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S. N. Singh
R. K. Pandey
Bijaya Ketan Panigrahi
D. P. Kothari *Editors*

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Preface

The book constitutes selected high-quality papers presented in the International Conference on Computing, Power, and Communication Technologies 2019 (GUCON 2019) organized by Galgotias University, India, in September 2019. It discusses the issues in electrical, computer, and electronics engineering and technologies. The selected papers are organized into three sections—power and energy, control system and power electronics, and drives and renewable energy. In-depth discussions on various issues under topics provide an interesting compilation for researchers, engineers, and students.

We are thankful to all the authors who have submitted papers for keeping the quality of the GUCON 2019 at high levels. We would like to acknowledge all the authors for their contributions and the reviewers. We have received invaluable help from the members of the International Program Committee and the chairs responsible for different aspects of the workshop. We also appreciate the role of special session organizers. Thanks to all of them, we had been able to collect many papers on interesting topics, and during the conference, we had very interesting presentations and stimulating discussions.

Our special thanks go to Leopoldo Angrisani (Editor in Chief, Springer, Lecture Notes in Electrical Engineering Series) for the opportunity to organize this guest-edited volume.

We are grateful to Springer, especially to Aninda Bose (Senior Editor, Hard Sciences Publishing), for the excellent collaboration, patience, and help during the evolvement of this volume.

We hope that the volume will provide useful information to professors, researchers, and graduated students in the areas of power, control, and renewable energy and applications, and all will find this collection of papers inspiring, informative, and useful. We also hope to see you at a future GUCON event.

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S. N. Singh is currently the Vice-Chancellor of Madan Mohan Malaviya University of Technology, Gorakhpur, India, and a Professor at the Department of Electrical Engineering, Indian Institute of Technology Kanpur, India. He is also the recipient of the German Humboldt Fellowship and the Danish Otto-Monsted Fellowship. In 2013, Professor Singh became the first Asian to receive the IEEE Educational Activity Board Meritorious Achievement Award in Continuing Education. His research interests include power system restructuring, FACTS, power system optimization and control, wind power, and security analysis. Professor Singh has published more than 440 papers in international/national journals/conferences, and written two books.

R. K. Pandey is a Professor at the Department of Electrical Engineering, Indian Institute of Technology (BHU), Varanasi, and is the Director General, National Power Training Institute (NPTI). He has over 36 years' experience in the fields of high-voltage direct current (HVDC) transmission technology and flexible AC transmission systems (FACTS) device control, intelligent power control along with the operation of power systems in open access. He has published more than 150 peer-reviewed papers in both national and international journals and at leading conferences.

Bijaya Ketan Panigrahi is a Professor of Electrical and Electronics at the Engineering Department, Indian Institute of Technology, Delhi, India. He received his Ph.D. degree from Sambalpur University. He is Chief Editor of the International Journal of Power and Energy Conversion. His interests include power quality, FACTS devices, power system protection, and AI applications in power systems.

D. P. Kothari is an educationist and a Professor who has held leadership positions at various engineering institutions in India, including IIT Delhi, Visvesvaraya National Institute of Technology, Nagpur, and VIT University, Vellore.

In recognition of his contributions to engineering education, he was made an IEEE Fellow. He has published and presented over 842 papers in national and international journals and conferences. He has authored and co-authored about fifty books. He is the recipient of numerous lifetime achievement and other awards.

An Investigation on Multi-junction Solar Cell for Maximum Power Point Tracking Using P&O and ANN Techniques

Prachi Rani and Omveer Singh

Abstract Renewable energy resources are becoming a vital part for the energy production in today's world. Generation of energy by using solar equipment is increasing day by day. A multi-junction solar cell is the one which consists of multiple junctions taking into consideration the tunnel junction in the solar cell so that efficiency of the solar cell is improved. Temperature and solar irradiance are consequential factors in order to determine the ability of the solar cell. A noticeable change in any one factor shows a clear change in the values in the Voltage-Current (V-I) and Power-Voltage (P-V) curves of the solar cell. The conversion efficiency can be improved by some MPPT techniques that are applied on the solar cell. Perturb & observe (P&O) and Artificial Neural Network (ANN) techniques are implemented and compared here to attain a better technique for the extraction of solar energy. The plots and graphs here depict the miscellaneous characteristics of the multi-junction solar cell including effect of strategies applied on it in MATLAB/Simulink.

