of a PV generator and which will cause a subsequent modification of the maximum power point, variations in time are negligible compared to the time switching period of the MPPT.

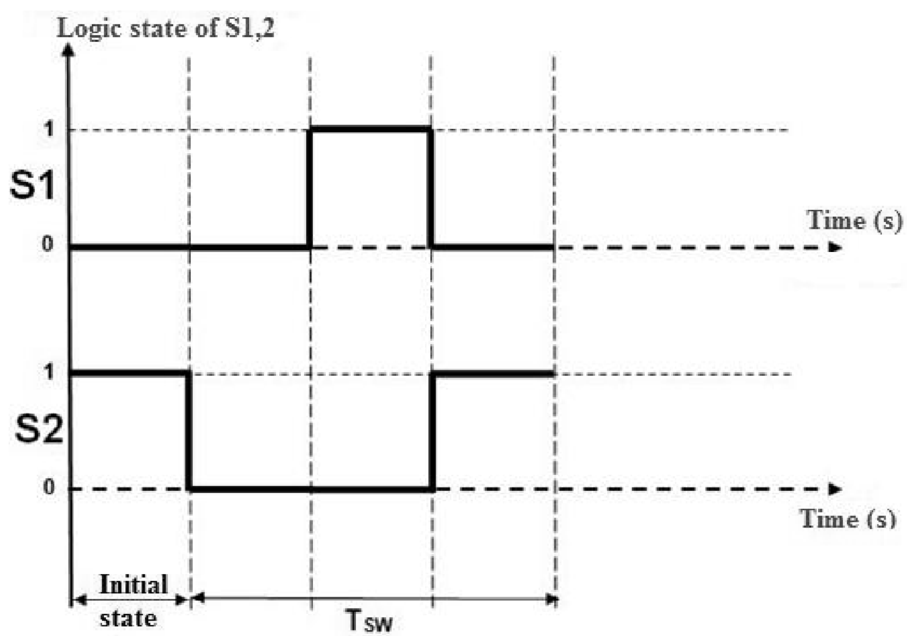


Figure 6: Logic state's chronogram of S1 and S2 for a Tsw period

with:

$$S_{1,2} = 1\text{: Switch On} \quad (7)$$

$$S_{1,2} = 0\text{: Switch Off} \quad (8)$$

Table 2
Switching scenario of S1 and S2 to ensure the online measure

STEP	*S1*	*S2*	*Action*
INITIAL	0	1	The MPPT is coupled to the PVG
1	0	0	Measuring the open circuit voltage Voc(PVG is isolated)
2	1	0	Measurement of short circuit current Isc current(PVG is shorted)
3	0	1	Measurement of current Iload and voltage Vload delivered to the load(MPPT is reconnected to the PVG)

(G) Measurement by redundancy

To ensure the reliability of our MPPT-PA system, we opted for the measurement by redundancy of the necessary values. This is resolved by the extent of N values of each parameter in one switching period Tsw and take the average of each parameter.

Table 3
Average of the parameter's values for the analysis

Parameters to measure	*Average value*
Short-circuit current Isc (A)	$\overline{I_{sc}} = \int_0^N \frac{I_{sc_n}}{N}$
Open circuit voltage Voc (V)	$\overline{V_{oc}} = \int_0^N \frac{V_{oc_n}}{N}$
Current delivered to the load by MPPT Iload (A)	$\overline{I_{load}} = \int_0^N \frac{I_{load_n}}{N}$
Voltage applied across the load by MPPT Vload (V)	$\overline{V_{load}} = \int_0^N \frac{V_{load_n}}{N}$

The switching device used in this work can reach a frequency up to 50hz which it can allow as to determine the time switching period Tsw for 10 samples using the equation below:

$$T_{SN} = N * t_{\text{one sample acquaring}} \tag{9}$$

with:

$t_{\text{one sample acquiring}}$: time to take single acquiring of four parameter's values.

(H) Errors in current, voltage and power

View that the performance factor is based on the relationship between the maximum power that can deliver the PVG and power delivering to load by the MPPT, this one can lead to errors on the components of powers mentioned previously (currents and voltages) as:

$$\Delta I = Imp - Iload \tag{10}$$

$$\Delta V = Vmp - Vload \tag{11}$$

$$\Delta P = Pmp - Pload \tag{12}$$

3. HARDWARE IMPLEMENTATION

MPPT-PA system includes a conversion part a transmission part a control part and a power switching part. Our MPPT-PA is designed on the basis of a Arduino uno card a current sensor's module a voltage divider as a voltage sensor's module and switch modules (relay).

4. SOFTWARE IMPLEMENTATION

The GUI has been completely developed in Labview environment provided by National Instruments. This allows great flexibility in relation to the available functions and adapts the test bench to the needs of the user.

