Performance Analysis of a Maximum Power Point Tracking Technique Using Silver Mean Method

Shobha Rani DEPURU[1], *Muralidhar MAHANKALI*[2]

[1]Department of Electrical and Electronics Engineering, Institute of Aeronautical Engineering, Jawaharlal Nehru Outer Ring Road, Dundigal, Hyderabad, Telangana 500043, India
[2]Department of Electrical and Electronics Engineering, Sri Venkateswara University College of Engineering, Gandhi Road, Sri Padmavati Mahila Visvavidyalayam, Tirupati, Andhra Pradesh 517502, India

depuru_shobha@yahoo.com, muralidhar6666@gmail.com

DOI: 10.15598/aeee.v16i1.2249

Abstract. *The proposed paper presents a simple and particularly efficacious Maximum Power Point Tracking (MPPT) algorithm based on Silver Mean Method (SMM). This method operates by choosing a search interval from the P-V characteristics of the given solar array and converges to MPP of the Solar Photo-Voltaic (SPV) system by shrinking its interval. After achieving the maximum power, the algorithm stops shrinking and maintains constant voltage until the next interval is decided. The tracking capability efficiency and performance analysis of the proposed algorithm are validated by the simulation and experimental results with a 100 W solar panel for variable temperature and irradiance conditions. The results obtained confirm that even without any perturbation and observation process, the proposed method still outperforms the traditional perturb and observe (P&O) method by demonstrating far better steady state output, more accuracy and higher efficiency.*

Keywords

Irradiance, maximum power point tracking, perturb and observe, silver mean method, solar photovoltaic system.

1. Introduction

SPV systems have the ability to convert solar power directly into electrical power. As solar energy is widely available and easily accessible, solar power generating systems are distinctly suitable as independent power supply. However, there are two major drawbacks of the SPV systems, the low energy conversion efficiency and high initial cost. The energy efficiency can be improved by tracking the maximum power from the sun irrespective of environmental conditions. Thus, maximum extraction of power is an enforced job that needs various methods to be adapted. Moreover, the output power of a PV panel is determined by the chief atmospheric factors such as the solar irradiance and the temperature. Hence, it is worth tracking maximum power from the PV system by introducing a new MPPT algorithm.

Various MPPT techniques have been proposed for Maximum Power Tracking (MPP) by using different control strategies.

Veerachary et al. [1] presented a converter based on PV cell voltage which has shown low ripple content and improved the array performance. But this method needs to detect the solar array power output and load power detection using the instantaneous voltage and current information, requiring voltage and current sensors.

Henry et al. [2] demonstrated a simple and elegant technique using SEPIC converter which can be used under a wide range of meteorological conditions.

Salas et al. [3] implemented a new tracker based on PV current which yields better results. But when experimentally compared with conventional methods, it has shown to consume more computational time .

Jancarle et al. [4] experimentally implemented a micro-controlled maximum power point tracker which improves the converter efficiency and reduces the electro-magnetic interference level. However, under the variable climatic conditions, the technique cannot operate efficiently.

Karils et al. [5] implemented Fuzzy Cognitive Networks (FCN) to a PV system which has good performance during different irradiance and temperature conditions. Nonetheless, in fuzzy implementation, several parameters are selected on a trial and error basis, which mainly depends on designer experience and intuition. To overcome these disadvantages, a fuzzy neural network based MP point tracking is proposed.

Hence, MPPT schemes are evaluated based on system response, efficiency, implementation complexity, accuracy and stability.Several recently proposed optimization techniques have been referred to evaluate the MPPT tracking schemes based on system response, efficiency, implementation complexity, accuracy and stability [6], [7], [8], [9], [10], [11], [12], [13], [14] and [15].

Among the existing MPPT algorithms, the traditional P&O method is widely employed because of easy implementation and low cost. Nevertheless, P&O method requires much time to track the MPP, as it compares power before and after perturbation.Vast amount of oscillations are observed at MPP which reduces system efficiency. In order to overcome the demerits associated with the traditional method, a simple and efficient MPPT algorithm based on SMM is proposed in this paper, which chooses the search interval from the PV characteristic of the system. Efficiency and performance of the proposed algorithm are calculated and compared with that of the traditional P&O. Figure 1 depicts the basic prototype of the PV system which consists of an SPV array, a boost converter and the proposed MPPT controller connected to the load system.The voltage and current generated by SPV array are the inputs of the MPPT system, and the task of the MPPT algorithm is to track the maximum power irrespective of environmental conditions. The PV array and the DC-DC boost converter of the system are modeled and simulated using MATLAB/simulink.

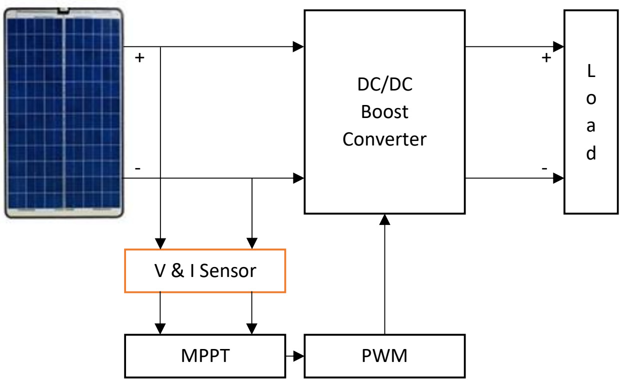

Fig. 1: Configuaration of the proposed SMM system.

The rest of the paper is organized as follows: Sec. 2. and Sec. 3. depicts the PV cell mathematical modeling and the boost converter modelling, respectively. The proposed MPPT method is presented in Sec. 4. In Sec. 5. the performance analysis based on simulation and experimental results are given in detail, and Sec. 6. summarizes the conclusion.

2. PV Cell Mathematical Modeling

A solar cell is usually quite small, producing about 1 or 2 W of power, yet forming a basic building block of any SPV system. The PV cells have to be connected together in the form of large units, called modules, to boost the power output. The modules, in turn, can be connected to form larger units called arrays, which can be interconnected to produce more power. The output voltage can be increased by connecting the cells or modules in series, whereas the output current can be enhanced by connecting the cells or modules in parallel. The equivalent circuit of a PV cell is shown in Fig. 2, which consists of a current source (I_{ph}), a diode, a series resistance (R_s) and a parallel resistance (R_{sh}). The parallel resistance is infinite, and the series resistance is zero for an ideal PV cell.The output current of an ideal PV cell is given by the Eq. (1) and Eq. (2).

$$I_{pv} = I_{ph} - I_d - I_{sh}, \tag{1}$$

$$I_{pv} = I_{ph} - I_s e^{\left(\frac{qv}{kTA}-1\right)} - \frac{V_{pv}}{R_{sh}}, \tag{2}$$

where I_{pv} is the solar output current, I_d is the solar diode current, I_{sh} is the solar shunt current, I_s is the saturation current, q is the electron charge $(1.6 \cdot 10^{-19}$ (C)), k is Boltzmann constant $(1.38 \cdot 10^{-23}$ (J·K^{-1})), A is the diode ideality factor and T is the PV cell temperature (K).