Keywords Multi-junction · Tandem cell · Perturb & observe · Artificial neural network · MATLAB/Simulink

1 Introduction

A source of energy can continue only until it is depleted. Well due to this fact, the conventional sources that are depleting will no longer be the source of generating energy. This fatal problem is affecting almost every section contributing in the economy of any country. Existence of renewable energy resources in ample amount is a boon for generating unlimited energy. The trail of these renewable energy resources includes many resources yet much has been said and done on solar energy [1].

For bringing forth solar energy into play, solar cells are required which later became a vital topic of research. These researches lead us to multiple types of solar

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cells, but the only motto was to maximize the efficiency of the solar cell. Multi-junction solar cell (MJSC) is one of these solar cells that have high conversion efficiency as compared to some of the solar cells [2]. These types of Photovoltaic (PV) cells have space and terrestrial applications in which many researches are done every now and then. Tandem solar cells have been studied since 1960. Earlier days, researchers encouraged R&D of tandem cells based on their computer analysis [3].

MJSCs consist of different semiconductor material that forms diversified p–n junction integrated to cell stack which is connected together with the help of tunnel junctions and window layer. The conversion efficiency of the whole solar cell is increased as each semiconductor material absorbs wide range of wavelength of light which extracts more sunlight. At present, InGaP/GaAs/Ge solar cell which is a MJSC efficiently absorbs the broad spectrum of sunlight and is used in space [3–8]. MJSCs are the solar cells in which maximum power point is greater than the single-junction silicon solar cell.

Higher resistance towards irradiance, increased conversion efficiency and lower temperature coefficient are some of the properties of MJSC. The efficiency of multi-junction solar cell is far more than that of silicon solar cell. These solar cells can be used in several other industrial, domestic and agriculture sectors. Implementation of solar cells in these section leads to more economic aspect. The operation of these devices is more effective as there is luminescent coupling that occurs in the multi-junction devices [9, 10].

As there are different semiconductor materials, the bandgap energy of each sub-cell is different depending upon the material. The top layer of the MJSC uses the largest band gap, and the lower layers reduce the band gap [5]. The bandgap energy of every material and the open-circuit voltage vary with respect to temperature. These solar cells convert sunlight to DC electricity which is then connected to inverter that converts into AC source through which it can be used in further applications in day-to-day life. Such connections form a PV system that can be certainly used in household chores as well as in street lights.

In this study, triple-junction solar cell is implemented, and then, its V–I and P–V characteristics are studied at standard as well as different radiations. Afterwards, P&O and ANN based MPPT techniques are exercised on the MJSC. This helps in enhancing the conversion efficiency at economical level.

2 Methodologies

When the laboratory experimental procedures were done, some challenges were faced in combining semiconducting material for the stack. These combinations are based on some basic criteria like lattice matching, bandgap energy matching and current matching.

Lattice constant of the material of the solar cell should match because even a small mismatch in lattice will lead to lattice dislocation. The bandgap energy matching deals with the fact that the energy levels should be in such a limit that absorption of the spectrum of sunlight is done in an efficient way. Lastly, current matching is the most important factor as the materials are stacked in a series form so it is required that the current of each sub-cell is equal. These criterions lead to higher conversion efficiency and also coherent application of the multi-junction solar cell. Keeping all the factors in mind, a triple-junction solar cell consisting of a GaInP solar cell as the top layer, InGaAs in the middle layer and Ge layer as the bottom layer [6], is formed and implemented.

Standard Test Condition (STC), i.e. 1000 W/m^2 irradiance and 25 °C temperature, is the condition under which the simulation is performed.

