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Fuzzy Sliding Mode Control for Photovoltaic System

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ABSTRACT

In this study, a fuzzy sliding mode control (FSMC) based maximum power point tracking strategy has been applied for photovoltaic (PV) system. The key idea of the proposed technique is to combine the performances of the fuzzy logic and the sliding mode control in order to improve the generated power for a given set of climatic conditions. Different from traditional sliding mode control, the developed FSMC integrates two parts. The first part uses a fuzzy logic controller with two inputs and 25 rules as an equivalent controller while the second part is designed for an online adjusting of the switching controller's gain using a fuzzy tuner with one input and one output. Simulation results showed the effectiveness of the proposed approach achieving maximum power point. The fuzzy sliding mode (FSM) controller takes less time to track the maximum power point, reduced the oscillation around the operating point and also removed the chattering phenomena that could lead to decrease the efficiency of the photovoltaic system.

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1. INTRODUCTION

As photovoltaic energy demand continues to increase dramatically research efforts are being made towards improving photovoltaic generator (PVG) output power efficiency. The PVG has two disadvantages: a) the output power characteristic depends on environmental conditions such as the change in solar insolation level, temperature and partial shading...etc and b) low conversion efficiency, especially under low irradiation [1]. There exists unique point called maximum power point (MPP) on the P-V curvecharacteristic, where power is maximum [2]. So it is important to operate the photovoltaic module at the maximum power point (MPP) to enhance the efficiency of the PV system. Hence, a maximum power point tracking controller is needed for a successful and productive PV system.

The MPPT control is a complex issue, because in the one hand the PV panel will always suffer from rapid external disturbances due to the variation in weather conditions. On the other hand the PV system could suffer from some internal disturbances such as load variation which remains the design of an appropriate maximum power point tracking (MPPT) controller so difficult [3]. Several techniques have been discussed in the literature for searching the MPP of photovoltaic systems such as the perturb and observe (P&O) [4]. The incremental conductance (INC) [4]. The hill climbing [5]. These approaches vary in complexity, time response, implementation cost, accuracy and other aspects. But they can, however, fail to achieve MPP under rapidly changing atmospheric conditions. Unconventional methods have been also used in literature [3], such as sliding mode controller (SMC) [6] and fuzzy logic controller (FLC) [7]. Although the SMC presents a good performance, it suffers from the chattering phenomena which causes high heat electronic power systems. Numerous techniques were proposed to attenuate the chattering amplitude, such as modifying the boundary layer about the sliding surface, using intelligent methods like genetic algorithm (GA) to choose the appropriate SMC discontinuous part's gain to reduce the problem of chattering in SMC. Adding to SMC technique, the fuzzy logic control is widely used to track the MPP. It has an excellent performances and an immunity to disturbances. But, the adjustment and setup of the FLC with a big numbers of rules lead to a big computing time and using big memory which remain the accuracy/speed trade-off inevitable. In this study, a fuzzy sliding mode controller is used to achieve the maximum power point of the photovoltaic system and to overcome the drawbacks of the classical methods. The designed approach integrates two parts. The first part employs a fuzzy controller with 25 rules to approach the equivalent control of SMC while the second part uses a fuzzy controller with one input and one output to approximate an optimal value of switching controller's gain of SMC. So a FSM controller is constructed and tested under different conditions using Matlab/Simulink software. The proposed controller is compared to the P&O, SM and FLC techniques in order to highlight its performances. The results show that the proposed controller exhibits good performances in terms of convergence, time response and precision. The proposed technique has also proved efficient ability to attenuate chattering compared to other methods.

This paper has been organized as follows. Section 2 presents a brief introduction of photovoltaic system modelling. In section 3 mostly referred existing MPPT approaches are presented. The structure of the fuzzy sliding mode controller is described in detail in section 4. Section 5 presents the simulation results. Finally, a conclusion is given in section 6.

2. PHOTOVOLTAIC SYSTEM MODELLING

As shown in Figure 1, the proposed photovoltaic generation system scheme contains a PV module, resistive load and DC-DC boost converter.

