Solar Energy 139 (2016) 213–220

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Takagi-Sugeno fuzzy approach for power optimization in standalone photovoltaic systems

Anbarasi Muthuswamy Palaniswamy *, Kanthalakshmi Srinivasan

Department of Instrumentation and Control Systems Engineering, PSG College of Technology, Coimbatore 641004, India

ARTICLE INFO

Article history:
Received 21 June 2016
Accepted 21 September 2016

Keywords:
Maximum Power Point Tracking
Standalone photovoltaic system
Boost converter

ABSTRACT

This paper presents Takagi-Sugeno (T-S) Fuzzy based approach for operating the solar panel in Standalone Photovoltaic (SPV) system at Maximum Power Point (MPP). The SPV system incorporated with T-S Fuzzy algorithm can be represented by four local models and each model in turn is characterized by an optimal operating point. This optimal operating point of local models pave a way to compute the optimal operating point of PV panel. The duty cycle of the boost converter placed between the panel and load has to be appropriately varied based on the computed value, allowing the panel to provide optimal power. The performance of T-S Fuzzy algorithm applied to the boost converter present in SPV system is tested in simulation for various operating conditions and compared with the performance obtained using Incremental Conductance Algorithm. The results indicate the effectiveness of the proposed T-S Fuzzy algorithm in tracking maximum power than the Incremental Conductance Algorithm.

1. Introduction

An important issue that the world will face in this century is energy famine. Due to its readily available nature, solar energy is the best solution to overcome the issue. Solar power utilizes photovoltaic effect to extract electrical energy from solar energy (Liang et al., 2001). The power delivered by PV panel depends largely on the environmental conditions. DC-DC converter allows to extract the maximum power from PV panel (Esram and Chapman, 2007). Approaches such as Perturb and Observe method, Incremental Conductance algorithm, Fuzzy Logic methods are proposed to track the optimal point (Chiu, 2009; Rameshkumar and Arumugam, 2009; Lalouni and Rekiou, 2009). Approach based on voltage corresponding to maximum power has also been developed. The disadvantage being, it requires two control loops. The first loop is meant for the determination of voltage corresponding to maximum power and the second loop is used to adjust the PV panel voltage to that of the determined one. The implementation of both the control loops increases the complexity. Therefore to overcome the aforementioned disadvantage, only one loop is used by considering maximum power condition as the objective.

The T-S Fuzzy method proposed by Takagi and Sugeno constitutes of fuzzy if-then rules that represents local input output relationship of a nonlinear system. The local dynamics of each rule can be expressed by a linear system model which obviously is the reason for choosing T-S Fuzzy Logic method (Hohm and Ropp, 2003). The method has become popular and is effective for non linear systems because of the requirement of small number of rules. The T-S fuzzy model based control is vastly explored in the literature. T-S Fuzzy can be applied for complex and high dimensional problems and the rules be generated systematically from a given input output data set. Minimal realization problems, design problems of controller, decomposition problems, etc., can be solved using T-S Fuzzy Logic approach. The Fuzzy Logic Controller (FLC) allows to determine its parameters without an accurate and complicated mathematical model. Provided, it is more suitable for non linear systems. Because of these reasons, FLC based Maximum Power Point Tracking (MPPT) algorithm attracts research interests and various FLC based MPPT techniques are proposed in the literatures (Chiu, 2009; Rameshkumar and Arumugam, 2009; Lalouni and Rekiou, 2009; Xu, 2009; Lian et al., 2001; Chuang et al., 2011; Lin et al., 2013; Narimani and Lam, 2009; Lee et al., 2011). T-S Fuzzy algorithm applied to standalone PV system that utilizes buck converter is reported in Chiu (2009). T-S Fuzzy model replaces the fuzzy consequent of Mamdani rule with the function of input variables.

Low cost, easy implementation and fast tracking under varying atmospheric conditions and small power fluctuations are the general requirements of Maximum Power Point Tracking. A method that can satisfy the above specified requirements become crucially important. The main objective of the current work is to assess the

* Corresponding author.
E-mail address: anbu.arasi@gmail.com (A.M. Palaniswamy).

http://dx.doi.org/10.1016/j.solener.2016.09.027
0038-092X/

effectiveness of T-S Fuzzy algorithm when applied to a Standalone Photovoltaic system. Therefore, Incremental Conductance algorithm and T-S fuzzy algorithm are considered for comparison. Incremental Conductance algorithm results in power chattering phenomenon due to continuously oscillating operating points around MPP and selection of the incremental step size of the duty ratio to adjust the terminal voltage becomes extremely difficult. On the other hand, FLC algorithm results in only approximate value of MPP. The T-S Fuzzy logic method meets all the requirements for MPP tracking and hence selected for the work.

The T-S Fuzzy algorithm utilised to track the MPP has the following characteristics:

(1) The controller need not be redesigned even when the insolation and temperature of the PV panel vary
(2) The Maximum Power Point can be tracked very close to the true value
(3) Same method can be applied to any of the other types of dc-dc converter configurations
(4) Desired value of Maximum Power Point need not be calculated

The remaining of this paper is organized as follows; Section 2 gives the model of a solar cell. Then, Power converter analysis and Maximum Power Point Tracking techniques are given in Sections 3 and 4 respectively. In Section 5, simulation results and associated discussions are presented. Finally, conclusion of the work is drawn in Section 6.