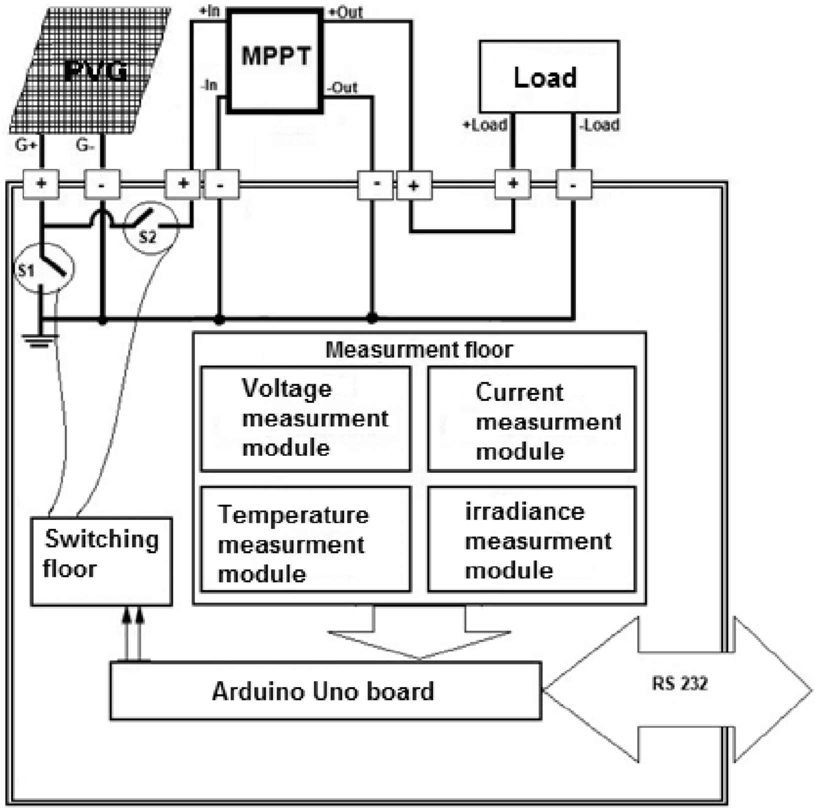


Figure 7: Block diagram of the modular structure of the MPPT-PA

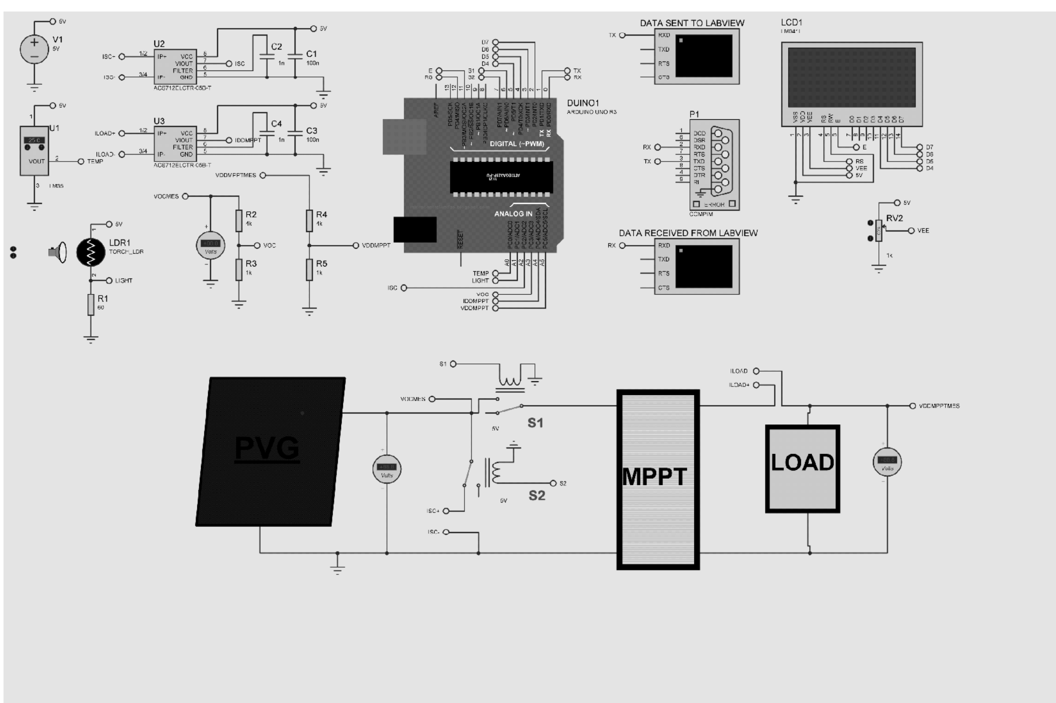


Figure 8: MPPT-PA implementation using ISIS-Proteus

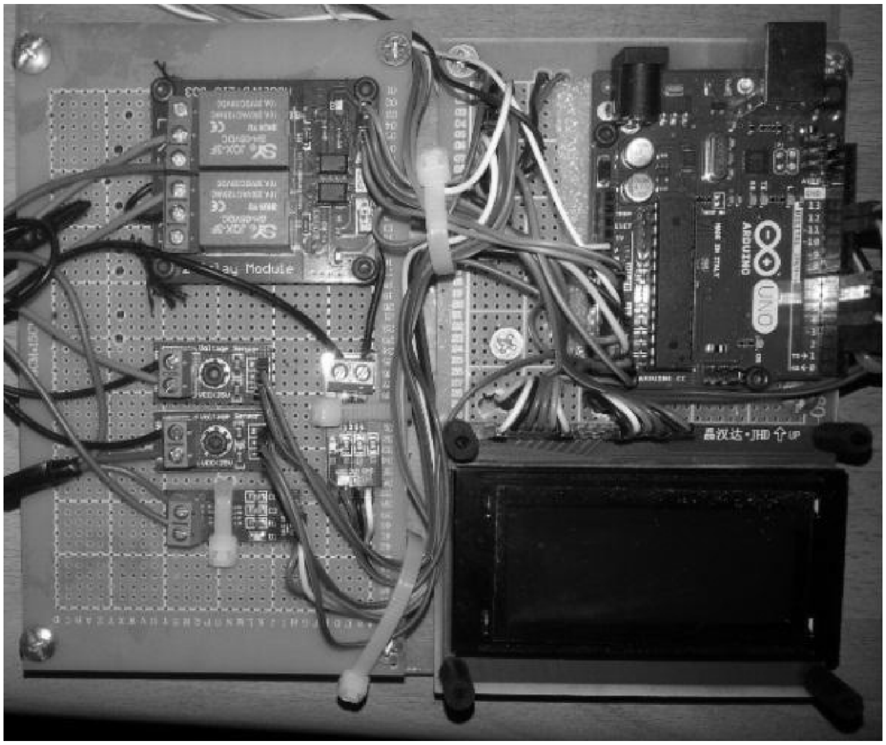


Figure 9: Developed MPPT-PA

Communication between this interface and the hardware part will be through the serial port by developing a well-studied protocol to