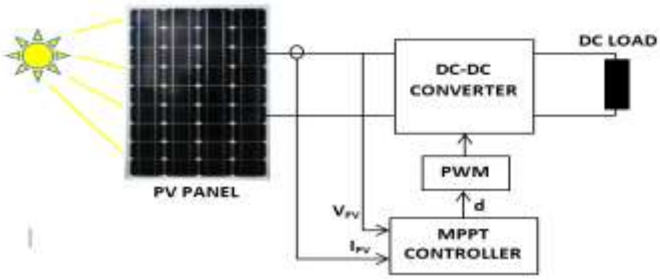


Figure 1. Photovoltaic system scheme [8]

2.1. Modelling and Characteristics of PV Module

A PV cell consists of semiconductor materials that convert solar insolation into electric energy. The equivalent circuit model of PV cell consists of a single diode connected in parallel with a light generated current source. A PV panel includes $\mathbf{N_p}$ parallel modules each one composed of $\mathbf{N_s}$ PV cell serial connected. The current-voltage characteristics of a PV generator are given by the following equation:

$$I_{pv} = N_p I_{ph} - N_p I_0 \left\{ exp\left[\frac{q}{AKT}\left(\frac{V_{pv}}{N_s} + \frac{I_{pv}R_s}{N_p}\right)\right] - 1\right\} - \frac{N_p}{R_{sh}}\left(\frac{V_{pv}}{N_s} + \frac{I_{pv}R_s}{N_p}\right) \tag{1}$$

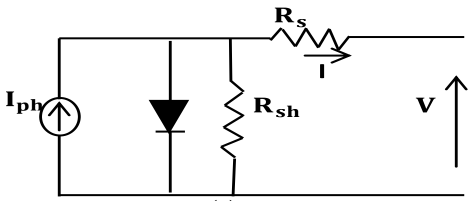
where $\mathbf{V_{pv}}$ and $\mathbf{I_{pv}}$ are the PV generator output voltage and current, $\mathbf{I_{ph}}$ is the photo-current, $\mathbf{N_p}$ and $\mathbf{N_s}$ are the number of the parallel and series cell; $\mathbf{R_{sh}}$ and $\mathbf{R_s}$ are the solar cell shunt and series resistances, respectively; is the reverse saturation current, k is the Boltzmann's constant (1.38*10-23J/K), A is the P-N junction ideality factor, q is the charge of an electron (1.6*10-19C) and T is the PV generator temperature. The PV cell photo-current $\mathbf{I_{ph}}$ depends on solar irradiation and temperature as stated in the following.

$$I_{ph} = [I_{SC} + K_I(T - T_r)]\frac{G}{1000} \tag{2}$$

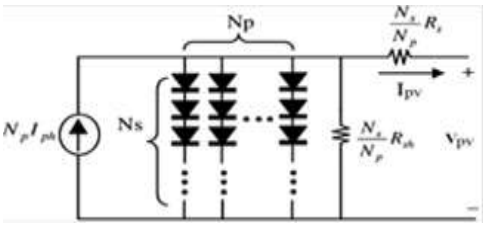
where G is the solar irradiation in watts per square meter, $\mathbf{K_I}$ is the short-circuit current temperature coefficient, $\mathbf{T_r}$ is the PV cell reference temperature and $\mathbf{I_{SC}}$ is the cell's short-circuit current at the reference temperature.The reverse saturation current $\mathbf{I_0}$ depends on temperature T as follows:

$$I_0 = I_{rs}(\frac{T}{T_r})^3 exp\left[\frac{qE_g}{nK}(\frac{1}{T_r}-\frac{1}{T})\right] \quad (3)$$

where E_g is the band gap energy of the semiconductor used in photovoltaic cell and. I_{rs} is the saturation current at the reference temperature.