2.1 Perturb & Observe Technique

Out of all the techniques, P&O is the most primary and prominent technique. The algorithm of P&O method is to measure the instantaneous current and instantaneous voltage of the output power. Then, a comparison of output power in current time point is made to previous time point's power output [3].

In this approach, yield voltage of sun-based board is perturbed and yield control is always recognized. The sun-powered board current and voltage are evaluated, and therefore, similar power is figured. Essential advance size is given by the external circuit. Perturbation in voltage is resolved, and many experiments are compared and observed as per control scheme. In case that the negative change is recognized concerning the change in voltage, the duty ratio is diminished; it is pretended by the nonlinear P–V characteristics that MPP is navigated and following inverse way begins. Just as the fixed step is given by the outer circuit, it significantly influences the rate of convergence and ripple content; however, the tracking speed enormously diminishes.

2.2 Artificial Neural Network

ANN is one of the best-utilized strategies to accomplish MPPT for PV frameworks of nonlinear ecological circumstances. It is a soft computing technique which helps in improving the conversion efficiency of the given MJSC. ANN technique works similar to that of a human brain.

This technique is used for exploring the MPP of the solar cell by the help of feed-forward network. These networks are characterized by acyclic graph which describes the topological structure of network [10]. Operating temperature and irradiance are served as inputs to the feed-forward network including the weights and the target output, and the network is processed just the same way as brain of human functions to obtain the most efficient output. This output is then served to pulse width modulation sub-system which produces the pulse passed on to the DC converter. The final outcomes of the whole set-up lead to more accurate result.

3 Mathematical Structure of the System

The basic model of MJSC in the software MATLAB/Simulink is implemented when the basic relation between current density and voltage is obtained. Therefore, the current density of a single cell of the MJSC can be represented by the following equation:

$$J = J_{\text{ph}} - J_{\text{diode}} - J_{\text{pr}} \tag{1}$$

where J_{ph} is the photo current density which is equal to the short-circuit current density at reference temperature and irradiance. J_{diode} is the diode current density, and J_{pr} is the shunt current density.

The diode current density is formulated as follows:

$$J_{\text{diode}} = J_{0i}\left(e^{\frac{q(V + J \times A \times R_{\text{S}})}{n_i \times kB \times T}} - 1\right) \tag{2}$$

where J_{0i} is the diode's reverse saturation current density, q is charge constant, A is the cell area, n_i is a constant, kB is Boltzmann constant and T is the operating temperature.

J_{0i} which characterizes diode saturation current density is given by:

$$J_{0i} = k_i \times T^{\frac{3+\Delta i}{2}} \times e^{\frac{-E_{\text{g}}}{(n_i \times kB \times T)}} \tag{3}$$

where k is a constant, J_{pr} is the shunt current density which is conventionally neglected as the shunt resistance is very large. E_{g} is the bandgap energy in eV whose value depends on operating temperature since its energy is inversely proportional to operating temperature [8].

Open-circuit voltage per cell of the multi-junction solar cell is given by the following equation:

$$V_{\text{oc}} = \frac{n_i \times kB \times T}{q} \ln\left(\frac{J_{\text{sci}}}{J_{0i}} + 1\right) \tag{4}$$

The sum of all three open-circuit voltages is the total open-circuit voltage of the multi-junction solar cell.

Figure 1 shows the equivalent circuit of multi-junction solar cell which is further implemented in the MATLAB/Simulink software for study and analysis keeping the physical conditions and limitations in mind.