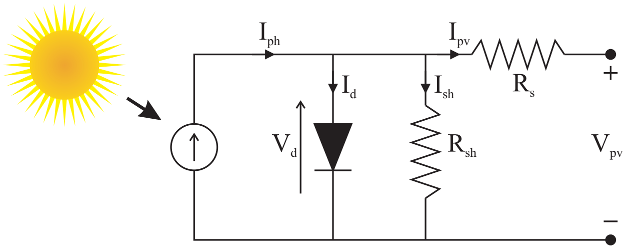

Fig. 2: PV Cell Equivalent Circuit.

The PV cells are connected in series or parallel combinations to increase the output voltage or the output current [16]. Let N_s be the number of cells connected in series and N_p the number of cells connected in parallel, then the output current of an ideal PV cell is given by the Eq. (3).

$$I_{pv} = N_p I_{ph} - N_p I_s \left(e^{\frac{qv}{N_s AkT}} - 1 \right). \tag{3}$$

The solar panel specifications for the proposed system are summarized in Tab. 1. The P-V and I-V curves

Tab. 1: PV panel specifications.

Parameter	Value
Short circuit current(I_{sc})	5.75 A
Open circuit voltage (V_{oc})	22.5 V
Maximum current ($I_{\max}$)	5.29 A
Maximum voltage($V_{\max}$)	18.9 V
Maximum power ($P_{\max}$)	100 W

at different irradiances and constant temperature of 25 °C is shown in Fig. 3, and the P-V and I-V curves at different temperatures and constant irradiance of 1000 W·m^{-2} are shown in Fig. 4. From Fig. 3, it is observed that with the increase in solar irradiance at constant ambient temperature, the current for the same voltage increases, and similarly, the maximum power also increases. The solar PV power increases nonlinearly with the increase in solar irradiance. From Fig. 4, it is observed that for a constant solar irradiance, as the ambient temperature increases, both the maximum power and the open circuit voltage decreases. Hence,the best climate condition for a solar PV cell is high solar irradiation and low ambient temperature.

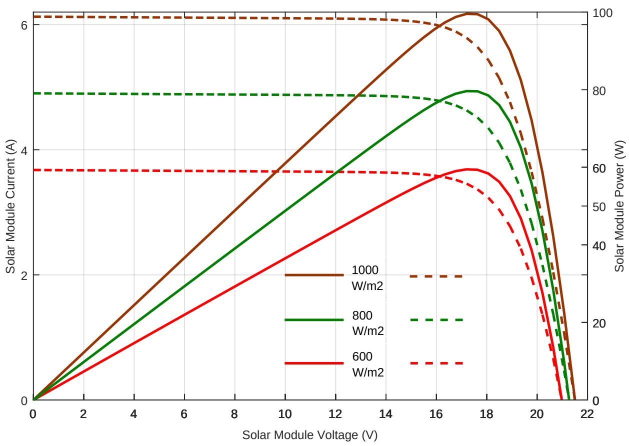

Fig. 3: P-V and I-V curves at variable irradiance and constant temperature of 25 °C.

3. Boost Converter Modeling

A DC-DC converter is employed to enhance the effectiveness of the PV system by equaling the voltage generated by PV array to the voltage required by the load. The input voltage of the converter is the solar module output voltage V_{pv} that varies all the time. However, its output voltage V_{dc} must be kept at a desired value. This is done by controlling the duty ratio, so that the operating point of the PV system can be adjusted to realize MPPT algorithm [17], [18] and [19]. A boost converter is chosen to control the PV module's output voltage. The duty ratio 'D' of the boost converter is evaluated by employing the input-output relationship as shown in Eq. (4) [20], [21], [22] and [23]. The equivalent circuit of the DC-DC boost converter is shown in Fig. 5, and the design parameters of the boost converter components specified in the proposed system are given in Tab. 2. The boost converter parameters are selected so that the performance of the proposed system is not deteriorated even under the low solar irradiance conditions.

$$D = \frac{V_{dc}}{V_{dc} + V_{pv}}. \tag{4}$$

Tab. 2: Boost converter specifications.

Parameter	Value
Filter capacitor	6 µF
Filter Inductor	10 mH
DC bus capacitor	470 µF
Switching frequency	25 kHz

4. Proposed Maximum Power Point Tracking Method

Due to low cost and simple implementation, P&O method is generally preferred for the tracking of maximum power from the solar panels. But the perturbation methodology involved in the tracker creates slow response and also generates oscillations after reaching MPP [24], [25] and [26]. Hence, a classical technique based on silver mean is proposed in this paper for optimizing the functions. Silver mean of two quantities is defined as the ratio of the sum of the smaller and twice the larger of those quantities, to the larger quantity, which is the same as the ratio of the larger to the smaller quantity. Let a be the larger quantity and b the smaller quantity in a search area and let α_S be the silver mean constant. Mathematically, it is expressed

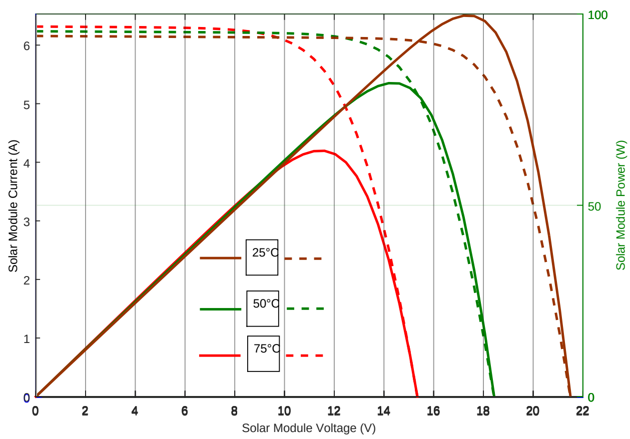

Fig. 4: P-V and I-V curves at variable temperature and constant irradiance of 1000 W·m^{-2}.