(a)



(b)

Figure 2. Equivalent solar cell/array circuit, (a) Single cell circuit. (b) Solar array circuit (Ns-series, Np-parallel). [9] [17]

Table 1. Electrical characteristics of the Kyocera KD135GX-LP panel

Parameter (at STC)	Value
Maximum power (Pmax)	135.04 w
Voltage at Pmax(Vmpp)	17.7v
Current at Pmax(Impp)	7.62A
Open circuit voltage (Voc)	22.09v
Short circuit current (Isc)	8.36A
Temperature coefficient of Isc(Ki)	5.022mA/°c
Cell serial modules (ns)	36

From Figure 3 and 4, it is clearly observed that the PV generator presents a nonlinear behaviour which depends on solar irradiation and temperature. We note that the output PV power increases with solar irradiation and that the open circuit voltage increases slightly. On contrary, increase in temperature is accomplished by a decrease in the output power of PV panel. The P-V curves show also that the maximum power point of PV module varies. So a control system is needed to track this point in order to use the PV system more efficiently as an electric power generator.

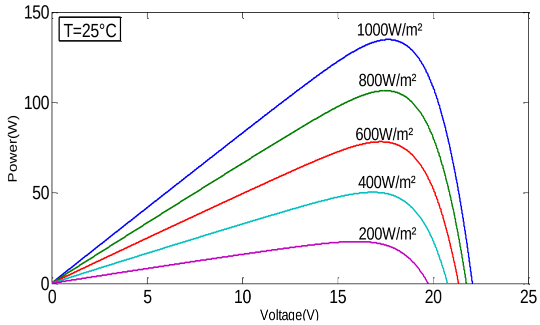


Figure 3. P-V Characteristic of the PV panel at constant temperature T=25°C

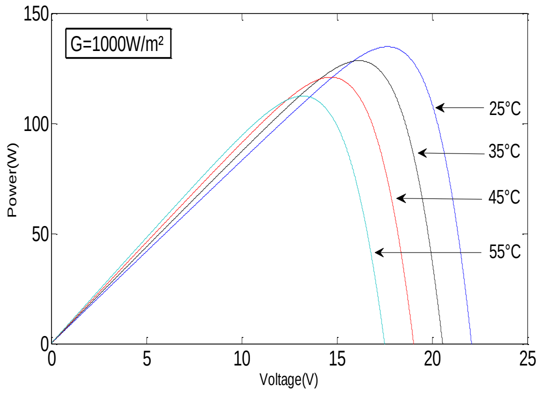


Figure 4. P-V Characteristic of the PV panel at irradiation G=1000W/m²

2.2. Power Converter Structure

The power converter considered in this study is a DC-DC boost converter, as shown in Figure 5, where the load is a constant resistance. The output voltage is adjusted according to the power available at the PV panel. The used converter is composed by an input filter C_{IN}, an inductor L, a MOSFET switch, a diode, and an output filter C_{out}.

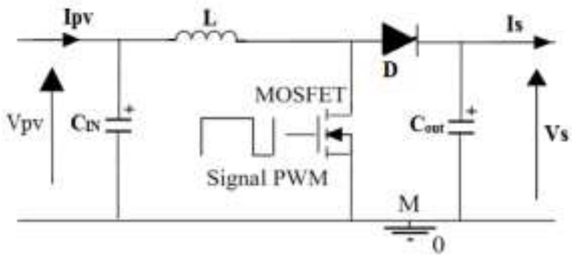


Figure 5. Schematic diagram of DC-DC boost converter [10]

The relationship between output voltage and input voltage in boost converter can be expressed as:

$$\frac{V_S}{Vpv} = \frac{1}{1-d} \quad (4)$$

3. MPPT METHODS

3.1. Perturb and Observe MPPT Method

Among all the MPPT techniques, the perturb and observe (P&O) strategy is widely used in practice because of its ease of implementation. This method is based on the perturbation of the photovoltaic system by the increase or decrease of the duty cycle, then observing the effect on the output power of PV generator.If the output power is increased due to the perturbation, this means that the operating point has moved toward the maximum power and, therefore, the following perturbation will be made in the same direction. But if the output power decreases, the new perturbation is made in the opposite direction. The major drawbacks of this strategy are deviation from the maximum power point during rapidly changing weather conditions.

