PERFORMANCE INVESTIGATION OF PHOTOVOLTAIC SYSTEMS UNDER PARTIAL SHADING CONDITIONS

Ph.D. THESIS

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ABSTRACT

Among all renewable energy sources, solar energy is considered most popular source due to its superior quality and abundant availability. The solar energy is used as an input energy with solar thermal energy systems and solar photo voltaic (SPV) systems. SPV systems have easy installation, require less maintenance and free from environmental issues. PV systems are composed of PV cell and a typical PV cell can produce very less power and to increase the power production, cells are configured to form modules and modules are arranged to constitute arrays. As power produced by PV array depends on the environmental conditions, it is therefore important to investigate the PV performance in terms of reliability and accuracy in simulated environment to predict the power production.

To predict the performance of PV module, a reliable and accurate simulation design of a PV generator afore its implementation in real practice is required. The output voltage and current depend on the solar irradiance, ambient temperature, and load. To investigate the effect of cell failure, module mismatch, partial shading on PV array and to analyze maximum power point tracking (MPPT) techniques afore its use in real practice, it is a prerequisite to simulate the complete electrical characteristics accurately and efficiently. Lumped circuit models are widely used for assessing cell performance and for complete characterization of PV modules. Single-diode model and Double-diode models are the lumped models which are extensively used as equivalent electrical circuit for a PV module. The complete physical characteristics of PV modules are represented by equivalent electrical circuit models and its parameters i.e. photo current (I_{ph}), saturation current (I_0), series resistance (R_S), shunt resistance (R_P) and ideality factor (a_1). These parameters are not given in manufacturer's data sheet specifications. Extraction of PV module parameters includes the evaluation of equivalent circuit parameters in order to simulate the output characteristics of PV module at varying irradiance and temperature.

Different studies have been carried on the modeling of PV modules. The methods to extract parameters are analytical, numerical evolutionary and hybrid. The analytical methods and hybrid methods use manufacturer's data sheet information and formulates equation using key operating points referred to as "remarkable points" of the I-V curve at standard test condition (STC) i.e. short-circuit current, open-circuit voltage and maximum power point. The analytical method reinforces approximations as the equations that to be solved are

implicit in nature. Parameter extraction using analytical and hybrid method lies in the fact that the curve obtained should pass through the remarkable points. The advantages of analytical methods are that it needs only manufacturer's data sheet information and have high execution speed. However, at the same time assumptions and approximations considered can affect the accuracy of results so obtained. Also its evaluation heavily depends on initial conditions. Numerical evolutionary approach encysts point by point curve fitting which minimizes the error between the experimental data and calculated values using suitable evolutionary algorithms. However, experimental data is a prerequisite to compare and minimize the predicted data. Also to compare and minimize large data points requires large execution time. The new parameter extraction methodology should balance between accuracy and execution speed.

Furthermore, the performance of PV array is considerably affected under partial shading conditions (PSC). In different studies, the partial shading losses are addressed with various array configurations apart from its conventional array configurations. These configurations are pre-configured and some of the typical configurations are Series-Parallel (SP), Total Cross Tied (TCT), Bridge Link (BL), and Honey Comb (HC). Some researchers have analyzed the series-parallel/Total Cross Tied (TCT) configurations under fixed or random shading patterns. Therefore, it is important to propose an improved array configuration and investigate its performance under different shading scenarios. It is also important to consider the dimension of shadings implemented for study.

Moreover, Bypass diodes enhance the power under PSCs. However, PV and IV characteristics curve are non-linear and multiple peaks can be evolved due to bypass diodes under PSCs. MPPT techniques are employed to find MPP automatically from PV module characteristics i.e. maximum power is always obtained through the PV system during changing solar insolation, PSC and load change. This is accomplished by matching the MPPT the operating current and voltage of converter. Therefore, a DC-DC converter is prerequisite in case of MPPT controller. Non-linear and multiple peaks in characteristics curve under partial shading makes a challenging task for the control algorithm to find the global maximum power point (GMPP). A robust and fast GMPPT algorithm need to be developed which can perform suitably under fast changing irradiance, partial shading and load variations.

