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Design and real time implementation of a novel rule compressed fuzzy logic method for the determination operating point in a photo voltaic system

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ABSTRACT

In the PhotoVoltaic (PV) system characteristics, a maximum power operating point exists for each value of solar irradiance. The operating point continuously varies as the solar irradiance vary and therefore tracking of maximum power in PV system is significant. This paper introduces a new rule compressed fuzzy logic method to track optimal power operating point of photovoltaic system under non-uniform irradiance. The method has three-input parameters and a single output parameter. The input parameters are the change in power, the change in voltage and change in duty cycle and the output parameter is the reference current to the converter. With respect to each combination of two input parameters, three set of output rules are developed and then compressed to a single set of rules based on tracking conditions. The step response, analysis under partial shading and with one day solar irradiance data are implemented in Matlab/simulink platform. The method confirms its effectiveness by attaining the optimal power at 2.46s with a low steady state error of 0.35%. The energy capitulation efficiency is obtained as 99.5%. The performance of the proposed method is also evaluated experimentally and its efficiency is proved by comparing with perturb & observe algorithm.

1. Introduction

Renewable energy sources have more consideration as alternative energy sources because of rising environmental concerns and depleting conventional energy resources. Solar energy has a significant role for meeting the increased requirement of electricity with reduced environmental impact. Solar energy conversion systems i.e. Photovoltaic systems are being more and more employed in grid connected hybrid and standalone system applications. However, the power generation from the PV system is dependent on the environmental factors such as temperature, solar irradiance, etc. Therefore, the variation of each solar irradiance leads to the variation of the corresponding maximum power of the PV system [1]. Hence, the operating points changes, which affects the power conversion of the system and in turn degrades the usage of electrical apparatus. Therefore, a PV system must necessarily function at the optimal operating point to achieve maximum power [2].

The optimal operating point is determined by the Current-Voltage (I-V) and power characteristics of the PV system. Under the change in environmental conditions, the I-V characteristic is disturbed highly; thereby the power characteristic is also perturbed and this causes power losses in PV system. As the solar irradiance varies in a continuous pattern, the power generated by the system does not follow the optimal point of the PV system characteristics [3]. An additional concern in PV system characteristics is that, the entire modules are not exposed to regular solar irradiance under partially shaded conditions. This results in multiple operating points in each I-V characteristics corresponding to each solar irradiance. In each I-V characteristics, one optimal operating power point exists where the power is maximum. Therefore, the tracking of the optimal power point which is the global point from the multiple local points becomes more problematic [4].

Various types of controllers for tracking the maximum power operating point are detailed in literature. This begins with the current and voltage feedback based simple Maximum Power Point Tracking (MPPT) methods [5], which are further enhanced by techniques such as the hill climbing [6], the perturb and observe (P&O) [7] and the incremental conductance algorithms [8]. Tracking and operation of such algorithms are satisfactory under

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slow and gradual change of solar irradiance. But for rapid changes in irradiance, the algorithms suffer by reaching the pesudo global point, or takes longer time to reach the convergence point or the global point, and by the occurrence of oscillatory power response [9].

To resolve the problems, optimization algorithms such as Particle Swarm Optimization [10], Artificial bee colony [11] and intelligent controllers such as Fuzzy Logic Control (FLC), Artificial Neural Network based MPPT techniques are introduced [12]. Among these algorithms, the FLC is notified as a better option [13] to track optimal power operating point under change in solar irradiance, change in temperature and electric load differences [14]. The reason is that, the design is simple where the nominal constraints are used for ideal mathematical model based on the behavior of system using the membership functions and the rules and also, it tends to regulate the system behavior towards robustness [15]. Several approaches exist based on Fuzzy Logic (FL) as MPPT controller [16], environmental factor classifier [17], and the output fluctuation regulator [18].

The modified model of the conventional controllers with the fuzzy logic algorithm proves improved performance interms of steady state oscillation under rapid change in irradiance. A fuzzy logic based modified hill climbing algorithm is developed by Bader et al. [19] which improved the tracking performance under rapid changes in irradiance. A FL based P&O algorithm is proposed by Ahmad et al. [20] to eliminate the steady state oscillations. However, the behavior of oscillation is not completely eliminated by this algorithm. The steady state oscillations are further reduced by the FL based MPPT controller developed by Chekired et al. and also the convergence point reached fastly [13]. In addition to performance enhancement, a modified fuzzy algorithm must be simple to be used as a MPPT controller. The integrated model of the incremental conductance algorithm with FL proposed by Punitha et al. [21] is little complex because of the consideration of two fuzzy system and input adaptation function.