3.2. Fuzzy Logic Based MPPT

Fuzzy logic controllers have been very successfully applied to many industrial applications over the past few decades [11]. The application of human thinking and natural language in FLC, made it to use in almost all sectors of science and industry [12]. Fuzzy logic-based MPPT tracker have exposed very excellent performances under changing irradiation and temperature conditions without any knowledge of PV generator model. It requires good design to select appropriate fuzzification, inference mechanism, rule base, and defuzzification processes [13]. The inputs of fuzzy controller are error and its variations; the output is the duty ratio of DC-DC converter or its variation. The fuzzy controller introduced in many researches uses the ratio dP_{pv}/dV_{pv} and its variation $\Delta(dP_{pv}/dV_{pv})$ as inputs and it considers the duty cycle as output.The inputs variables are defines as follow:

$$e(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{5}$$

$$ce(k) = e(k)\text{-}e(k\text{-}1) \tag{6}$$

The fuzzy logic controller can be reasonably implemented by using fuzzification, inference rules, defuzzification. As shown in Figure 6, scaling factors k1, k2 and k3 are introduced to provide normalized input and output signals for this controller.

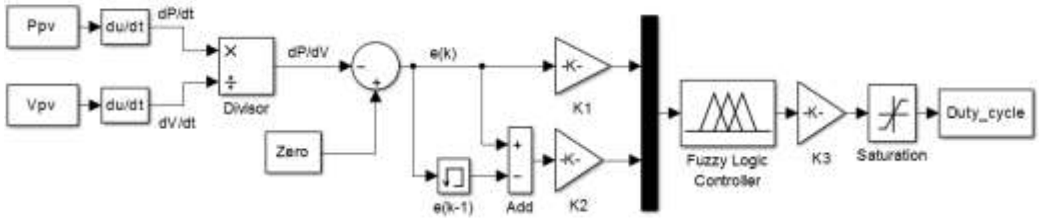


Figure 6. General diagram of a fuzzy MPPT controller [14]

3.3. Sliding Mode Based MPPT

Sliding mode control (SMC) is one of the powerful nonlinear control methods. The SMC based MPPT controller provides control of DC-DC converter which achieves the MPP during changing weather conditions. The MPP tracking speed is faster with the increase in switching but voltage output and power output oscillations increases. The performances of the SMC based MPPT is high as compared to other classical techniques [2]. SMC is based on the implementation of a control equation, which forces the system variables to stay on a selected surface, called sliding surface.

4. PROPOSED FUZZY SLIDING MODE BASED MPPT CONTROLLER

A fuzzy sliding mode controller is designed for a stand-alone photovoltaic system. The control aims of the proposed control law are to track the maximum power point of PV system, minimize oscillations around MPP and also reduce the chattering phenomena which lead to losses power. The proposed control strategy consists of two parts as illustrated in Figure 7. The first part is based on fuzzy controller which work as an equivalent control to maintain the state on the sliding surface s(x)=0. The second part is a nonlinear controller used to stabilize the control. The combined sliding mode and fuzzy logic control term is given by equation (7).

$$U = U_{fuzzy} + U_{fsmc} \tag{7}$$

$$U = U_{fuzzy} + K.Sat\big(s(x)\big) \tag{8}$$

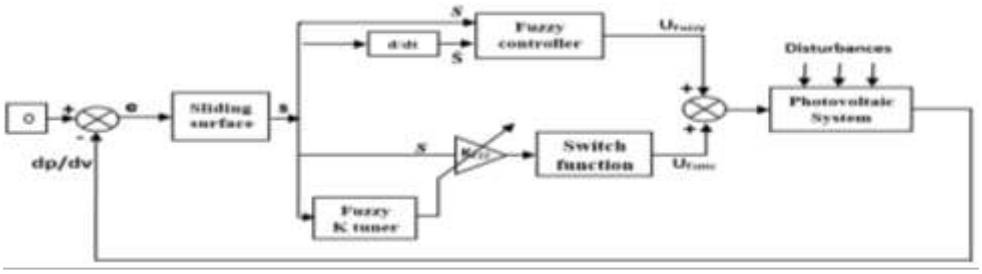


Figure 7. Structure of the fuzzy sliding mode control system

4.1. Fuzzy Logic Controller Design

In this study the inputs of the proposed fuzzy logic controller are error (e) and change error (ce) while the output of this controller is duty cycle (d). It known that the performance of the fuzzy controller will be affected by the shape of membership functions (MFs), so triangular MFs are adopted to reduce the computation complexity and also to facilate the implementation of the proposed controller on real circuit. The variables inputs and output are divided into five fuzzy subsets: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB).