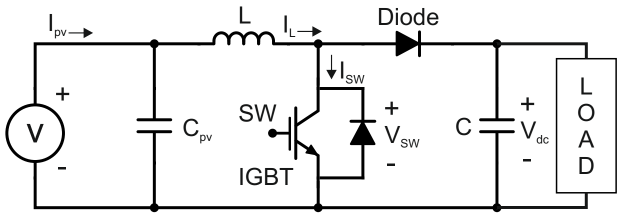

Fig. 5: Equivalent circuit of a DC-DC boost converter.

by the following Eq. (5), Eq. (6), Eq. (7) and Eq. (8).

$$\frac{2a+b}{a} = \frac{a}{b} = \alpha_S, \tag{5}$$

$$2 + \frac{b}{a} = \frac{a}{b} = \alpha_S, \tag{6}$$

$$2 + \frac{1}{\alpha_S} = \alpha_S, \tag{7}$$

$$\alpha_S^2 - 2\alpha_S - 1 = 0. \tag{8}$$

The silver mean α_S conjugate value is 0.41, which is obtained from the ratios of larger and smaller quantities. Using the conjugate value, the optimization function is chosen from P-V curve as a closed interval $[a, b]$ which is equal to $[0, V_{OC}]$. Since MPP of the PV system always stays close to the open interval, it can be further reduced from the left of the P-V curve. Initially, the two voltages V_1 and V_2 obtained in the interval $[a, b]$ are given in Eq. (9) and Eq. (10).

$$V_1 = a + 0.41(b - a), \tag{9}$$

$$V_2 = b - 0.41(b - a). \tag{10}$$

Corresponding powers at P (V_1) and P (V_2) are obtained from the PV system. By comparing the obtained powers, the interval shrinks either to $[a, V_1]$ or $[b, V_2]$. The iterations are further continued until the condition $V_2 - V_1 \leq \varepsilon$ is satisfied. The algorithm for the proposed SMM based MPPT is shown in Fig. 6. This algorithm operates in a given interval and converges to MPP of the PV system by shrinking its interval. After achieving MPP, the proposed algorithm stops shrinking and maintains constant voltage until the next interval is decided.

The proposed MPPT controller can thus be used to track the maximum power. This algorithm has an advantage over P&O in that it can determine when the MPPT controller has reached the MPP, whereas P&O oscillates around the MPP. Also, this method can track the rapidly increasing and decreasing irradiance conditions with higher accuracy than P&O [27], [28], [29], [30] and [31].

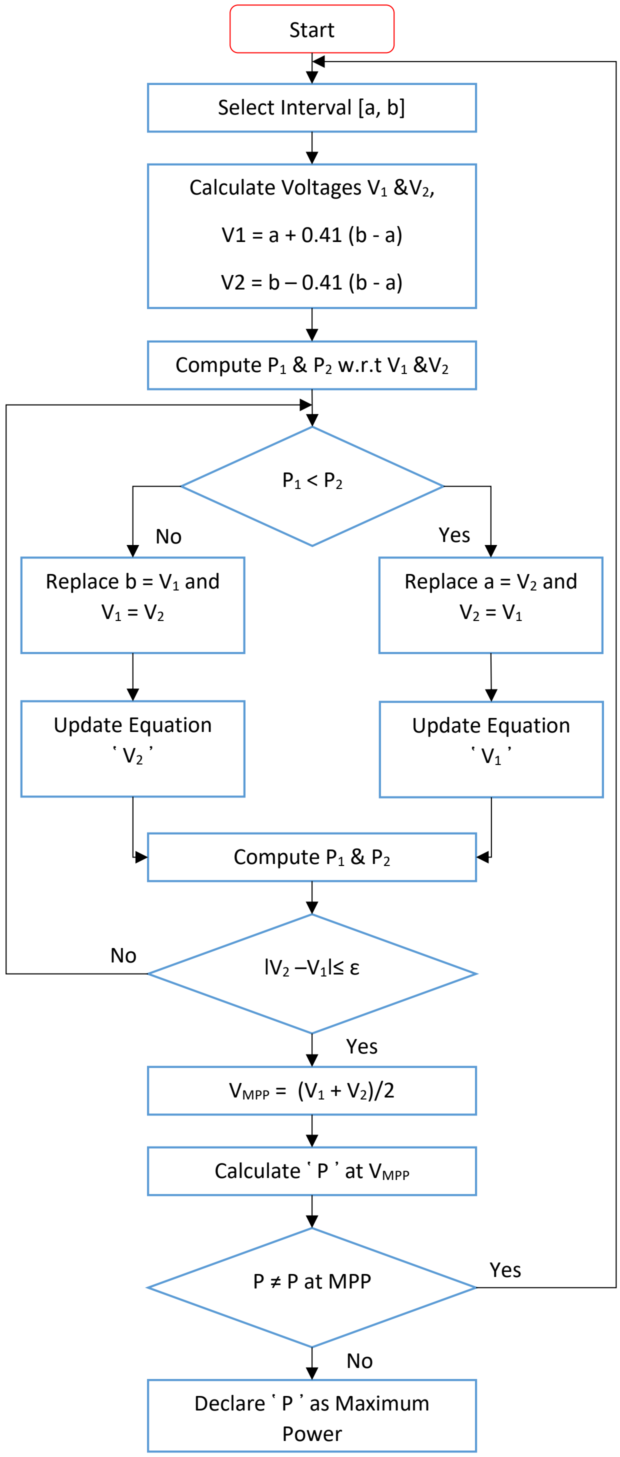

Fig. 6: Flow chart of the proposed MPPT algorithm.

5. Performance Analysis

Performance analysis of the proposed MPPT algorithm is carried out using simulated results in MATLAB/simulink and is compared with that of the traditional P&O. To validate the performance of SMM algorithm, experimental test is conducted considering the variations in irradiance and temperature.

5.1. Simulation Results

The performance of the proposed MPPT algorithm is analysed through simulation using the MATLAB/simulink environment. These results successfully validate the satisfactory performance of the proposed system even under varying weather conditions. The solar irradiance is varied dynamically from 1000 W·m^{-2} to 200 W·m^{-2}, as depicted in Fig. 7. The corresponding PV output power obtained for both the proposed and P&O schemes is shown in Fig. 8. Figure 8 shows many oscillations for traditional P&O for a fixed step of 1 V, where the proposed scheme shows better steady state and dynamic performance. A smooth drift is observed when there is a change in irradiance using the SMM method. The figures also show that the peak power tracked is in accordance with the variation of the solar irradiance.