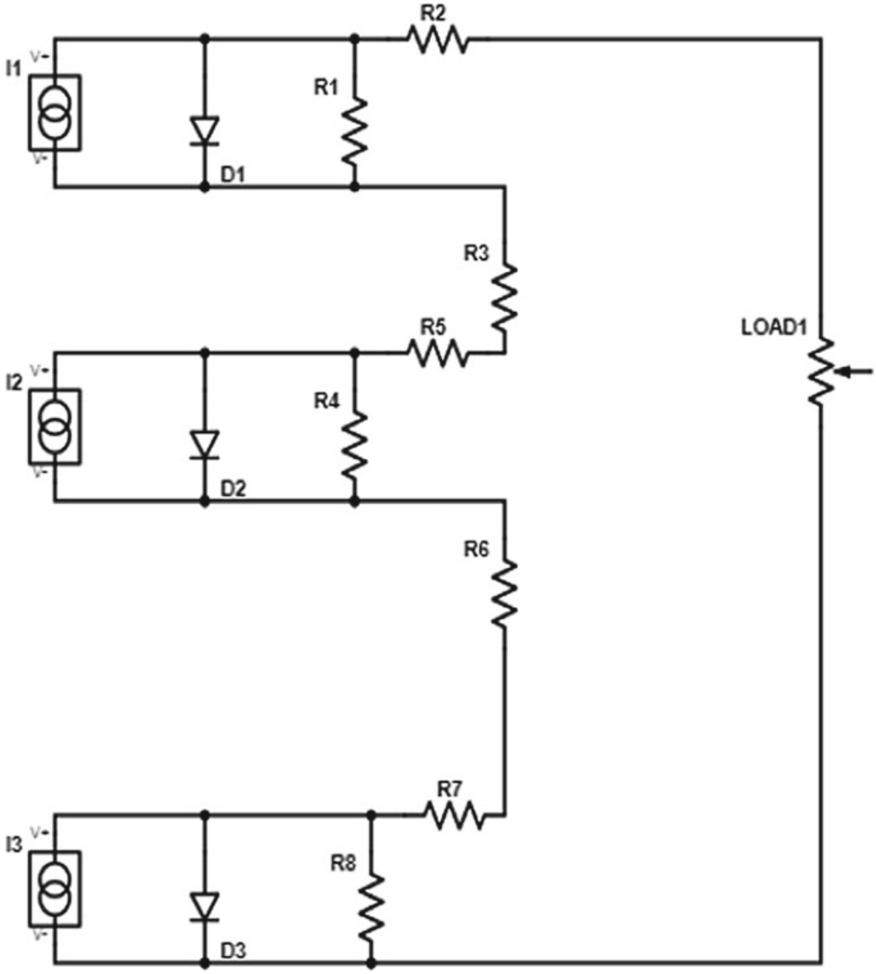

Fig. 1 Equivalent circuit diagram of MJSC

4 Way of Implementation

A MATLAB/Simulink of multi-junction solar cell is created on the basis of above theories and equations. Triple-junction solar cell is simulated, and then, various results are examined. The block diagram of single cell of MJSC is drawn in Fig. 2.

Current density and voltage and also power and voltage characteristics can be easily obtained by the simulation model of the solar cell. These curves give the value of short-circuit current, open-circuit voltage, maximum voltage and maximum power. The simulated results show how each stacked cell can perform for PV energy generation. Note that sampling curves were created at 1-sun radiation and fixed

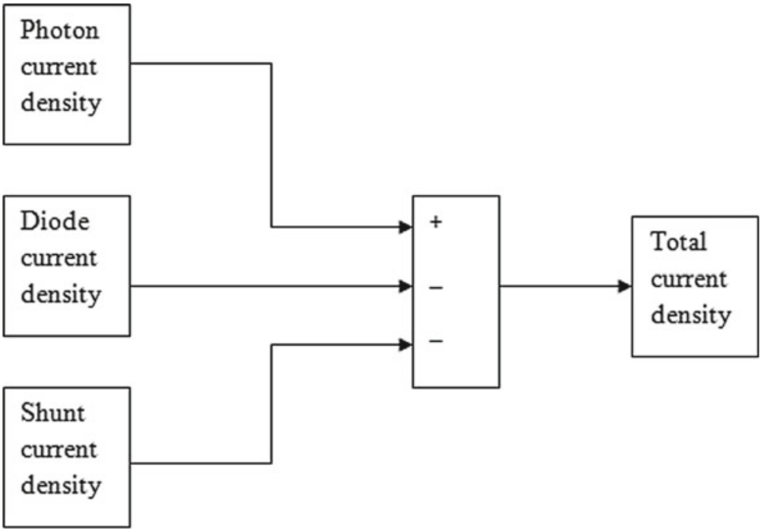

Fig. 2 Block diagram of single cell of MJSC

ambient temperature same as reference [7]. Implemented model of MJSC is presented in the Fig. 3.

