MODELING OF SOLAR PHOTOVOLTAIC ARRAY UNDER NON-UNIFORM INSOLATION

A THESIS

Submitted in partial fulfilment of the

requirements for the award of the degree

of

DOCTOR OF PHILOSOPHY

in

ALTERNATE HYDRO ENERGY CENTRE

by

SANGRAM BANA

ALTERNATE HYDRO ENERGY CENTRE
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE – 247 667 (INDIA)
JUNE, 2017

ABSTRACT

Solar photovoltaic (PV) systems are environmentally friendly and assist in minimizing greenhouse gases (GHG) emissions that arise due to the use of fossil fuels for power generation. In India, most power grids receive electricity from coal based power plants. Feeding electricity into the grid by solar PV plants can help in transmitting equal amounts of electricity as would have been generated from a GHG intensive grid. Therefore, PV power generation systems become increasingly important all over the world due its availability, cleanness, low maintenance cost and inexhaustible nature. Standalone or grid connected PV generating system can be opted for rural electrification. Considering the high cost of photovoltaic power system, it is necessary that reliability and accuracy of the system is ascertained in simulated environments. Also, the optimum and utmost utilization of available solar energy must be ensured before actually installing the system.

PV cell is the fundamental component of PV systems. The PV cells are arranged in series to form modules. Modules are connected in series or parallel to form an array. The power generated by solar PV modules is a function of environmental parameters such as irradiation and temperature. To predict the performance of a PV module, a reliable and accurate simulation design of a PV generator before being installed is a necessity. PV module is commonly modelled on the basis of its equivalent circuit. Appropriate modelling of PV module is crucial for simulation design, evaluation, optimization and maximum power point tracking (MPPT). Also, the Modelling of PV module includes appropriate circuit model and accurate circuit model parameters. Finding the circuit model parameters of PV module is referred as identification of model parameters. As, the information provided in the manufacturers' data sheet may not be sufficient for developing a simulation model of PV module. Associated and unidentified parameters such as diode ideality factor (a), series resistance (R_s), and shunt resistance (R_{sh}) are required to accurately determine the power output of a PV module under varying environmental conditions.

Various studies have been carried out on the model development of the PV modules. However, these models have different level of complexity of their own. These PV models may be differentiated on the basis of number of employed diodes, finite or infinite shunt resistance, fixed or variable ideality factor and the techniques used to determine the unknown

parameters. Earlier, comparative studies do not provide information about which model will provide better results under real environmental exposure conditions and which model should be considered to study the effect of different possible shading conditions. Moreover, most of the proposed PV models discussed in the literature have been tested mostly for crystalline technology.

Further, various parameter extraction methods have been developed to determine the unknown parameters of the PV panel. These methods are employed, to study the effect of module or cell failure, module mismatch, effect of partial shading on power output and to plot P-V and I-V characteristics. In literature, it is found that analytical parameter extraction algorithms are based on empirical relationship between PV module voltage (V_{pv}) and current (I_{pv}). However, iterative algorithms require a lot of time to converge and makes difficult to get an optimal solution. While, these techniques work efficiently in Standard Test Conditions (STC), they may not be efficient and accurate while operating under varying environmental conditions. Newton-Raphson method used in earlier studies suffers from singularity problem and parameters a, R_s, and R_{sh} are assumed constant under changing weather conditions. But in actual conditions, these parameters vary with changing environmental conditions just like photo-current (I_{ph}) and module current (I_{pv}). There are no boundary limits for parameters demarcated in any of the conferred techniques. In order to identify the unknown parameters of a solar PV module, reliable and accurate parameter extraction algorithms are essential. The new parameter extraction algorithms should consider upper as well as lower boundary limits of the parameters and should not suffer from singularity and premature convergence problems.

Furthermore, the power output of photovoltaic systems is considerably affected by complete or partial shading of the modules in an array. These modules can be interconnected in different manners to form different types of PV array configurations such as series; parallel, series-parallel (SP), Total-cross-tied (TCT), Bridge-linked (BL) and Honey-comb configuration (HC). These configurations are employed to reduce the impact of shading on PV array power output. Various researchers have analyzed the performance of different array configurations but the utility of interests vary. Some researchers have analyzed only elementary configurations (series and parallel) whereas others have considered only total-cross-tied (TCT) configurations. Further, the shading patterns considered for evaluation were either fixed or random patterns. Therefore, it is essential to determine a PV array configuration which provides optimum performance under various possible shading scenarios. On the other hand, selecting various shading patterns is an important issue. Some shadow patterns may provide similar response for distinctive configuration or a particular configuration may perform better only under a certain shading pattern. These problems lead to confusion in selecting an appropriate configuration with superior tolerance against shading effects. It is also important to consider the shape and size of the shadow.