prevent loss of information that can impact the judgment with respect to the performance of the MPPT.

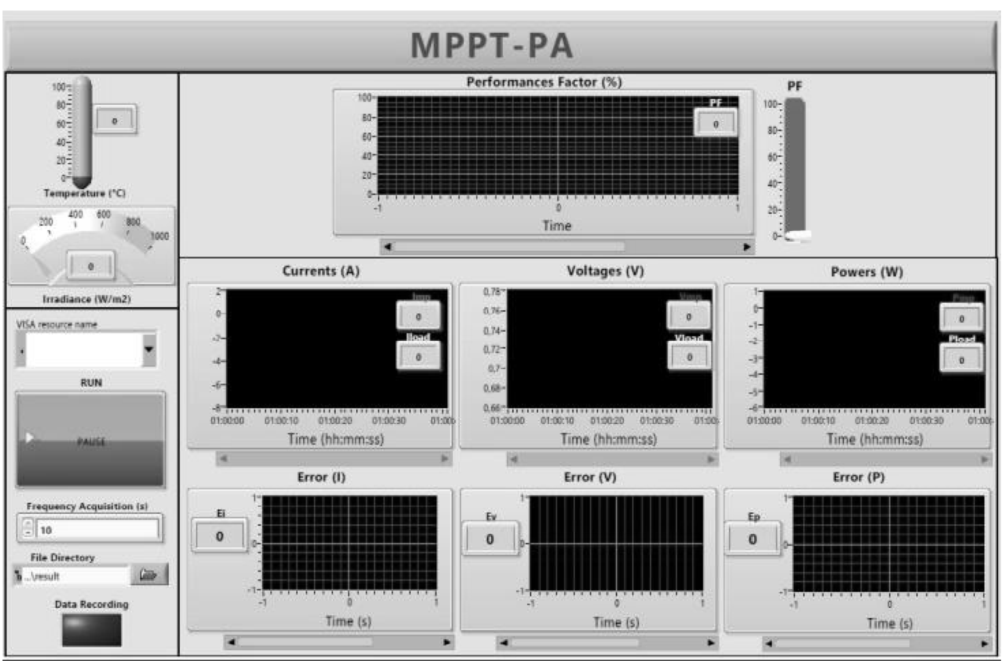


Figure 10: MPPT-PA GUI

It should be noted that the measure of two climatic parameters (temperature and irradiance) is made to have just an information on the conditions where the MPPT-PA device is working but they are not taken into account in the analysis process.