Perturb & observe is a consistent procedure; it is recasting intermittently up until the MPP occurs. The Simulink model of the system is given as in Fig. 4. The simulation model of MPPT controller, i.e. a sub-system for fundamental simulation defined in the light of the ANN, appears in the given Fig. 5.

5 Results and Analysis

Figure 6 gives the V–I curve of solar cell and its sub-cell at 1000 W/m^2 radiation and temperature of 25 °C. Due to the values of the parameters in the above formulae, the following graphs are attained with Ge having the lowest values then InGaAs and after that InGaP. The total of all the sub-cells is equal to MJSC graph.

Following graphs depict the various characteristics of triple-junction solar cell.

Figure 7 shows the V–I curve of multi-junction solar cell at different radiations. The following graph depicts that as the radiation decreases, similarly the value of current density in the graph decreases. The values of the irradiance vary from 300 to 1000 W/m^2.

In the Fig. 8, plot gives the P–V curve of solar cell at 1000 W/m^2 radiations and temperature of 25 °C. The peak of this curve gives the maximum power point at which the voltage attained is maximum voltage.

Figure 9 shows the P–V curve of multi-junction solar cell at different radiations.

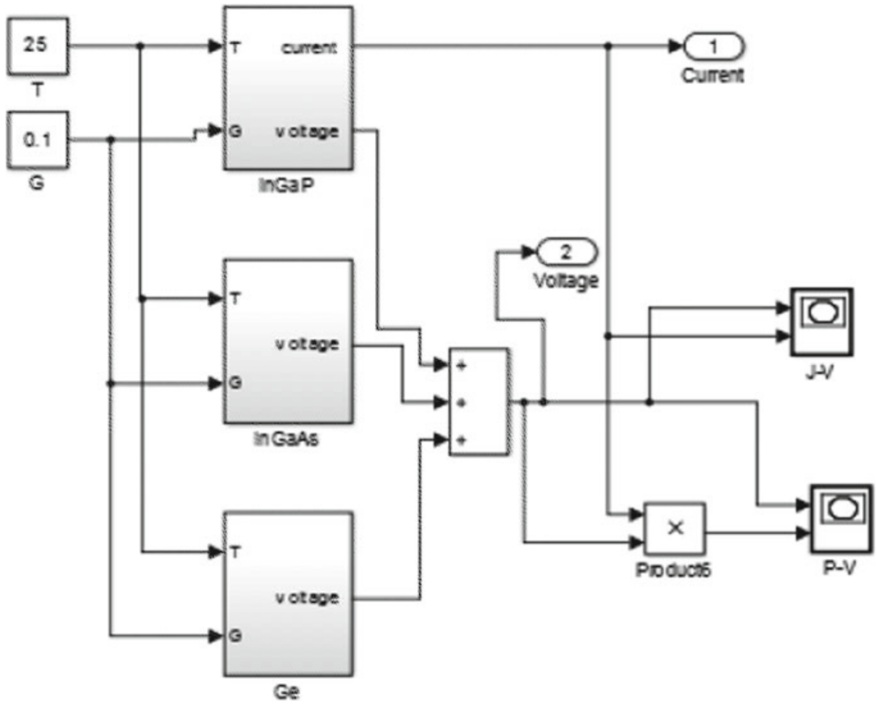

Fig. 3 Implemented model of MJSC

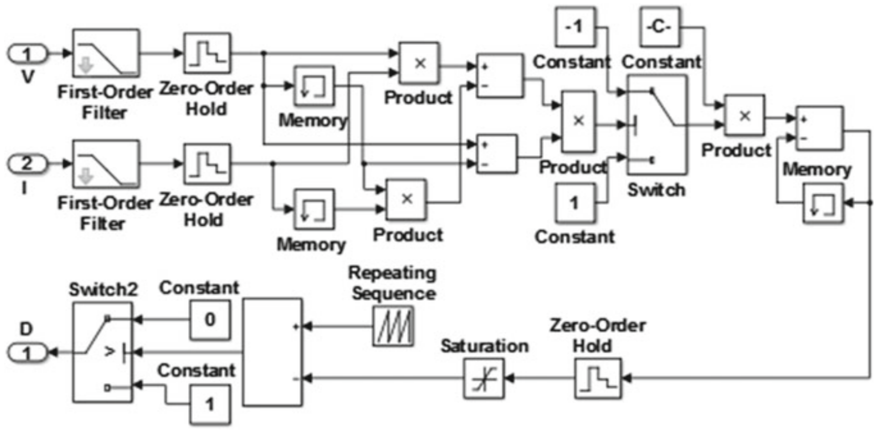

Fig. 4 MATLAB/Simulink model using P&O technique

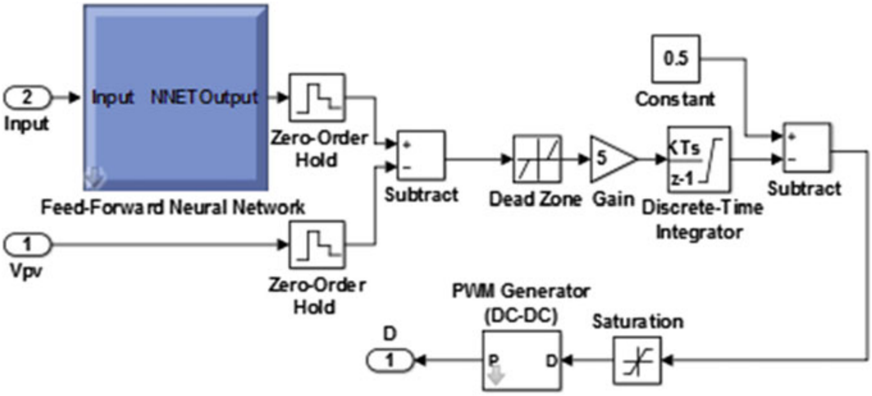

Fig. 5 MATLAB/Simulink model using ANN technique

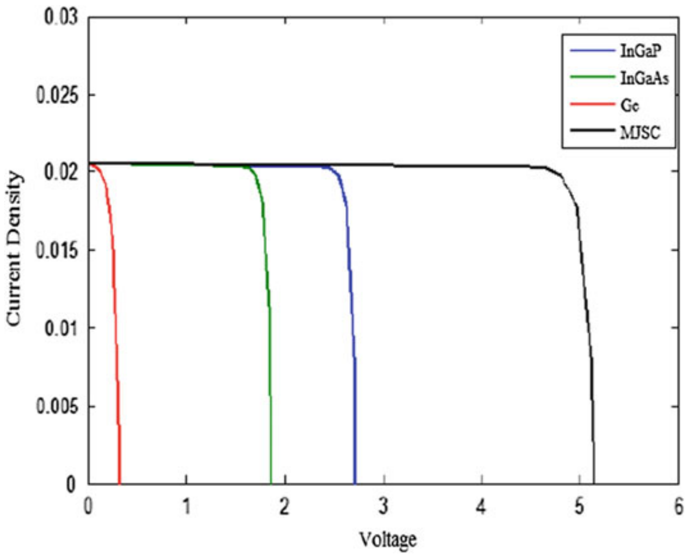

Fig. 6 V–I characteristics of MJSC and its sub-cell

It can be inferred from the given below graph that as the radiation changes the P–V graph also changes accordingly.

The response of output power after implementing P&O strategy is shown in Fig. 10. It is noticed that P&O is an effective control method to overcome the non-linear characteristics of PV cell and improve the efficiency of PV power generation system but still causes some oscillations and the output produced by the system.