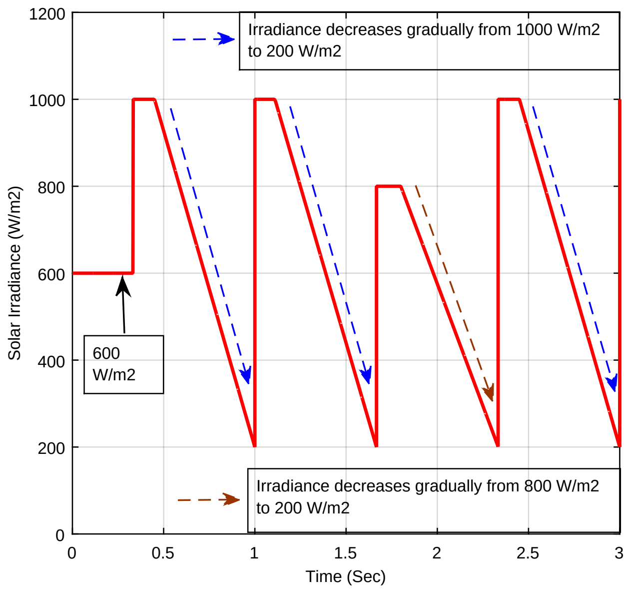

Fig. 7: Dynamic variation of irradiance.

MPPT efficiency (η) is the main parameter which projects the effectiveness of the MPPT scheme. The performance analysis is obtained by calculating the MPPT efficiency (η) given by Eq. (11) for both the P&O technique and the proposed MPPT technique [32], [33], [34] and [35].

$$\text{MPPT } (\eta(\%)) = \frac{P_{obtained}}{P_{actual}}. \quad (11)$$

The obtained power is the maximum extracted power using either P&O or the proposed scheme, and the actual power is the theoretical maximum power provided by the basic PV model [36], [37] and [38].

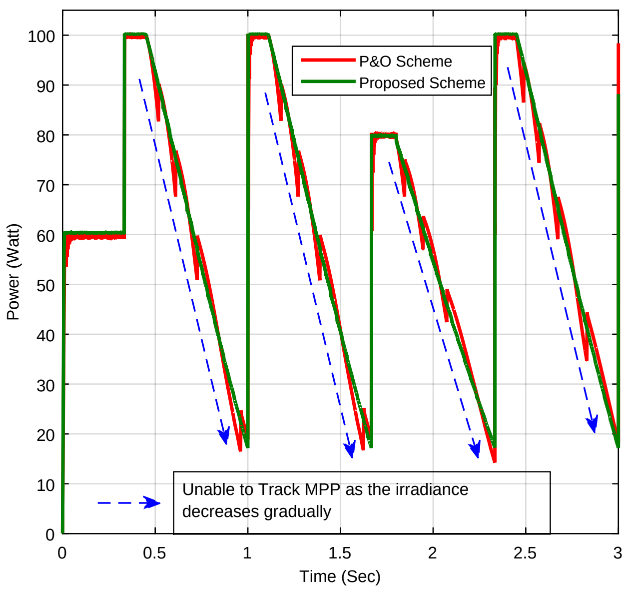

Fig. 8: Dynamic variation of PV power for P&O and proposed methods.

Table 3 and Fig. 9 show the PV output power using traditional P&O scheme for a fixed step of 1 V and 2 V and the proposed scheme for a change in irradiance from 200 W·m^{-2} to 1000 W·m^{-2} at a constant temperature of 25 °C. Table 4 and Fig. 10 show the PV output power using traditional P&O scheme for a fixed step of 1 V and 2 V and the proposed scheme for a change in temperature from 25°C to 65 °C at a constant irradiance of 1000 W·m^{-2}.

Tab. 3: PV power obtained at different irradiance.

Irradiance (W·m^{-2})	Actual Power (Watts)	P&O Watts)		SMM (Watts)
		1 V	2 V	
1000	100	99	98	100
800	80	78.75	76.2	80
600	60	58.5	56.1	59.2
400	40	37.3	34.3	39.2
200	19	17.5	15.5	18.9

The MPPT efficiencies using traditional P&O scheme for a fixed step of 1 V and 2 V and the proposed scheme for a change in irradiance from 200 W·m^{-2} to 1000 W·m^{-2} at a constant temperature from 25 °C are depicted in Tab. 5 and Fig. 11. The MPPT efficiencies for a change in temperature from 25 °C to 65 °C at a constant irradiance of 1000 W·m^{-2} using traditional P&O scheme for a fixed step of 1 V and 2 V and the proposed scheme are shown in Tab. 6 and Fig. 11. From the simulated results, the proposed scheme shows top efficiency and superior performance compared to the traditional P&O scheme.

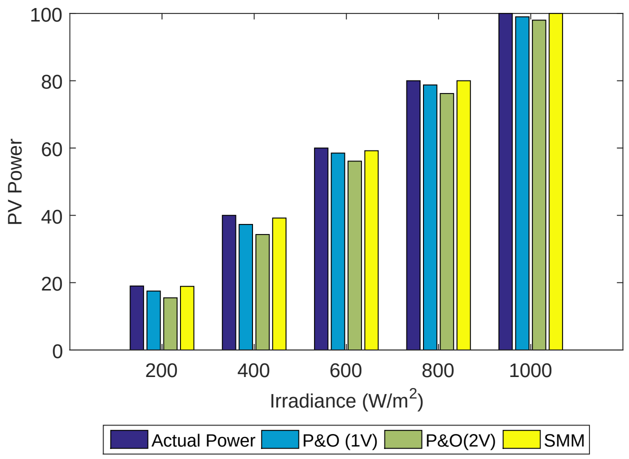

Fig. 9: PV power obtained at different irradiance.

Tab. 4: PV power obtained at different temperatures.

Temperature (°C)	Actual Power (Watts)	P&O (Watts)		SMM (Watts)
		1 V	2 V	
25	100	99	98	100
35	92.53	89	87.8	90.5
45	85.52	77	75.1	85
55	78.46	60.3	59.7	77.5
65	71.33	45.5	43.6	69.8

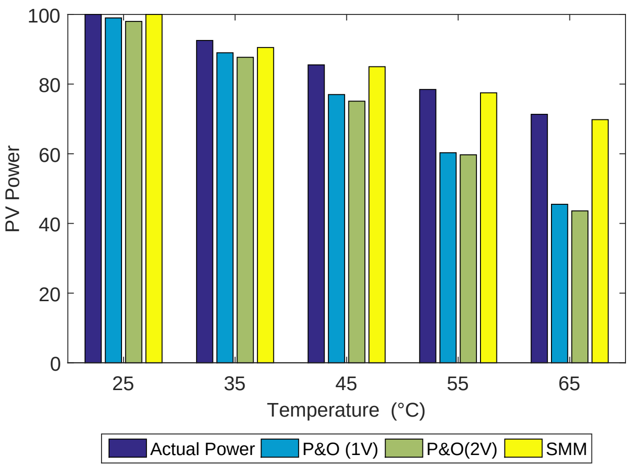

Fig. 10: PV power obtained at different temperature.