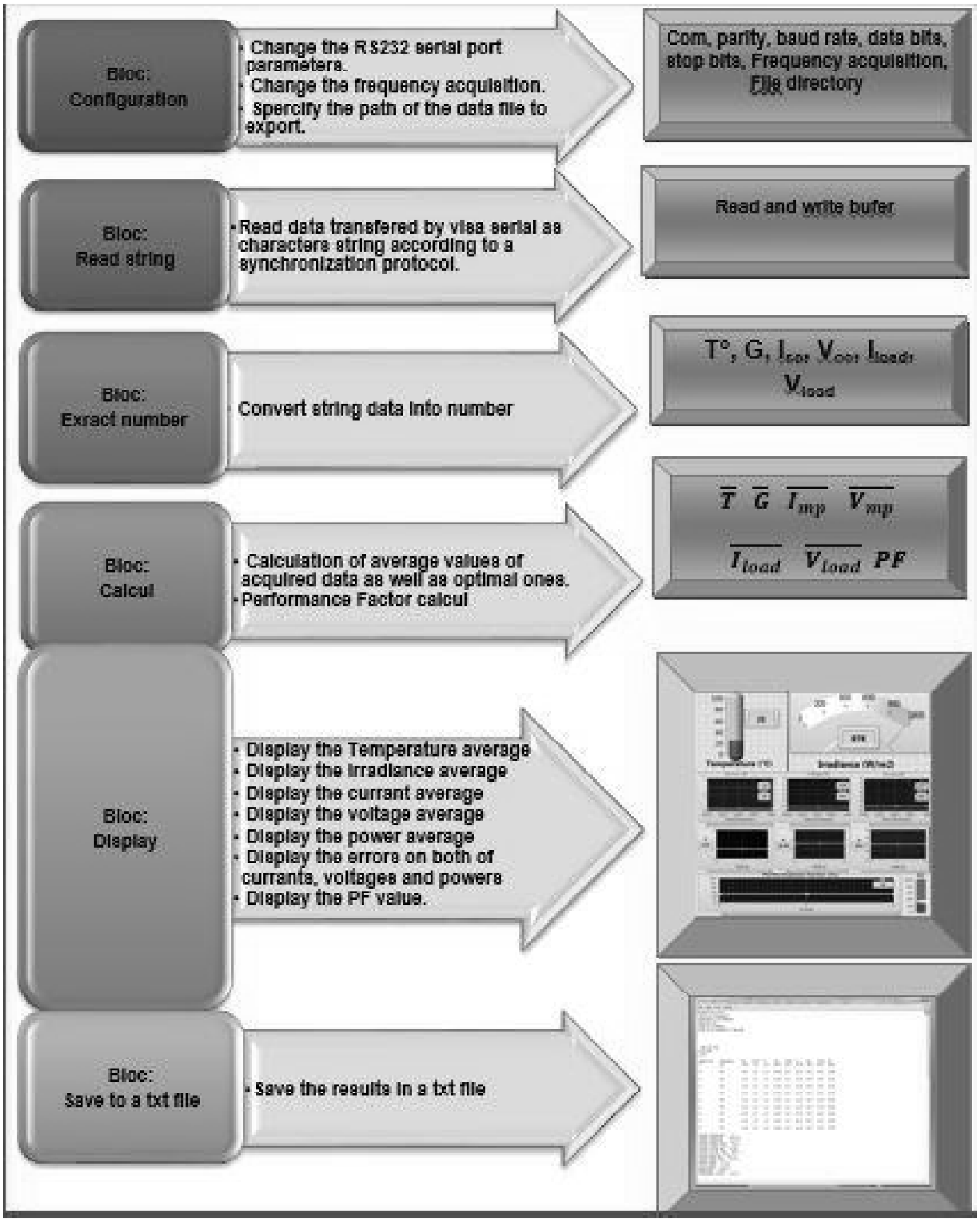


Figure 11: Schematic block diagram constituting the MPPT-PA interface

We used the Arduino Uno board it has the IC FTDI USB-to-serial. Instead of the usual serial port (DB9), it uses a Atmega8U2 programmed USB-to-serial converter. So this is to operate with a standard serial port RS232.

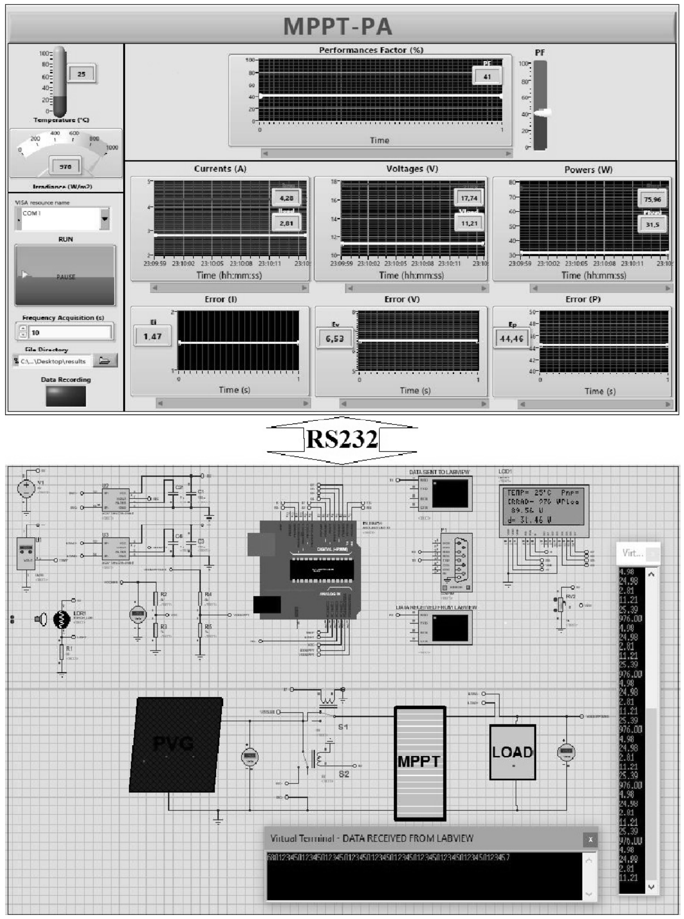
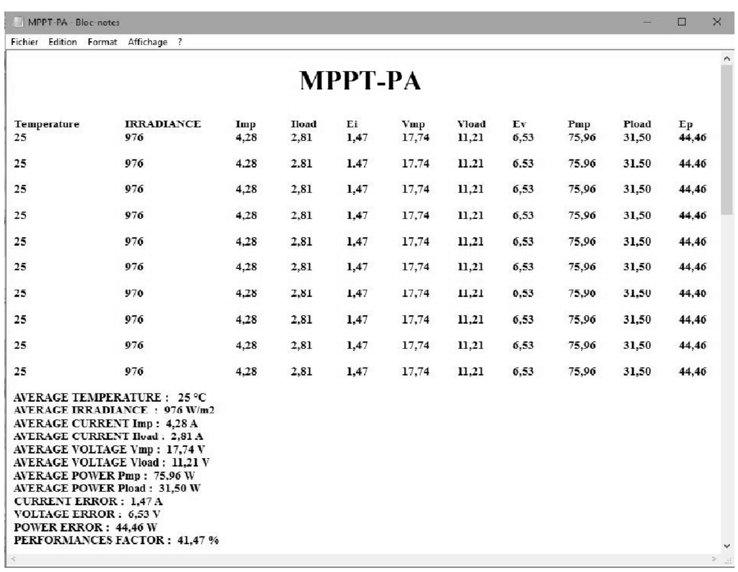