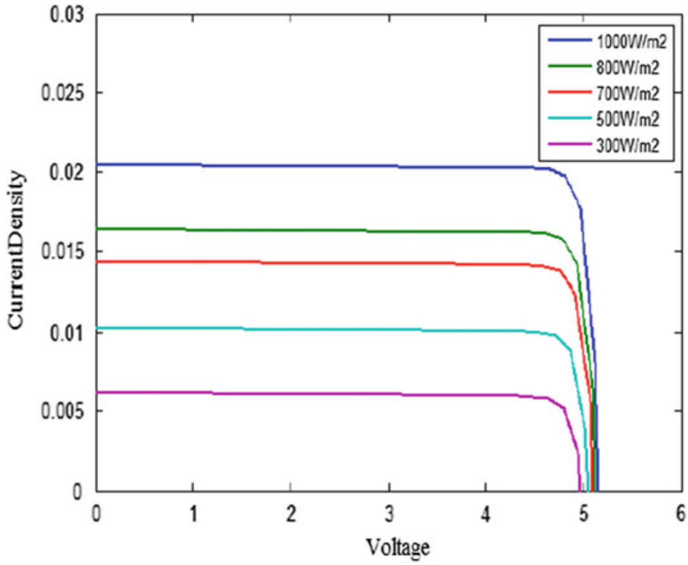

Fig. 7 V–I characteristics of MJSC at different radiations

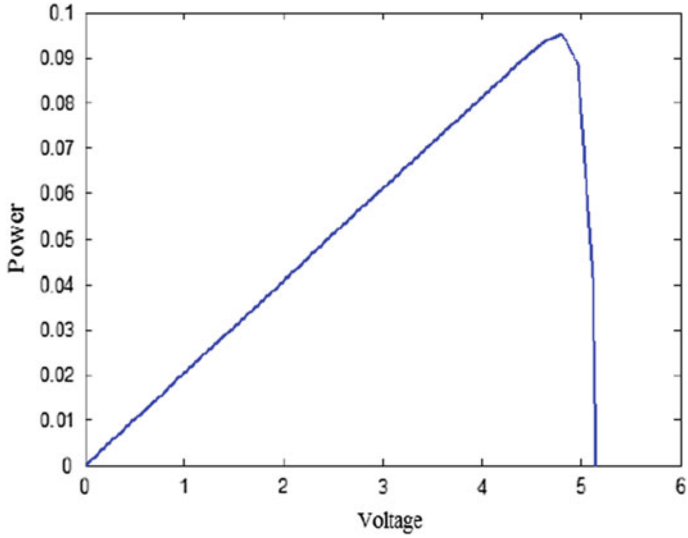

Fig. 8 P–V characteristics of MJSC

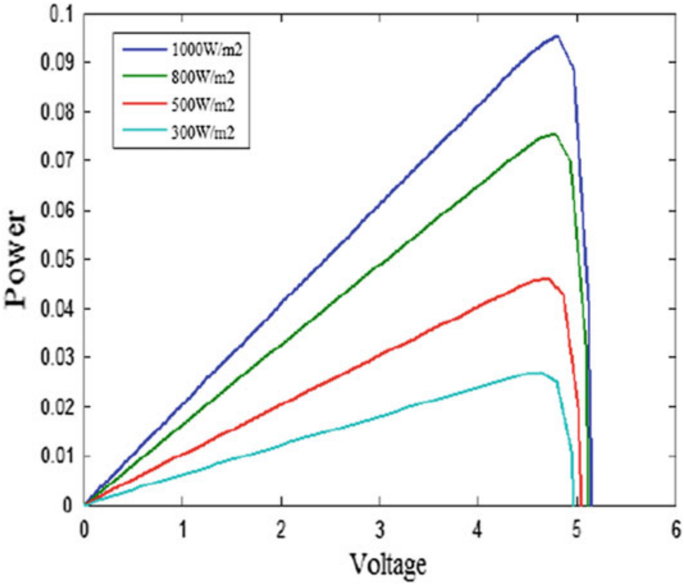

Fig. 9 P–V characteristics of MJSC at different radiations

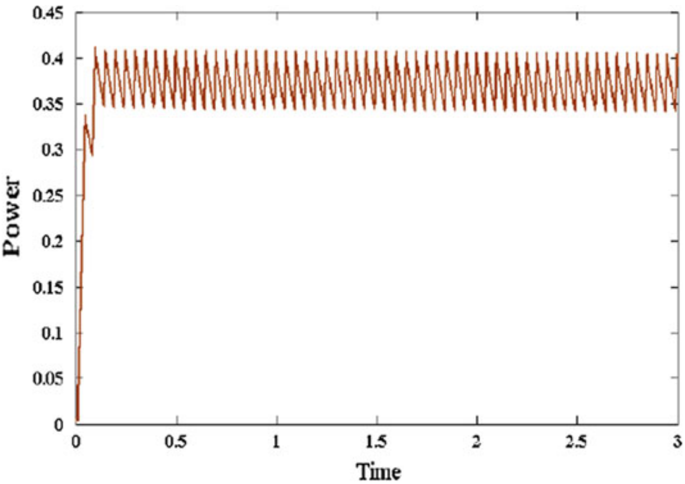

Fig. 10 Power vs Time graph after implementing P&O MPPT technique

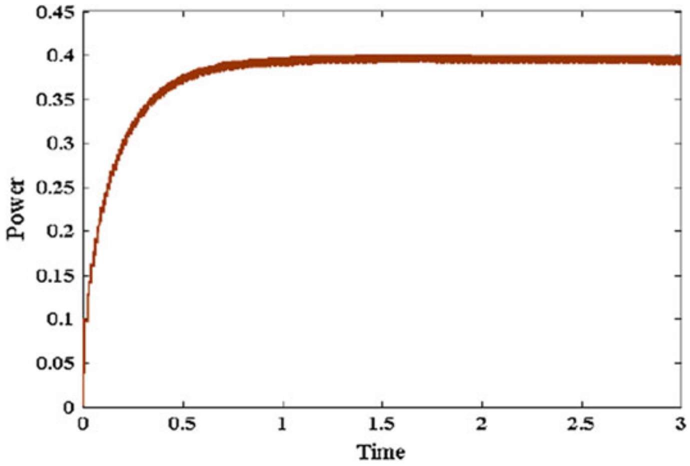

Fig. 11 Power vs Time graph after implementing ANN MPPT technique

The response of output power after implementing ANN is shown in Fig. 11. Through simulation