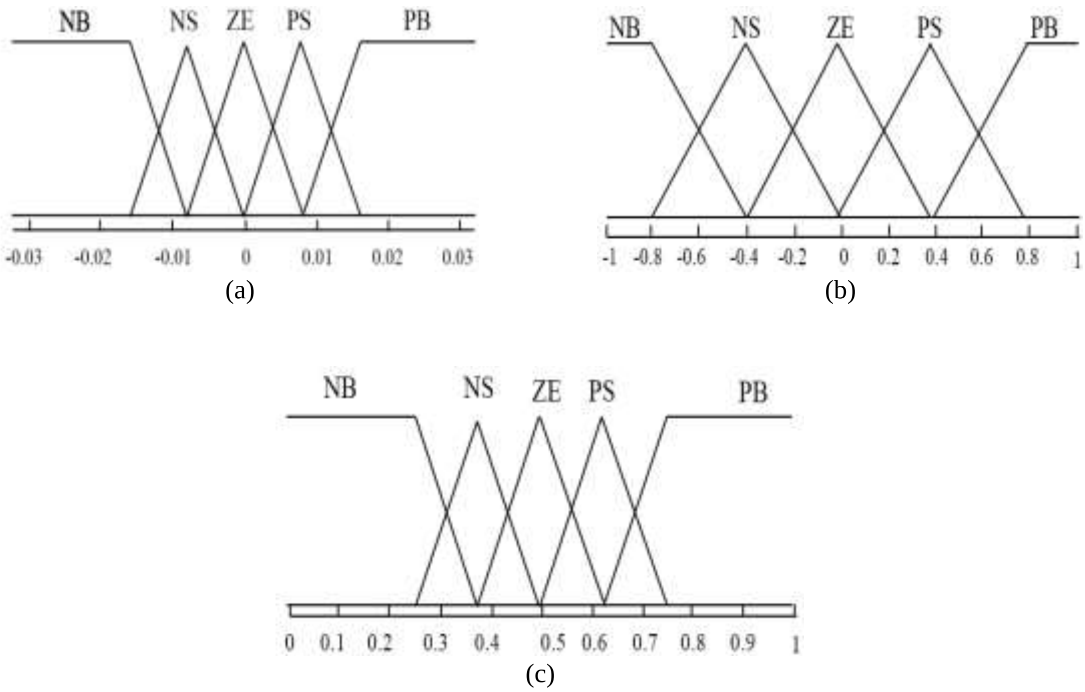


Figure 8. Membership functions of (a) error E (b) Changing error CE (c) duty cycle

Table 2. Fuzzy Rule Table

	E				
CE	NB	NS	ZE	PS	PB
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PS	NS	NS	NS	ZE	ZE
PB	NS	NB	NB	ZE	ZE

4.2. Fuzzy Sliding Mode Controller Design

The fuzzy sliding mode control is applied to assure the optimal operation of PV system under changing solar conditions and load. In the present study a fuzzy sliding mode controller has been designed to provide a smooth control action to stabilise the system responses during large disturbances. Usually, the chattering amplitude of the sliding mode controller depends on the switching gain K. The chattering could be reduced by tuning k adaptively [15]. So the proposed controller based on a fuzzy parameter tuner that supervises and modifies the gain K of the sliding mode controller. Replace K by K_{fzz} in equation 8 and the following equation can be obtained.

$$U_{fsmc} = K_{fzz}.Sat(s(x)) \tag{9}$$

where sat is the saturation function [16], given by:

$$Sat(s) = \begin{cases} \frac{S}{\varepsilon} & if \quad |s| < \varepsilon \\ sgn(s) & otherwise \end{cases} \tag{10}$$