Figure 12: MPPT-PA simulation using ISIS proteus and GUI under Labview

To save the parameters describing the performance of the analyzed MPPT and the results of measurement and calculation, we used a VI that acquires an output file format txt.



MPPT-PA - Bloc-notes

Fichier Edition Format Affichage ?

MPPT-PA

Temperature	IRRADIANCE	Imp	Iload	Ei	Vmp	Vload	Ev	Pmp	Pload	Ep
25	976	4,28	2,81	1,47	17,74	11,21	6,53	75,96	31,50	44,46
25	976	4.28	2.81	1.47	17.74	11.21	6.53	75.96	31.50	44.46
25	976	4,28	2,81	1,47	17,74	11,21	6,53	75,96	31,50	44,46
25	976	4,28	2,81	1,47	17,74	11,21	6,53	75,96	31,50	44,46
25	976	4,28	2,81	1,47	17,74	11,21	6,53	75,96	31,50	44,46
25	976	4,28	2,81	1,47	17,74	11,21	6,53	75,96	31,50	44,46
25	970	4,28	2,81	1,47	17,74	11,21	0,53	75,90	31,50	44,40
25	976	4,28	2,81	1,47	17,74	11,21	6,53	75,96	31,50	44,46
25	976	4,28	2,81	1,47	17,74	11,21	6,53	75,96	31,50	44,46
25	976	4,28	2,81	1,47	17,74	11,21	6,53	75,96	31,50	44,46

AVERAGE TEMPERATURE : 25 °C
AVERAGE IRRADIANCE : 976 W/m2
AVERAGE CURRENT Imp : 4,28 A
AVERAGE CURRENT Iload : 2,81 A
AVERAGE VOLTAGE Vmp : 17,74 V
AVERAGE VOLTAGE Vload : 11,21 V
AVERAGE POWER Pmp : 75,96 W
AVERAGE POWER Pload : 31,50 W
CURRENT ERROR : 1,47 A
VOLTAGE ERROR : 6,53 V
POWER ERROR : 44,46 W
PERFORMANCES FACTOR : 41,47 %

Figure 13: Output file in txt format

For example, we have established a significant PVG model using Isis-Proteus with Isc = 5 A and Voc = 25,5 V feeding a resistive load of 4 Ù.

Using the k_i and k_v method as mentioned in [51] the maximum power is calculated as:

$Pmp = K_i * I_{sc} * K_v * V_{oc} = 77.85$ W

As at MPPT, we calculated a Ropt optimum strength corresponding to the point of maximum power.

The test results are displayed on the user interface and the output file.

In this case, we can see that the MPPT system used in this simulation is operating with 41.47 % at its performance

5. CONCLUSION

In general, the photovoltaic conversion system include a photovoltaic generator and a power conditioning system with an MPPT control and a load. As the PV generator thereof, has a relative characteristic of power. The maximum power remains only a single operating point defined by a known voltage and a current, called the maximum power point. The change in the position of this point is expressed in terms of climate parameters (temperature and light). This requires a tracking system of this point so that the maximum power is continuously generated. The major problem of the MPPTs, is the difficulty to validate their performances. It should be noted that few studies (or almost no) addressing this problem are cited in the literature. Therefore, the main objective of this paper is the development of a new method of analyzing based on the outdoor measurement of maximum power in dynamic mode and also the development of an electronic device that could serve as an analyzer helping tool.

This device, which we called MPPT-PA will be responsible for monitoring the MPPT performance through a user interface developed in LABVIEW.

A performance factor was calculated to give an idea about at what percentage is this MPPT is performing.

It should be noted that the feature of this device is that the values of temperature and irradiance are not required in this process.

REFERENCES

[1] E. Koutroulis, K. Kalaitzakis and N.C. Voulgaris. “Development of a microcontroller-based, photovoltaic maximum power point tracking control system”, *IEEE Transactions on Power Electronics*, 16 (1), 46-54, 2001.

[2] K. Shankar, M. Thangaraj, and A. Abudhahir. “Performance analysis of mppt algorithms for enhancing the efficiency of spv power generation system: A simulation study.” 2013 International Conference on Emerging Trends in VLSI, Embedded System, Nano Electronics and Telecommunication System (ICEVENT),. IEEE, 2013.

[3] L. Abderezak, B. Aissa, and S. Hamza. “Comparative study of three MPPT algorithms for a photovoltaic system control.” 2015 World Congress on Information Technology and Computer Applications Congress (WCITCA), IEEE, 2015.

[4] 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*, 55 (7), 2622-2628, 2008.