After carrying out an extensive literature review it is found that most of the work in PV system modeling have considered single diode, which have drawbacks. MPPT algorithm also needs improvement as it requires improvement in tracking speed, oscillations nearby GMPP under PSCs and load changing conditions. Therefore, development of MPPT algorithms become essential to address the above discussed issues. In order to address the above mentioned research gaps, the present study is organized with the objectives; i.) To develop a PV double-diode model in MATLAB/ Simulink, extract parameters for double diode model so that it fits experimental I-V characteristics, ii.) To establish a PV system experimental setup for conducting experiments and validate its results with numerical simulation results, iii.) To investigate the PV system performance under uniform and PSCs, iv.) To investigate PV system performance with and without bypass diode under PSCs and with different static array interconnection techniques to minimize mismatch losses of PV system and v.) To minimize mismatch losses of PV systems in partial shading using energy flow control via power converter and MPPT controller and to set-up a hardware prototype to validate the performance of developed MPPT algorithm under partial shading conditions.

In order achieve the above mentioned objectives, a lumped model of double-diode PV module has been developed for accurate performance prediction of the PV system. A comparative analysis has also been carried out for the selection of superior model among single diode and double diode. The double diode model is built through the extraction of unknown parameters with analytical and numerical evolutionary algorithms. The double-diode performance investigation has been carried out at standard temperature conditions, controlled environmental conditions and partial shading conditions. Different kind of PV module characteristics are evaluated under uncontrolled environmental conditions to confirm the robustness of PV models. Based on the comparative analysis it is found that prediction of double-diode model is more accurate under lower solar radiations. Therefore, double-diode model has been employed for subsequent analysis under this study.

An improved hybrid algorithm, which consists of analytical and numerical evolutionary method has been developed to improve the accuracy and reduce computational speed for double-diode PV model. External environmental parameters such as irradiance and temperature have been considered for evaluating the unknown parameters of double-diode PV model. To confirm the robustness of considered methodology, four different kinds of PV modules i.e. two mono-crystalline (SP-75, SM110-24), one polycrystalline (RSM-50), and one thin film (ST-20) performance are investigated. Under controlled environmental conditions it has been found out that the normalized root mean square deviation (NRMSD) value is found to be low as 0.0093, 0.004, 0.0055 and 0.0177 for RSM-50, SP-75, ST-20 and SM110-24 modules at 1000 W/m^2. The average mean absolute error in power (MAEP) calculated for RSM-50, SP-75, ST-20, and SM110-24 is 0.0969, 0.04071, 0.1001 and 0.3062. The average root mean square deviation (RMSD) calculated at varying temperature for RSM-50, SP-75, ST-20, and SM110-24 is 0.0261, 0.070, 0.0122 and 0.0619.

Further, an experimental setup has been designed and fabricated to study the behavior of different static PV array configuration in uncontrolled environmental. The average RMSD calculated for RSM-50, SP-75, ST-20 and SM110-24 are 0.0377, 0.0340, 0.0089 and 0.0209. However, the MAEP calculated are 0.4063, 0.3694, 0.1079 and 0.5039 under uncontrolled environmental conditions. The performance of different static PV array configuration with and without bypass diode has also been investigated.

A MPPT algorithm has also been developed which resolves the concerns found out during literature survey such as tracking GMPP under partial shading conditions and distinguishing between change in irradiance and change in load. The MPPT algorithm has been developed with a social learning differential evolution and by adopting an inspection step, which can track the GMPP under partial shading, improves the tracking speed and accuracy. An experimental setup is composed of solar array simulator, OPAL-RT controller, DC-DC buck converter and programmable load has been designed and fabricated for the validation of simulation results. The proposed MPPT strategy tracks the GMPP within 1.5 s for simulation studies and within 2 s with experimentation under different kinds of shading scenarios. Moreover, the efficiency of 99% is achieved in the experimental study.

An improved SuDoKu static configuration strategy has been developed and its outcomes are investigated under different shading scenarios. Power enhanced by employing an improved SuDoKu static configuration has been compared with power enhancement in other static PV array configurations. It has been found that improved SuDoKu static array configuration outperforms other array configurations under different shading scenarios and it is closely followed by the TCT configuration. The proposed improved SuDoKu strategy shows 24.70% enhancement in power for shading scenario 2 and 3.6% enhancement in power for shading scenario 4, when compared with TCT configuration.

Summarizing, PV model which follows accurate PV characteristics, improved array configuration and a maximum power point tracking algorithm has been developed for performance investigation of PV system under PSCs. The obtained results in this study may be useful to predict PV system performance afore its installation in uncontrolled environmental conditions.