2. Modeling of PV module

The potential energy of charge carrier increases when sunlight falls on the solar cell and the carrier separate thereby collecting the energy of a photon in the form of electrical energy. An ideal solar cell is considered as a current source wherein a current proportional to solar insolation is produced. Because of the optical and electrical losses, the practical behavior of the cell is different from ideal and therefore appropriate components are added with ideal current source. The optical loss is represented by current source where the current generated is proportional to the light input. The recombination is represented by a diode connected parallel to the current source but in reverse direction as the recombination current flows in the opposite direction to the light generated current. Typically, in a simple diode model recombination in the space charge region is neglected and only one diode is added in the solar cell equivalent circuit (Solanki, 2011). The solar cell equivalent is shown in Fig. 1. R_s and R_{sh} are respectively the shunt and series resistances that accounts to the ohmic losses in the cell. In most practical cases the shunt resistance is high and often neglected during analysis (Pandiarajan and Muthu, 2011). Array of several solar cells connected in series and parallel forms the solar PV module.

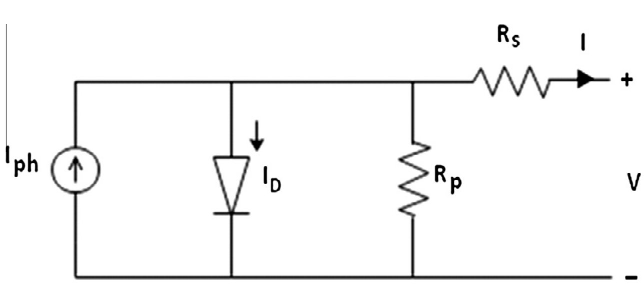

Fig. 1. Solar cell equivalent circuit.

The IV equation of a single cell using the single diode model is given by

$$I = I_L - \left[I_o e^{\frac{q(V+IR_S)}{nkT}} - 1\right] - \frac{V+IR_s}{R_{sh}} \tag{1}$$

where I_L is light generated current, I_o is reverse saturation current, n is diode ideality factor, k is Boltzmann's constant and T is temperature.

IV equation of PV module is similar to that of solar cells and is the combination of IV curves of all solar cells connected in the module.

Light generated current of the module depends linearly on the solar insolation and is also affected by temperature and is given by equation,

$$I_L = I_{sc} + K_i(T_a - T_r) * \frac{\lambda}{1000} \tag{2}$$

where K_i is the temperature coefficient usually 0.0017 A/K, T_a and T_r are actual and reference temperatures in Kelvin respectively, λ is the insolation on the device surface in W/m^2.

The module reverse saturation current I_{rs} is given by

$$I_{rs} = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{N_s knT_a}\right) - 1} \tag{3}$$

where q is the electron charge ($1.6 * 10^{-19}$ C), V_{oc} is open circuit voltage and N_s is the number of cells connected in series.

Module saturation current I_o is given by

$$I_o = I_{rs}\left[\frac{T_a}{T_r}\right]^3 \exp\left[\frac{qE_{go}}{nk}\left\{\frac{1}{T_r} - \frac{1}{T_a}\right\}\right] \tag{4}$$

where E_{go} is the bandgap energy of the semiconductor which is approximately equal to 1.1 eV for the polycrystalline silicon at 25 °C.

The module output current represented as I_{pv} is given by

$$I_{pv} = N_p * I_{ph} - N_p * I_o\left[\exp\left\{\frac{q*(V_{pv} + I_{pv}R_s)}{N_s knT_a}\right\} - 1\right] - \left[\frac{V_{pv} + I_{pv}R_s}{R_{sh}}\right] \tag{5}$$

where N_p and N_s are the number of parallel and series cells respectively. To simplify the model, the parallel resistance of higher value is neglected. The equation for I_{pv} thereby becomes

$$I_{pv} = N_p * I_{ph} - N_p * I_o\left[\exp\left\{\frac{q*(V_{pv} + I_{pv}R_s)}{N_s knT_a}\right\} - 1\right] \tag{6}$$

37 W Solkar module is taken as the reference module and the electrical characteristics are given in Table 1. The electrical characteristics provided is for Standard Test Conditions (STC) of 1000 W/m^2 and 25 °C.

The simulation is carried out in Matlab/Simulink by considering the electrical characteristics provided in the data sheet of the solkar PV module used. Fig. 2 shows the Current versus Voltage characteristics at constant temperature of 25 °C. Fig. 3 shows the Current versus Voltage characteristics at constant insolation of

Table 1
Electrical characteristics data of 37 W solkar PV module.

Description	Rating
Rated power	37.08 W_p
Voltage at maximum power (V_{mp})	16.56 V
Current at maximum power (I_{mp})	2.25 A
Open circuit voltage (V_{oc})	21.24 V
Short circuit current (I_{sc})	2.55 A
Total number of cells in series (N_s)	36
Total number of cells in parallel (N_p)	1