[5] X. Xiao, X. Huang, and Q. Kang. “A hill-climbing-method-based maximum-power-point-tracking strategy for direct-drive wave energy converters.” *IEEE Transactions on Industrial Electronics*, 63 (1), 257-267, 2016.

[6] S.B. Kjaer, “Evaluation of the “hill climbing” and the “incremental conductance” maximum power point trackers for photovoltaic power systems.” *IEEE Transactions on Energy Conversion*, 27 (4), 922-929, 2012.

[7] B.N. Alajmi, K.H. Ahmed, S.J. Finney and B.W. Williams, “Fuzzy-logic-control approach of a modified hill-climbing method for maximum power point in microgrid standalone photovoltaic system.” *IEEE Transactions on Power Electronics,* 26 (4), 1022-1030, 2011.

[8] H. Al-Atrash, I. Batarseh, and K. Rustom. "Effect of measurement noise and bias on hill-climbing MPPT algorithms." *IEEE Transactions on Aerospace and Electronic Systems*, 46 (2), 745-760, 2010.

[9] C. Manickam, G.R. Raman, G.P. Raman, S.I. Ganesan and C. Nagamani, "A hybrid algorithm for tracking of GMPP based on P&O and PSO with reduced power oscillation in string inverters." *IEEE Transactions on Industrial Electronics*, 63 (10), 6097-6106, 2016.

[10] J. Ahmed and Z. Salam. "A modified P&O maximum power point tracking method with reduced steady-state oscillation and improved tracking efficiency." *IEEE Transactions on Sustainable Energy,* 7 (4), 1506-1515, 2016.

[11] M.W. Rahman, C. Bathina, V. Karthikeyan and R. Prasanth, "Comparative analysis of developed incremental conductance (IC) and perturb & observe (P&O) MPPT algorithm for photovoltaic applications." 10th IEEE International Conference on Intelligent Systems and Control (ISCO), Jan 7-8, 2016.

[12] K. Sundareswaran, V. Vigneshkumar, P. Sankar, S.P. Simon, P.S.R. Nayak and S. Palani, Development of an improved P&O algorithm assisted through a colony of foraging ants for MPPT in PV system." *IEEE Transactions on Industrial Informatics*, 12 (1), 187-200, 2016.

[13] K. Sundareswaran, V. Vigneshkumar, S.P. Simon and P.S.R. Nayak, "Gravitational search algorithm combined with P & O method for MPPT in PV systems." 2016 IEEE Annual India Conference (INDICON), 2016.

[14] Y. Jaisa-ard and A. Jangwanitlert. "Interleaved buck-boost charger by using automatically selective technique between P&O and Lookup Table for novel MPPT application." 13th IEEE International Conference on Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2016.

[15] E.K. Anto, J.A. Asumadu, and P.Y. Okyere. "PID control for improving P&O-MPPT performance of a grid-connected solar PV system with Ziegler-Nichols tuning method." 11th IEEE Conference on Industrial Electronics and Applications (ICIEA), 2016.

[16] B. Hossam and K. Itako. "Real time hotspot detection using scan-method adopted with P&O MPPT for PV generation system." IEEE Annual Southern Power Electronics Conference (SPEC), 2016.

[17] M. Farhat, O. Barambones, and L. Sbita, "A real-time implementation of MPPT-based on P&O method." 5th IEEE International Conference on Electronic Devices, Systems and Applications (ICEDSA), 2016.

[18] R.H. Ashique, Z. Salam, and J. Ahmed. "An adaptive P&O MPPT using a sectionalized piece-wise linear PV curve." 2015 IEEE Conference on Energy Conversion (CENCON), 2015.

[19] M. Killi and S. Samanta, "Modified perturb and observe MPPT algorithm for drift avoidance in photovoltaic systems." *IEEE Transactions on Industrial Electronics*, 62 (9), 5549-5559, 2015.

[20] S.K. Kollimalla and M.K. Mishra. "A novel adaptive P & O MPPT algorithm considering sudden changes in the irradiance." *IEEE Transactions on Energy Conversion*, 29 (3), 602-610, 2014.

[21] N. Femia, D. Granozio, G. Petrone and M. Vitelli, "Predictive & adaptive MPPT perturb and observe method." *IEEE Transactions on Aerospace and Electronic Systems*, 43 (3), 934-950, 2007.

[22] N. Femia, G. Petrone, G. Spagnuolo and M. Vitelli, "Optimization of perturb and observe maximum power point tracking method." *IEEE Transactions on Power Electronics*, 20 (4), 963-973, 2005.

[23] M.A. Elgendy, D.J. Atkinson, and B. Zahawi. "Experimental investigation of the incremental conductance maximum power point tracking algorithm at high perturbation rates." *IET Renewable Power Generation*, 10 (2), 133-139, 2016.

[24] N.E. Zakzouk, M.A. Elsaharty, A.K. Abdelsalam, A.A. Helal and B.W. Williams, "Improved performance low-cost incremental conductance PV MPPT technique." *IET Renewable Power Generation*, 10 (4), 561-574, 2016.

[25] R. Faraji, A. Rouholamini, H.R. Naji, R. Fadaeinedjad and M.R. Chavoshian, "FPGA-based real time incremental conductance maximum power point tracking controller for photovoltaic systems." *IET Power Electronics*, 7 (5), 1294-1304, 2014.