Tab. 5: Efficiency obtained at different irradiance.

Irradiance (W·m^{-2})	P&O η (%)		SMM η (%)
	1V	2V	
1000	99	98	100
800	98	95	100
600	97	93	98
400	93	85	98
200	92	81	99

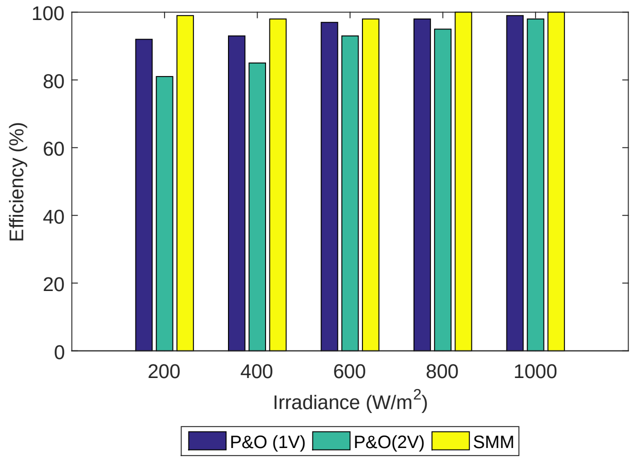

Fig. 11: Efficiency obtained at different irradiance.

Tab. 6: Efficiency obtained at different temperatures.

Temperature (°C)	P&O η (%)		SMM η (%)
	1 V	2 V	
25	99	98	100
35	96	94	97
45	90	87	99
55	76	74	98
65	63	61	97

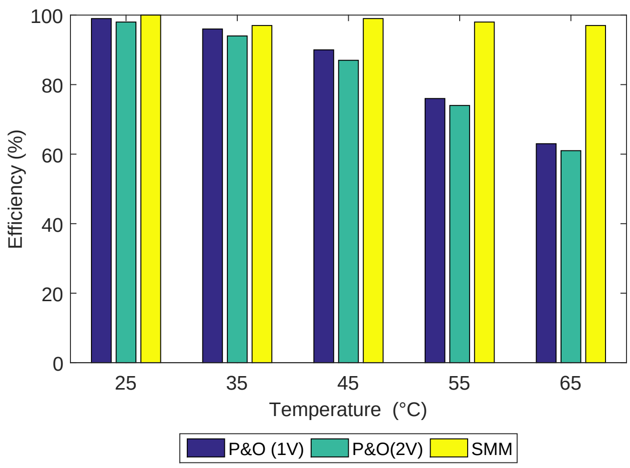

Fig. 12: Efficiency obtained at different temperature.

5.2. Experimental Validation

A prototype MPPT system has been developed using the proposed method, as shown in Fig. 13. The experimental setup comprises an E4360 solar array simulator, which is connected to a boost converter [39], [40] and [41]. The proposed algorithm is implemented using MSP430 (G2553) microcontroller, and the PWM signal generated by the controller is given to TLP250 opto-isolator. Over all circuit voltage and current protection is supervised by 4027 and 4098 ICs. The switching frequency of converter is set to 25 kHz, and it is connected to a 50 Ω, 5 A resistive load.

To analyze the proposed scheme experimentally, the performance of the system for variable irradiance and

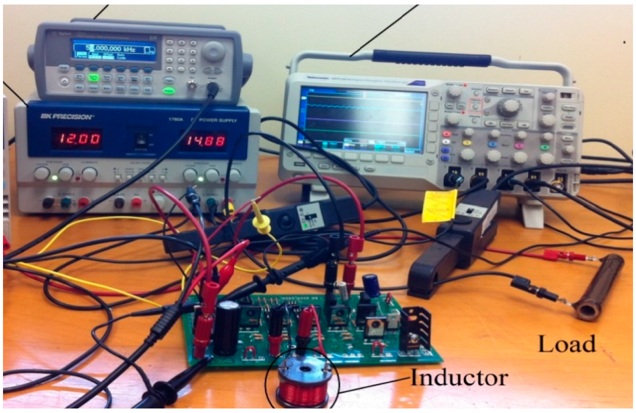

Fig. 13: Experimental setup of the proposed SMM system.

temperature has been tested, and the experimental results obtained are shown in Fig. 14 and Fig. 15.

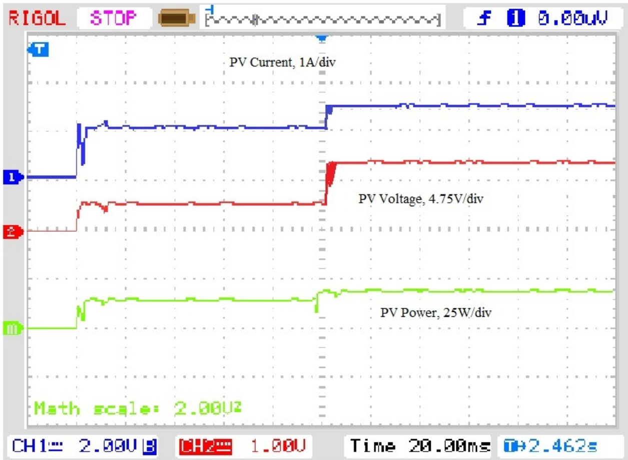

Fig. 14: Variation of PV parameters by varying irradiance.

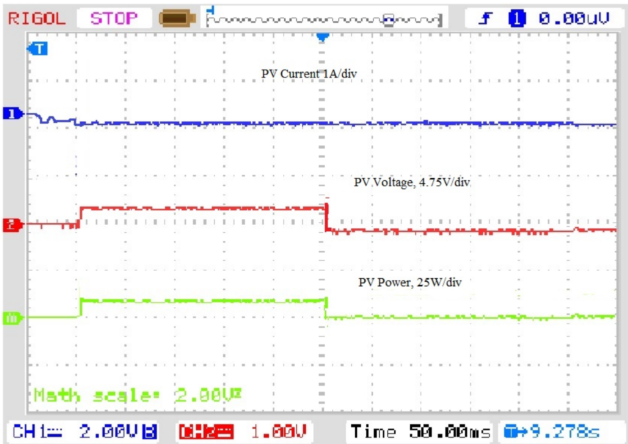

Fig. 15: Variation of PV parameters by varying temperature.