With ε is the boundary layer thickness, sgn is the sign function and K_{fzz} switching gain is estimated by fuzzy inference mechanism to provide an insensitivity to disturbance change and also to compensate the fuzzy approximation errors. The fuzzy gain K tuner has been constructed with one input (S: sliding surface) and one output (K_{fzz}). Triangular membership functions with five fuzzy sets have been adopted for the input and output variables. The structure of the fuzzy gain k tuner is given in Figure 9. The gain K must be larger when it's farther to the sliding surface and smaller when it is near to the sliding surface. Based on this fact, the following rules for the fuzzy gain K tuner can be developed:
a. If error is NB then K is NB
b. If error is NS then K is NS
c. If error is ZE then K is ZE
d. If error is PS then K is PS
e. If error is PB then K is PB

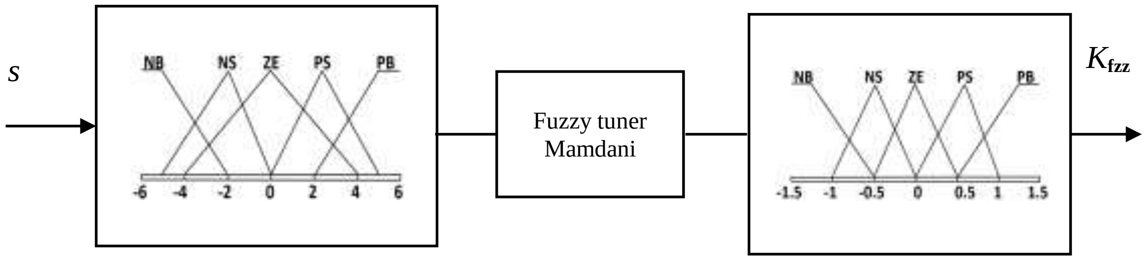


Figure 9. Structure of the fuzzy gain k tuner

5. RESULTS AND DISCUSSION

To test the dynamic behaviour of the selected PV system, four MPPT techniques based on P&O, on fuzzy logic, on sliding mode and on the proposed controller were simulated, evaluated, and compared using Matlab/Simulink software, taking into consideration the variation in solar irradiation, temperature and load. The proposed PV generator was coupled to boost dc-dc converter to design a unit PV system. The selected PV generator in this work is a Kyocera KD135GX-LP panel that produces 135w at 1000w/m² and its parameters are presented in Table 1. The parameters of the boost converter are chosen as f=10khz, Cin=1000µF, Cout=1000µF, L=300mH. In each of the following figures, different levels of irradiation, temperature or load are presented for comparison in order to validate the robustness of the proposed controller. Figure 10 shows the variation of the PV output power and voltage with step irradiation input (1000 to 600w/m² respectively 600 to 1000w/m²). In this case, the temperature is constant and equal to 25°C while the load is equal to 20Ω.