By contrast, using bypass diodes on related configurations of PV modules produces a partial shading effect. The detrimental effects of partial shading on PV array efficiency still exist despite advancements in technology. Due to partial shading, the internal resistance of a PV panel varies with variation in weather conditions but the load resistance remains the same. Therefore, converter controlled with MPPT algorithm is used to achieve load matching and extracting maximum power from PV array. Specifically, partial shading alters the PV array output, resulting in a nonlinear *P–V* relationship and multiple-peak characteristics. Under shading conditions, a PV module which belongs to the same string, receives different insolation and the output *P–V* characteristic curve becomes complicated by consequently yielding a multi-peak curve. Presence of multiple peaks in the output characteristics of PV systems reduces the efficiency of ordinary MPPT methods, assuming that an individual maximum power point (MPP) exists on the *P–V* characteristic curve. Therefore, these strategies obtain only a local MPP because the *P–V* curve is multimodal. Considering the drawbacks associated with partial shading, an appropriate maximum power point tracking (MPPT) technique which can find the global maximum power point (GMPP) under any mismatching condition should be developed.

Based on the extensive literature review carried out, it is observed that most of the studies in the area of PV system modelling are only focused on the performance of either single diode or double diode based solar PV models where each model has certain advantages of its own. However, the mathematical framework of these models has different levels of complexities. A comparative study signifying the performance of both the models under real environmental exposure conditions including shading effect will enable us to select an efficient PV model. Under earlier studies, PV array configurations have been investigated for different shading scenarios in simulated environment. Moreover, these studies have not considered the impact of crossties on power output of PV array configurations. In the literature, it has also been found that no comparative study of PV array configurations is reported under real operating conditions. Furthermore, the effect of size and intensity of shade on the PV modules interconnected to form different PV array configurations have not been discussed much. MPPT algorithms in the literature have a number of shortcomings such as: high tracking error, fluctuation around the actual MPP depending on the perturbation size, inefficiency to cope with changing weather conditions, singularity and slow response problems. Therefore, there is a need for developing new MPPT algorithms considering the above discussed problems.

Keeping in view the identified gaps in earlier studies discussed above, the present study is planned with following objectives:

(i) To develop reliable PV models in Simulink environment based on single diode and double diode equivalent circuits; in order to carry out a comparative study to identify a suitable, feasible and robust PV model for practical applications.

(ii) To extract unknown parameters of the suggested model of a PV module using soft computing technique in order to maximize accuracy and reduce computational time.

(iii) To investigate the combined effect of uniform and non-uniform solar radiations on PV output in order to find the most suitable configuration compatible with different shading scenarios.

(iv) To develop an algorithm for maximum power point tracking in a PV system, in order to maximize the power output under uniform and non-uniform insolation.

(v) To design and develop hardware set-up for authentication of developed MPPT technique and to establish optimal maximum power points under uniform and non-uniform (Partial) shading conditions.

To fulfil the above mentioned objectives, a systematic and optimal PV system model has been developed. The present study has been carried out to establish optimal maximum power points of a PV system operating under both uniform and non-uniform shading conditions. Therefore, an efficient PV system model employing an effective array configuration and utilizing an effective maximum power point technique is proposed to predict the performance of a PV system more accurately under real operating conditions. In order to validate the obtained results, experimental tests have been conducted at National institute of Solar Energy (NISE) located in Gawalpahari, Gurgaon-Faridabad road, Haryana, India (latitude = 28.4700 ^{0}N and longitude = 77.0300 ^{0}E).

Subsequently, a reliable and robust model of a PV module is developed to predict the performance of a PV system more accurately. To achieve this, a single diode and double diode based models of a PV module are developed initially. A comparative study is then conducted to evaluate the performance of both models. Development of these models is done by evaluating their respective equivalent circuits and the unknown parameters of the respective models are identified through an iterative technique. Performance assessment of single diode and double diode models of solar PV module is carried out under STC, real operating conditions and partial shading conditions. The effect of variation in environmental factors (insolation and temperature) and internal parameters (ideality factor, series and shunt resistance) on both models are evaluated and extensively discussed. In order to ensure the robustness of the developed models, the performance and power deviation of these models are also evaluated for different PV technologies under real outdoor conditions. Based on the comparative analysis, it is found that single diode model provides better results under high insolation level whereas under shading condition the accuracy of double diode model is found to be slightly better than single diode model. However, the single diode model is less complex, needs less computation time, easier to implement and has relatively similar accuracy under shading conditions as compared to double diode model. Therefore, single diode model is selected for further investigation. The accuracy of the selected model can be further improved by determining unknown parameters more accurately.

In order to improve the accuracy of the suggested single diode model, the unknown parameters are identified using particle swarm optimization (PSO) technique with binary constraints. The proposed method completely eliminates the requirement of assuming ideality factor. Effect of temperature and irradiance are also taken into account for extracting the unknown parameters of the PV model. The evaluation of three different PV modules KD210GH-2PU, SP70 and SQ85 (mono-crystalline and polycrystalline based technology) ensures the robustness of the proposed technique. Two novel approaches have been considered as a point of reference for the proposed technique. Considerable accuracy in the results is achieved irrespective of temperature variations. The PSO algorithm is iterated 100 times with same initial condition as well as with standard parameter values provided by the manufacturer. Absolute power error for KD210GH-2PU, SP70 and SQ85 at STC are found as

0.002%, 0.003 % and 0.001 % respectively. The mean maximum modelling error at MPP is found to be less than 0.02 % for maximum voltage and 0.26 % for maximum power. It is observed that after every 100 generations the fitness value drops down to zero in 8ms of time to confirm the convergence of the fitness value. The identification of accurate unknown parameters provides an optimum model of a PV module. This model is further used to develop a PV array for further investigation. The output of a PV system is considerably affected by shading. Therefore, the selection of an appropriate array configuration plays a significant role in minimizing the effect of various possible shading scenarios.