For the control applications, FL controllers are categorized as single input single output, single input multi output, multi input single output (MISO), and multi input multi output systems respectively [22]. A MISO FL based MPPT improves the performance and is used under nonuniform solar irradiance [23] and under partial shading conditions [24] respectively. A MISO FL model uses asymmetrical input fuzzy sets with single set of decision making rules. However, with multiple inputs, each input parameter has its own influence on the output parameter. The combination of all input parameters in a single fuzzy logic system leads to inaccuracy in the output because it makes the input membership functions to be merged in some closed interval at a point [25]. In addition, the complexity of this fuzzy logic is enlarged and the system accuracy is reduced by inappropriate tuning rules [26].

It can be understood that, MISO type FL controllers are considered as better tracking controllers. But the rule design is one of the complex problems in nonlinear system when the number of input parameters is more than two. On the other hand, in more difficult situations, where the system parameters are subjected to disturbances, the dynamics of the system are too complex to characterize [27].

From the study of literature, it is observed that when multiple power points occur, the dynamics of the system becomes complex which degrades the accuracy of the output. Also, a MISO FL controller suffers from the rule design. Hence, in this paper a rule compressed fuzzy interference model is proposed which uses multiple input parameters and compresses the multiple rules developed to a single rule, and makes the fuzzy control system simple and increases the accuracy of the output.

Here, three input parameters are used to control the converter. The input parameters are the change in PV power, the change in PV voltage and the change in converter duty cycle. Initially, three set of tracking rules are developed for input and output parameters. Then, the rules are compressed by the maximum point condition of PV system. With the help of compressed rules, interference system is designed for the proposed FL controller. The proposed method is analyzed under rapid change of solar irradiance and partial shading conditions. The detailed description of the Rule Compressed Fuzzy Logic (RCFL) MPPT controller is explained in Section 3.

2. Modelling of PV system

PV systems used for high power generation consists of several combinations of series and parallel PV modules. The connection of the series and parallel combination of modules are varied as per the requirement or rating of the connected load. In this work, two series and four parallel connected modules are considered for the analysis. Fig. 1 shows the configuration of the PV modules. The number of series and parallel connected modules are denoted as N_p and N_s respectively. The equivalent circuit model of a PV cell is illustrated in Fig. 2.

In fact, the characteristics of a PV system are nonlinear, as the diode exhibits non linearity. From Fig. 2, the nonlinear characteristics and the equations are obtained for n number of modules. The total output current and power equation of the parallel and series connected PV modules are expressed in equations (1) and (2) [28].

$$I_{pv} = \sum_{n\in N} N_{p(n)} \left(I_{ph(n)} - I_{0(n)} \left[\exp\left(\frac{q\left(V_{pv(n)} + R_{s(n)} I_{pv(n)}\right)}{N_{s(n)} AkT} \right) - 1 \right] - \frac{\left(V_{pv(n)} + R_{s(n)} I_{pv(n)}\right)}{N_{s(n)} R_{p(n)}} \right) \tag{1}$$

where, n is the number of PV modules ($n = 1, 2, \ldots N$), $I_{pv(n)}$ and $V_{pv(n)}$ are the output current and voltage of n^{th} PV module, $R_{s(n)}$ and $R_{p(n)}$ are the series and parallel resistance of n^{th} PV module, N_p and N_s are the number of modules connected in parallel and in series, A is the P-N junction ideality factor, k is the Boltzmann's constant (1.38×10^{-23}J/K), T is the temperature in Kelvin, $I_{ph(n)}$ is the photon current at n^{th} module, $I_{0(n)}$ is the reverse saturation current of n^{th} module, and q is the electron charge (1.6×10^{-19}C).

In equation (1), the series resistance R_s value is extremely low and the parallel resistance R_p value is extremely high for silicon in idyllic state. Therefore, the value of R_s and R_p can be neglected. With V_{pv} and the simplified I_{pv}, the power produced by the PV modules is represented as,

$$P_{pv} = V_{pv} \sum_{n\in N} N_{p(n)} \left(I_{ph(n)} - I_{0(n)} \exp\left(\frac{qV_{pv(n)}}{N_{s(n)} AkT} \right) - \frac{V_{pv(n)}}{N_{s(n)}} \right) \tag{2}$$

Fig. 3(a)–(c) illustrates the characteristics of photovoltaic power, photovoltaic voltage and converter duty cycle with respect to the photovoltaic current at different solar irradiance as 250 W/m^2, 500 W/m^2, 750 W/m^2, and 1000 W/m^2. The specification of the PV system is given in Table 1.

2.1. Effect of partial shading of PV modules

Partial shading is one of the concerning problems which diminish the performance of the system. When the PV modules get shaded, the irradiance is distributed inequitably to the modules. Under such condition, the nonlinear characteristic is highly affected