[26] K.S. Tey and S. Mekhilef. "Modified incremental conductance algorithm for photovoltaic system under partial shading conditions and load variation." *IEEE Transactions on Industrial Electronics*, 61 (10), 5384-5392, 2014.

[27] S. Dezso, M. Laszlo, T. Kerekes, S.V. Spataru and R. Teodorescu, "On the perturb-and-observe and incremental conductance MPPT methods for PV systems." *IEEE Journal of Photovoltaics*, 3 (3), 1070-1078, 2013.

[28] G.C. Hsieh, H.I. Hsieh, C.Y. Tsai and C.H. Wang, "Photovoltaic power-increment-aided incremental-conductance MPPT with two-phased tracking." *IEEE Transactions on Power Electronics,* 28 (6), 2895-2911, 2013.

[29] Q. Mei, M. Shan, L. Liu and J.M. Guerrero, "A novel improved variable step-size incremental-resistance MPPT method for PV systems." *IEEE Transactions on Industrial Electronics*, 58 (6), 2427-2434, 2011.

[30] 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*, 55 (7), 2622-2628, 2008.

[31] L.M. Elobaid, A.K. Abdelsalam, and E.E. Zakzouk. "Artificial neural network-based photovoltaic maximum power point tracking techniques: a survey." *IET Renewable Power Generation*, 9 (8), 1043-1063, 2015.

[32] A.E. Khateb, N.A. Rahim, J. Selvaraj and M.N. Uddin, "Fuzzy-logic-controller-based SEPIC converter for maximum power point tracking." *IEEE Transactions on Industry Applications,* 50 (4), 2349-2358, 2014.

[33] A. Al Nabulsi and R. Dhaouadi, "Efficiency optimization of a DSP-based standalone PV system using fuzzy logic and dual-MPPT control." *IEEE Transactions on Industrial Informatics*, 8 (3), 573-584, 2012.

[34] B.N. Alajmi, K.H. Ahmed, S.J. Finney and B.W. Williams, "Fuzzy-logic-control approach of a modified hill-climbing method for maximum power point in microgrid standalone photovoltaic system." *IEEE Transactions on Power Electronics*, 26 (4), 1022-1030, 2011.

[35] W.M. Lin, C.M. Hong, and C.H. Chen. "Neural-network-based MPPT control of a stand-alone hybrid power generation system." *IEEE Transactions on Power Electronics*, 26 (12), 3571-3581, 2011.

[36] E. Karatepe and T. Hiyama. "Artificial neural network-polar coordinated fuzzy controller based maximum power point tracking control under partially shaded conditions." *IET Renewable Power Generation,* 3 (2), 239-253, 2009.

[37] T.A. Ocran, J. Cao, B. Cao, and X. Sun, "Artificial neural network maximum power point tracker for solar electric vehicle." *Tsinghua Science & Technology*, 10 (2), 204-208, 2005.

[38] C. Manickam, G.R. Raman, G.P. Raman, S.I. Ganesan and C. Nagamani, "A hybrid algorithm for tracking of GMPP based on P&O and PSO with reduced power oscillation in string inverters." *IEEE Transactions on Industrial Electronics*, 63 (10), 6097-6106, 2016.

[39] F.M. de Oliveira, S.A. Olveira da Silva, F.R. Durand, L.P. Sampaio, V.D. Bacon and L.B.G. Campanhol, "Grid-tied photovoltaic system based on PSO MPPT technique with active power line conditioning." *IET Power Electronics*, 9 (6), 1180-1191, 2016.

[40] V.N. Lal and S.N. Singh. "Modified particle swarm optimisation-based maximum power point tracking controller for single-stage utility-scale photovoltaic system with reactive power injection capability." *IET Renewable Power Generation*, 10 (7), 899-907, 2016.

[41] H. Renaudineau, F. Donatantonio, J. Fontchastagner, G. Petrone, G. Spagnuolo, J.P. Martin and S. Pierfederici, "A PSO-based global MPPT technique for distributed PV power generation." *IEEE Transactions on Industrial Electronics*, 62 (2), 1047-1058, 2015.

[42] M. Seyedmahmoudian, R. Rahmani, S. Mekhilef, A.M.T. Oo, A. Stojcevski, T.K. Soon and A.S. Ghandhari, "Simulation and hardware implementation of new maximum power point tracking technique for partially shaded PV system using hybrid DEPSO method." *IEEE Transactions on Sustainable Energy*, 6 (3), 850-862, 2015.

[43] K.L. Lian, J.H. Jhang, and I.S. Tian, "A maximum power point tracking method based on perturb-and-observe combined with particle swarm optimization." *IEEE Journal of Photovoltaics*, 4 (2), 626-633, 2014.

[44] K. Ishaque and Z. Salam, "A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition." *IEEE Transactions on Industrial Electronics*, 60 (8), 3195-3206, 2013.

[45] Y.H. Liu, S.C. Huang, J.W. Huang and W.C. Liang, "A particle swarm optimization-based maximum power point tracking algorithm for PV systems operating under partially shaded conditions." *IEEE Transactions on Energy Conversion*, 27 (4), 1027-1035, 2012.

[46] K. Ishaque, Z. Salam, M. Amjad and S. Mekhilef, "An improved particle swarm optimization (PSO)–based MPPT for PV with reduced steady-state oscillation," *IEEE Transactions on Power Electronics*, 27 (8), 3627-3638, 2012.