results, it is observed that the system completes the MPPT successfully, and it has fewer fluctuations as compared to the other strategy. The plot given in Fig. 12 depicts the comparison of the two MPPT techniques, i.e. P&O and ANN. This clearly shows that ANN technique is the most appropriate technique as it has less oscillation and is more efficient than the P&O technique. ANN is faster, accurate, efficient and accessible as compared to the conventional strategies.

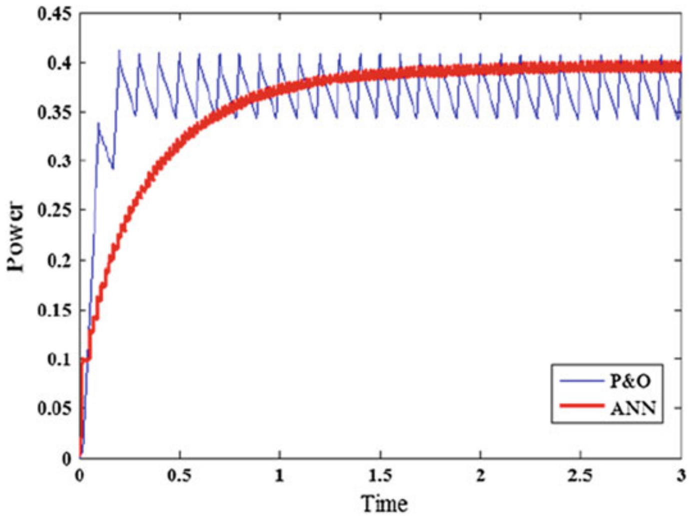

Fig. 12 Power vs Time graph depicting comparison of P&O and ANN techniques