During variable irradiance testing, initially an irradiance of 800 W·m^{-2} is applied to the system and after a short duration irradiance is increased to 1000 W·m^{-2}. As the irradiance changes, there is a change in PV voltage, PV current and PV power of the PV system. From Fig. 14, it is observed that as the irradiance changes from 800 W·m^{-2} to 1000 W·m^{-2}, the PV current changes from 4.5 A to 5.01 A, the PV voltage changes from 14.25 V to 23.05 V, and PV power from 64 W to 100 W.

In order to validate the performance of PV system during variable temperature, experimental test is conducted at 25 °C and 35°C temperatures. The PV current, voltage and power experimental results depicted in Fig. 15 show the robustness of the proposed MPPT method for changes in the temperature. From the P-V characteristics, it is evident that the change in temperature of the PV system is inversely proportional to the voltage and hence,there is a dip in system voltage and power as the temperature increases. From Fig. 15, it is observed that as the temperature changes from 25 °C to 35 °C, the PV current remains constant at 5.7 A whereas the PV voltage reduces from 18.1 V to 9 V and the PV power from 100 W to 51 W.

The performance comparison of the proposed method with the traditionally used P&O is shown in Tab. 7, and energy extracted per day and the revenue generated by selling the energy are presented in Tab. 8. From the results, it is evident that proposed SMM based MPPT method provides a very good dynamic performance.

Tab. 7: Performance comparison of the proposed MPPT method.

Parameters	P & O Method	Proposed SMM Method
System performance	High	Very High
Implementation complexity	Easy	Simple & Easy
Efficiency	High	Very High
Tracking speed	Moderate	High
System Dependency	Dependent	Independent
Stability	High	Very High

6. Conclusion

A newly developed algorithm proposed in this paper has been able to track efficiently the maximum power of a solar array in a simple way. The simulation results, when implemented in MATLAB/Simulink for varying solar irradiance, showed maximum efficiency of 99 % even at 20 % of standard solar irradiance. Also, for varying temperature conditions, the maximum efficiency was observed to be significantly high. It's worth noting that even at high temperature of 65 °C, the high level of efficiency was maintained at 97 %. The annual energy extracted using the proposed method at 30 °C and 40 °C is 89012 kWh and 86596 kWh, respectively,

Tab. 8: Energy extracted and revenue generated by selling the energy.

Temperature (°C)	Method	Energy Extracted per Day (kWh)	Annual Energy (kWh)	Revenue in Indian rupees	Revenue in US dollars
30	P&O	224.92	82095	1018798	16979
	Proposed SMM	243.87	89012	1104638	18410
40	P&O	218.44	79730	989449	16490
	Proposed SMM	237.25	86596	1074656	17910

which is approximately 10 % more than that extracted from traditional P&O method. Thus, the test results demonstrate an outstanding effectiveness of the proposed method under varying solar irradiance and temperature conditions. Also, the system is found to be more efficient and simpler than the conventional P&O technique.

Furthermore, the robustness and feasibility of the proposed method, when validated by the experimental results for variable temperature and irradiance, exhibited superior performance with better MPP tracking and reduced oscillations during steady-state condition.

References

[1] VEERACHARY, M., T. SENJYU and K. UEZATO. Voltage based maximum power point tracking control of PV system. *IEEE Transactions On Aerospace and Electrical System*. 2002, vol. 38, iss. 1, pp. 262–270. ISSN 0018-9251. DOI: 10.1109/7.993245.

[2] CHUNG, H. S. H., K. K. TSE, S. Y. R. HUI, C. M. MOK and M. T. HO. A novel maximum power point tracking technique for solar panels using a SEPIC or cuk converter. *IEEE Transactions on Power Electronics*. 2003, vol. 18, iss. 3, pp. 717–724. ISSN 0885-8993. DOI: 10.1109/TPEL.2003.810841.

[3] SALAS, V., E. OLIAS, A. LAZARO and A. BARRADO. Evaluation of a new maximum power point tracker (MPPT) applied to the photovoltaic stand-alone systems. *Solar Energy Materials and Solar Cells*. 2005, vol. 87, iss. 1–4, pp. 807–815. ISSN 0927-0248. DOI: 10.1016/j.solmat.2004.07.053.

[4] SANTOS, J. L., F. ANTUNES, A. CHEHAB and C. CRUZ. A maximum power point tracker for PV systems using a high performance boost converter. *Solar Energy*. 2006, vol. 80, iss. 7, pp. 772–778. ISSN 0038-092x. DOI: 10.1016/j.solener.2005.06.014.

[5] KARLIS, A. D., T. L. KOTTAS and Y. S. BOUTALIS. A novel maximum power point tracking method for PV systems using fuzzy cognitive networks. *Electric Power Systems Research*. 2007, vol. 77, iss. 3–4, pp. 315–327. ISSN 0378-7796. DOI: 10.1016/j.epsr.2006.03.008.

[6] MODIRI-DELSHAD, M., S. H. AGHAY-KABOLI, E. TASLIMI-RENANI and N. A. RAHIM. Backtracking search algorithm for solving economic dispatch problems with valve-point effects and multiple fuel options. *Energy*. 2016, vol. 116, iss. 1, pp. 637–649. ISSN 0360-5442. DOI: 10.1016/j.energy.2016.09.140.

[7] KABOLI, S. H. A., J. SELVARAJ and N. A. RAHIM. Long-term electric energy consumption forecasting via artificial cooperative search algorithm. *Energy*. 2016, vol. 115, iss. 1, pp. 857–871. ISSN 0360-5442. DOI: 10.1016/j.energy.2016.09.015.

[8] RAFIEERAD, A. R., A. R. BUSHROA and B. NASIRI-TABRIZI. Toward improved mechanical, tribological, corrosion and in-vitro bioactivity properties of mixed oxide nanotubes on Ti–6Al–7Nb implant using multi-objective PSO. *Journal of the Mechanical Behavior of Biomedical Materials*. 2017, vol. 69, iss. 1, pp. 1–18. ISSN 1751-6161. DOI: 10.1016/j.jmbbm.2016.11.019.