To study the possible shading effect and to minimize its consequences on the performance of a PV system, the modelling of different PV array configurations is presented. Further, an experimental setup has been established to investigate the performance of different PV array configurations in outdoor conditions. The inconsistent solar insolation distributions are mimicked (artificial uniform and partial shading patterns) by using different types of meshes. In order to reduce the effect of crossties on power generation, a novel PV array configuration is investigated under 14 possible shading scenarios. Power output of novel PV array configuration is compared with other PV array configurations (SP, TCT, BL and HC) for all the considered shading scenarios. The shadows of different shapes, sizes and intensity are retained in the considered 14 shading scenarios. The spectrum and transmissivity analysis is also discussed to determine the effect of different types of employed meshes, on the spectrum of incident solar radiations.

In order to perform the spectrum analysis, a sun simulator namely Oriel Sol3A simulator certified to IEC 60904-9 Edition 2 (2007), JIS C 8912, and ASTM E 927-05 standards for Spectral Match, Non-Uniformity of Irradiance, and Temporal Instability of Irradiance is used to generate incident solar radiation flash. Class AAA systems reduce binning variability of PV cell testing as compared to so called Class A, Class B or non-classified sources. This performance consistency allows for precise comparison of performance data. Further, the electrical measurements were performed using the data acquisition system PVPM-2540 C. PVPM device measures the I-V curves of PV modules as well as of strings or arrays. Irradiation reference sensor SOZ-03 and Pt100/Pt1000 temperature sensor are also integrated with the measuring device.

All PV array configurations are also investigated with and without the presence of bypass diodes. The average deviation in power output is observed minimum, 0.12 % (with bypass diode) and 0.18 % (without bypass diode) in TCT configuration and maximum 0.19 % (with bypass diode) and 0.57 % (without bypass diode) in SP configuration. The TCT configuration is found to be an ameliorate selection for any type of shading pattern and is closely followed by the proposed Novel configuration. The proposed novel configuration scheme can considerably reduce the partial shading losses with the advantage of lesser crossties and provide power output very close to that of TCT configuration.

Under the present study, the cell-to-module-to-array modelling has been developed to predict the effect of varying operating conditions on the performance of a PV generator. It is also verified that the effect of shading can be minimized by employing an optimal PV array configuration. However, there are challenges related with a PV system operating under shading conditions to track maximum power point (MPP) as it varies with change in temperature and insolation. Due to partial shading many local maxima and one global maxima are experienced, so it is difficult to get and operate at global maxima. Consequently, partial shading interrupts a PV system to operate at GMPP and reduces its efficiency. In order to track MPP efficiently under diverse operating conditions, a maximum power point tracking algorithm is employed. In order to extract maximum possible power, the utilized array for MPPT is interconnected in TCT configuration. Dynamic response, tracking speed, rapidly changing atmospheric conditions, partial shading and complexity are the main factors that should be taken into consideration while developing an efficient MPPT algorithm.

By taking the above concerns into account, the present study focuses on formulation of a new MPPT algorithm that is simple and yet robust. The developed algorithm has addressed all the concerns that are pointed out in the literature (e.g. rapidly changing atmospheric conditions, partial shading, tracking speed, steady state oscillations etc.).

In order to develop the algorithm, a system independent Dynamic PSO (DPSO) based MPPT technique is developed, to improve the tracking speed, tracking accuracy and performance under partial shading conditions. Further, to accelerate the convergence speed towards global best (G_{best}) and to increase the tracking ability inertia weight constant (ω), cognitive and social coefficients (c_1 and c_2) often called as acceleration coefficients are modified respectively. An experimental setup using a solar array simulator, DC-DC SEPIC converter, OPAL-RT controller and load with improved MPPT algorithm is implemented for tracking optimal peak power from PV array under various possible partial shading conditions. Eighteen different possible shading patterns were tested experimentally to validate the simulation results to show the effectiveness of the proposed method. Based on the validation of the results, it is found that the proposed method can be used to obtain global maximum power point (GMPP) in all the cases irrespective of GMPP location. Experimental and simulated results also show that the proposed method can successfully detect the shading pattern changes and reinitialize the MPPT process. The developed MPPT technique has the advantage of easy implementation, fast convergence speed, quickly tracks MPP under rapidly varying atmospheric conditions and has better tracking efficiency as compared to other GMPP tracking algorithms.

To Summarize, an optimal PV system model which emphasizes on accuracy, array configuration and maximum power point tracking was developed to accurately predict the performance of a PV system under both uniform and non-uniform shading conditions. The results obtained in this study may be useful in order to predict the performance of a PV system under variable outdoor conditions before being installed.