[47] M. Miyatake, M. Veerachary, F. Toriumi, N. Fuji and H. Ko, "Maximum power point tracking of multiple photovoltaic arrays: A PSO approach," *IEEE Transactions on Aerospace and Electronic Systems*, 47 (1), 367-380, 2011.

[48] A.A.S. Mohamed, A. Berzoy, and O.A. Mohammed. "Design and hardware Implementation of FL-MPPT control of PV systems based on GA and small-signal analysis," *IEEE Transactions on Sustainable Energy*, 8 (1), 279-290, 2017.

[49] A. Dolara, R. Faranda and S. Leva, "Energy comparison of seven MPPT techniques for PV systems." *Journal of Electromagnetic Analysis and Applications,* 1 (3), 152-162, 2009.

[50] M. Jantsch, M. Real, H. Haberlin, C. Whitaker, K. Kurokawa, G. Blasser, P. Kremer and C.W.G. Verhoeve, "Measurement of PV maximum power point tracking performance," Netherlands Energy Research Foundation, ECN, 1997.

[51] M.A.S. Masoum, H. Dehbonei and E.F. Fuchs, "Theoretical and experimental analyses of photovoltaic systems with voltage and current-based maximum power-point tracking." *IEEE Transactions on Energy Conversion*, 17 (4), 514-522, 2002.

[52] A.T. Azar and S. Vaidyanathan, *Chaos Modeling and Control Systems Design*, Springer, Berlin, Germany, 2015.

[53] A.T. Azar and S. Vaidyanathan, *Advances in Chaos Theory and Intelligent Control*, Springer, Berlin, Germany, 2016.

[54] S. Vaidyanathan and C. Volos, *Advances and Applications in Nonlinear Control Systems*, Springer, Berlin, Germany, 2016.

[55] S. Vaidyanathan and C. Volos, *Advances and Applications in Chaotic Systems*, Springer, Berlin, 2016.

[56] S. Vaidyanathan and C. Volos, *Advances in Memristors, Memristive Devices and Systems*, Springer, Berlin, 2017.

[57] S. Vaidyanathan and C.H. Lien, *Applications of Sliding Mode Control in Science and Engineering*, Springer, Berlin, 2017.

[58] S. Vaidyanathan, "A novel 3-D conservative chaotic system with sinusoidal nonlinearity and its adaptive control", *International Journal of Control Theory and Applications,* 9 (1), 115-132, 2016.

[59] S. Vaidyanathan and S. Pakiriswamy, "A five-term 3-D novel conservative chaotic system and its generalized projective synchronization via adaptive control method*", International Journal of Control Theory and Applications*, 9 (1), 61-78, 2016.

[60] V.T. Pham, S. Jafari, C. Volos, A. Giakoumis, S. Vaidyanathan and T. Kapitaniak, "A chaotic system with equilibria located on the rounded square loop and its circuit implementation," *IEEE Transactions on Circuits and Systems-II: Express Briefs*, 63 (9), 2016.

[61] S. Vaidyanathan and S. Sampath, "Anti-synchronisation of identical chaotic systems via novel sliding control and its application to a novel chaotic system," *International Journal of Modelling, Identification and Control*, 27 (1), 3-13, 2017.

[62] S. Vaidyanathan, K. Madhavan and B.A. Idowu, "Backstepping control design for the adaptive stabilization and synchronization of the Pandey jerk chaotic system with unknown parameters," *International Journal of Control Theory and Applications*, 9 (1), 299-319, 2016.

[63] R.K. Goyal, S. Kaushal and S. Vaidyanathan, "Fuzzy AHP for control of data transmission by network selection in heterogeneous wireless networks," *International Journal of Control Theory and Applications*, 9 (1), 133-140, 2016.

[64] C.K. Volos, D. Prousalis, I.M. Kyprianidis, I. Stouboulos, S. Vaidyanathan and V.T. Pham, "Synchronization and anti-synchronization of coupled Hindmarsh-Rose neuron models," *International Journal of Control Theory and Applications*, 9 (1), 101-114, 2016.

[65] S.M.B. Mansour and V. Sundarapandian, "Design and control with improved predictive algorithm for obstacles detection for two wheeled mobile robot navigation," *International Journal of Control Theory and Applications*, 9 (38), 37-54, 2016.

[66] A. Ouannas, A.T. Azar and S. Vaidyanathan, "A robust method for new fractional hybrid chaos synchronization," *Mathematical Methods in the Applied Sciences*, 40 (5), 1804-1812, 2017.

[67] S. Vaidyanathan and S. Sampath, "Anti-synchronisation of identical chaotic systems via novel sliding control and its application to a novel chaotic system," *International Journal of Modelling, Identification and Control*, 27 (1), 3-13, 2017.

[68] A. Ouannas, A.T. Azar and S. Vaidyanathan, "New hybrid synchronisation schemes based on coexistence of various types of synchronisation between master-slave hyperchaotic systems," *International Journal of Computer Applications in Technology*, 55 (2), 112-120, 2017.

[69] S. Vaidyanathan, "A conservative hyperchaotic hyperjerk system based on memristive device," *Studies in Computational Intelligence*, 701, 393-423, 2017.

[70] B. Raj and S. Vaidyanathan, "Analysis of dynamic linear memristor device models," *Studies in Computational Intelligence*, 701, 449-476.