[9] KABOLI, S. H., J. SELVARAJ and N. A. RAHIM. Rain-fall optimization algorithm: A population based algorithm for solving constrained optimization problems. *Journal of Computational Science*. 2017, vol. 19, iss. 1, pp. 31–42. ISSN 1877-7503. DOI: 10.1016/j.jocs.2016.12.010.

[10] SEBTAHMADI, S. S., H. B. AZAD, S. H. A. KABOLI, M. D. ISLAM and S. MEKHILEF. A PSO-DQ Current Control Scheme for Performance Enhancement of Z-Source Matrix Converter to Drive IM Fed by Abnormal Voltage. *IEEE Transactions on Power Electronics*. 2018, vol. 33, iss. 2, pp. 1666–1681. ISSN 0885-8993. DOI: 10.1109/tpel.2017.2679118.

[11] KABOLI, S. H. A., A. FALLAHPOUR, J. SELVARAJ and N. A. RAHIM. Long-term electrical energy consumption formulating and forecasting via optimized gene expression programming. *Energy*. 2017, vol. 126, iss. 1, pp. 144–164. ISSN 0360-5442. DOI: 10.1016/j.energy.2017.03.009.

[12] ASADI, H., S. H. A. KABOLI, A. MOHAMMADI and M. OLADAZIMI. Fuzzy-control-based five-step Li-ion battery charger by using AC impedance technique. In: *Proceedings of SPIE 8349: Fourth International Conference on Machine Vision: Machine Vision, Image Processing, and Pattern Analysis*. Singapore: SPIE, 2012, pp. 1-6. ISBN 978-0-8194-9005-6. DOI: 10.1117/12.920980.

[13] MODIRI-DELSHAD, M., S. KOOHI-KAMALI, E. TASLIMI, S. H. AGHAY KABOLI and N. A. RAHIM. Economic dispatch in a microgrid through an iterated-based algorithm. In: *IEEE Conference on Clean Energy and Technology (CEAT)*. Lankgkawi: IEEE, 2013, pp. 82–87. ISBN 978-1-4799-3238-2. DOI: 10.1109/ceat.2013.6775604.

[14] MODIRI-DELSHAD, M., S. H. A. KABOLI, E. TASLIMI, J. SELVARAJ and N. A. RAHIM. An iterated-based optimization method for economic dispatch in power system. In: *IEEE Conference on Clean Energy and Technology (CEAT)*. Lankgkawi: IEEE, 2013, pp. 88–92. ISBN 978-1-4799-3238-2. DOI: 10.1109/ceat.2013.6775605.

[15] MANSOURI, M., S. H. A. KABOLI, J. AHMADIAN and J. SELVARAJ. A hybrid Neuro-Fuzzy — P.I. speed controller for B.L.D.C. enriched with an integral steady state error eliminator. In: *IEEE International Conference on Control System, Computing and Engineering*. Penang: IEEE, 2012, pp. 234–237. ISBN 978-1-4673-3143-2. DOI: 10.1109/iccsce.2012.6487147.

[16] TIANZE, L., L. HENGWEI, J. CHUAN, H. LUAN and Z. XIA. Application and design of solar photovoltaic system. *Journal of Physics: Conference Series*. 2011, vol. 276, no. 1, pp. 1–6. ISSN 1742-6596. DOI: 10.1088/1742-6596/276/1/012175.

[17] TAGHVAEE, M. H., M. A. M. RADZI, S. M. MOOSAVAIN, H. HIZAM and M. H. MARHABAN. A current and future study on non-isolated DC–DC converters for photovoltaic applications. *Renewable and Sustainable Energy Reviews*. 2013, vol. 17, iss. 1, pp. 216–227. ISSN 1364-0321. DOI: 10.1016/j.rser.2012.09.023.

[18] SINGH, B. and V. BIST. A BL-CSC Converter-Fed BLDC Motor Drive With Power Factor Correction. *IEEE Transactions on Industrial Electronics*. 2015, vol. 62, iss. 1, pp. 172–183. ISSN 0278-0046. DOI: 10.1109/tie.2014.2327551.

[19] M. H. RASHID. *Power Electronics Circuits, Devices and Applications*. 3rd ed. Delhi: Pearson Education, 2006. ISBN 978-8120325036.

[20] BERNARDO, P. C. M., Z. M. A. PEIXOTO and L. V. B. MACHADO NETO. A high-efficient microcontrolled buck converter with maximum power point tracking for photovoltaic systems. *Renewable Energy and Power Quality*. 2009, vol. 1, iss. 7, pp. 775–780. ISSN 2172-038x. DOI: 10.24084/repqj07.502.

[21] MAMARELIS, E., G. PETRONE and G. SPAGNUOLO. Design of a Sliding-Mode-Controlled SEPIC for PV MPPT Applications. *IEEE Transactions on Industrial Electronics*. 2014, vol. 61, iss. 7, pp. 3387–3398. ISSN 0278-0046. DOI: 10.1109/tie.2013.2279361.

[22] SAMANTARA, S., B. ROY, R. SHARMA, S. CHOUDHURY and B. JENA. Modeling and simulation of integrated CUK converter for grid connected PV system with EPP MPPT hybridization. In: *IEEE Power, Communication and Information Technology Conference (PCITC)*. Bhubaneswar: IEEE, 2015, pp. 397–402. ISBN 978-1-4799-7455-9. DOI: 10.1109/pcitc.2015.7438199.

[23] HUSSEIN, K. H. Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions. *IEE Proceedings - Generation, Transmission and Distribution*. 1995, vol. 142, iss. 1, pp. 59-64. ISSN 1350-2360. DOI: 10.1049/ip-gtd:19951577.

[24] ESRAM, T. and P. L. CHAPMAN. Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques. *IEEE Transactions on Energy Conversion*. 2007, vol. 22, iss. 2, pp. 439–449. ISSN 0885-8969. DOI: 10.1109/tec.2006.874230.

[25] SUBUDHI, B. and R. PRADHAN. A Comparative Study on Maximum Power Point Tracking Techniques for Photovoltaic Power Systems. *IEEE Transactions on Sustainable Energy*. 2013, vol. 4, iss. 1, pp. 89–98. ISSN 1949-3029. DOI: 10.1109/tste.2012.2202294.

[26] AASHOOR, F. A. O. and F. V. P. ROBINSON. Maximum power point tracking of photovoltaic water pumping system using fuzzy logic controller. In: *48th International Universities' Power Engineering Conference (UPEC)*. Dublin: IEEE, 2013, pp. 1–5. ISBN 978-1-4799-3254-2. DOI: 10.1109/upec.2013.6714969.

[27] OUADA, M., M. S. MERIDJET and N. TALBI. Optimization photovoltaic pumping system based BLDC using fuzzy logic MPPT control. In: *International Renewable and Sustainable Energy Conference (IRSEC)*. Ouarzazate: IEEE, 2013, pp. 27–31. ISBN 978-1-4673-6374-7. DOI: 10.1109/irsec.2013.6529718.

[28] ALGAZAR, M. M., H. AL-MONIER, H. A. EL-HALIM and M. E. K. SALEM. Maximum power point tracking using fuzzy logic control. *International Journal of Electrical Power & Energy Systems*. 2012, vol. 39, iss. 1, pp. 21–28. ISSN 0142-0615. DOI: 10.1016/j.ijepes.2011.12.006.

[29] CHEN, Y. and K. M. SMEDLEY. A Cost-Effective Single-Stage Inverter With Maximum Power Point Tracking. *IEEE Transactions on Power Electronics*. 2004, vol. 19, iss. 5, pp. 1289–1294. ISSN 0885-8993. DOI: 10.1109/tpel.2004.833458.

[30] RTIZ-RIVERA, E. I. and F. PENG. A novel method to estimate the maximum power for a photovoltaic inverter system. In: *IEEE 35th Annual Power Electronics Specialists Conference*. Aachen: IEEE, 2004, pp. 2065–2069. ISBN 0-7803-8399-0. DOI: 10.1109/pesc.2004.1355436.

[31] DE CARVALHO, P. C. M., R. S. T. PONTES, D. S. OLIVEIRA, D. B. RIFFEL, R. G. V. DE OLIVEIRA and S. B. MESQUITA. Control method of a photovoltaic powered reverse osmosis plant without batteries based on maximum power point tracking. In: *IEEE/PES Transmision and Distribution Conference and Exposition: Latin America*. Sao Paulo: IEEE, 2004, pp. 137–142. ISBN 0-7803-8775-9. DOI: 10.1109/tdc.2004.1432366.

[32] NAFEH, A. E. A., F. H. FAHMY, O. A. MAHGOUB and E. M. A. EL-ZAHAB. Developed Algorithm of Maximum Power Tracking for Stand-Alone Photovoltaic System. *Energy Sources*. 1998, vol. 20, iss. 1, pp. 45–53. ISSN 0090-8312. DOI: 10.1080/00908319808970042.

[33] KOUTROULIS, E., K. KALAITZAKIS and N. C. VOULGARIS. Development of a microcontroller-based, photovoltaic maximum power point tracking control system. *IEEE Transactions on Power Electronics*. 2001, vol. 16, iss. 1, pp. 46–54. ISSN 0885-8993. DOI: 10.1109/63.903988.

[34] KOTA, V. R. and M. N. BHUKYA. A simple and efficient MPPT scheme for PV module using 2-Dimensional Lookup Table. In: *IEEE Power and Energy Conference at Illinois*. Urbana: IEEE, 2016, pp. 1–7. ISBN 978-1-5090-0261-0. DOI: 10.1109/peci.2016.7459226.

[35] TAKASHIMA, T., T. TANAKA, M. AMANO and Y. ANDO. Maximum output control of photovoltaic (PV) array. In: *35th Intersociety Energy Conversion Engineering Conference and Exhibit (IECEC)*. Las Vegas: IEEE, 2000, pp. 380–383. ISBN 1-56347-375-5. DOI: 10.1109/iecec.2000.870713.

[36] HUSSEIN, K. H. Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions. *IEE Proceedings - Generation, Transmission and Distribution*. 1995, vol. 142, iss. 1, pp. 59–64. ISSN 1350-2360. DOI: 10.1049/ip-gtd:19951577.

[37] FEMIA, N., G. PETRONE, G. SPAGNUOLO and M. VITELLI. Optimization of Perturb and Observe Maximum Power Point Tracking Method. *IEEE Transactions on Power Electronics*. 2005, vol. 20, iss. 4, pp. 963–973. ISSN 0885-8993. DOI: 10.1109/tpel.2005.850975.

[38] PANDA, B., B. PANDA, P. K. HOTA and S. K. BHUYAN. A comparative analysis of Maximum Power Point techniques for photovoltaic system. In: *IEEE Power, Communication and Information Technology Conference (PCITC)*. Bhubaneswar: IEEE, 2015, pp. 732–737. ISBN 978-1-4799-7455-9. DOI: 10.1109/pcitc.2015.7438093.

[39] SOLODOVNIK, E. V., S. LIU and R. A. DOUGAL. Power Controller Design for Maximum Power Tracking in Solar Installations. *IEEE Transactions on Power Electronics*. 2004, vol. 19, iss. 5, pp. 1295–1304. ISSN 0885-8993. DOI: 10.1109/tpel.2004.833457.

[40] SAHU, H. S. and S. K. NAYAK. A novel approach to extract maximum power from partially shaded PV array. In: *IEEE Power, Communication and Information Technology Conference (PCITC)*. Bhubaneswar: IEEE, 2015, pp. 337–342. ISBN 978-1-4799-7455-9. DOI: 10.1109/pcitc.2015.7438188.

[41] YETAYEW, T. T. and T. R. JYOTHSNA. Evaluation of fuzzy logic based maximum power point tracking for photovoltaic power system. In: *IEEE Power, Communication and Information Technology Conference (PCITC)*. Bhubaneswar: IEEE, 2015, pp. 217–222. ISBN 978-1-4799-7455-9. DOI: 10.1109/pcitc.2015.7438163.

About Authors

Shobha Rani DEPURU received her B.Tech degree in Electrical and Electronics Engineering from JNTU, Hyderabad, India and the M.Tech degree in Electrical Power Systems from JNTU, Ananthapur, India and currently pursuing Ph.D. in the department of Electrical and Electronics Engineering, SriVenkateswara University College of Engineering,Tirupati, India. Her research interests are renewable energy sources, power system optimization, artificial intelligence techniques and power system reliability.

Muralidhar MAHANKALI received his B.Tech degree in Electrical Engineering and the M.Tech degree in Instrumentation & Control systems from the Sri Venkateswara University College of Engineering, Tirupati, India, and the Ph.D. degree from Sri Venkateswara University College of Engineering, Tirupati, India. He is currently a Professor of Electrical Engineering in Sri Venkateswara College of Engineering and Technology, Tirupati, India. He published more than 70 research papers. So far, he has guided 9 Ph.D., and 38 M.Tech students. His research interests include electrical engineering, instrumentation & control systems and High Voltage Engineering.