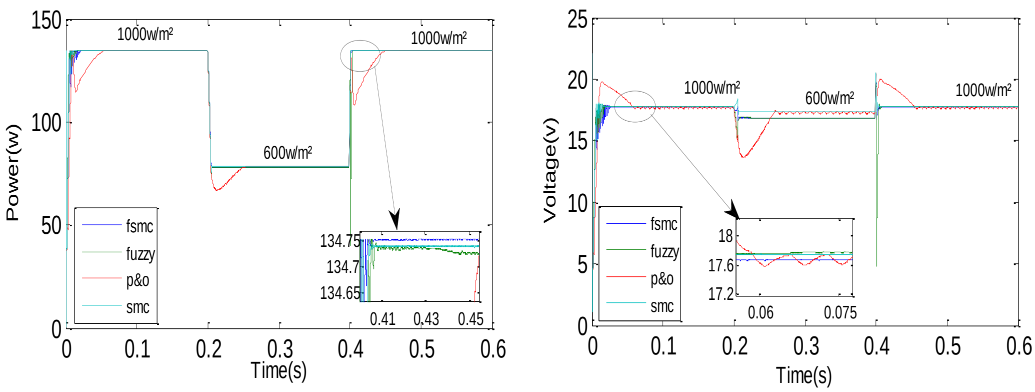


Figure 10. PV panel output power and voltage under varying irradiation levels

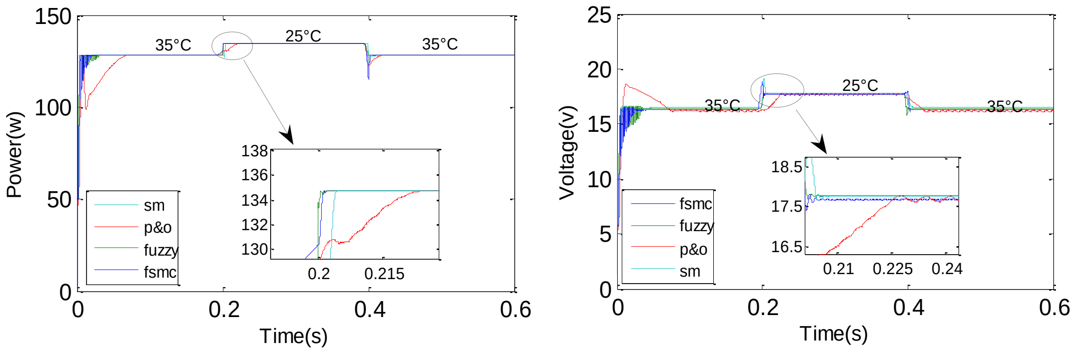


Figure 11. PV panel output power and voltage under varying temperature levels

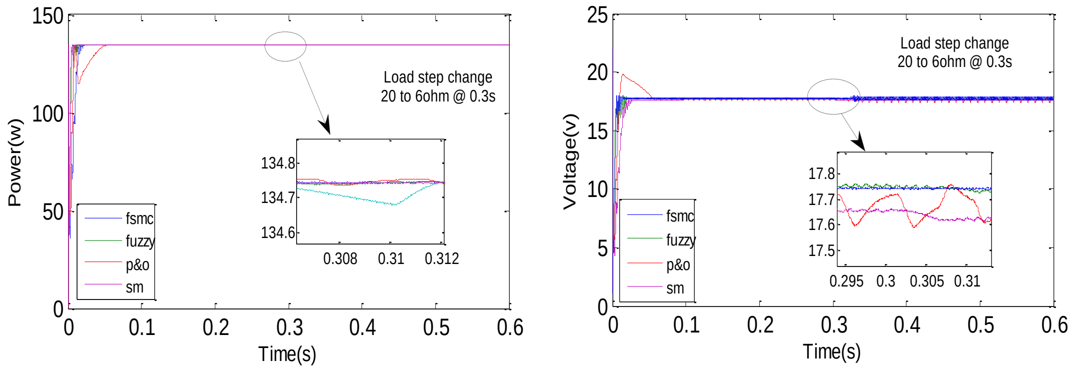


Figure 12. PV panel output power and voltage under varying load conditions

The results show that all techniques introduced here are able to track the MPP with different time but we note that the system with the FSMC MPPT reaches steady state of both irradiance steps much faster compared to the other tracking strategies while the P&O method is slow under rapidly irradiation changing. We note also here that the proposed FSMC provides quickly moving of the operating point toward the MPP which reduce the power losses due to search process. Figures 11 and 12 illustrate the power and voltage responses of PV system under rapid temperature variation and load changing in order to verify the robustness of proposed technique. The obtained results show a good robustness of the FSMC technique. It takes less time to track accurately and maintains the output power at MPP all time.From the above results, it can be clearly seen that the FSMC technique overcomes the chattering problem and exhibits very good performance compared to classical sliding mode controller. However we note that the perturb and observe method exhibits a hard oscillation which reduces the output power of the PV system.

Finally, a comparative study of the performance of the proposed method with two algorithms published recently by Chiu et al. [18] and Guenounou et al. [19] is done. The proposed technique in [19] is based on the adaptive fuzzy controller to track MPP for PV system while the algorithm elaborated in [18] is based on terminal sliding mode control to maximize the produced PV power. These two techniques are compared with the FSMC technique which consists of two control techniques (Fuzzy logic and sliding mode control) as described above. The simulation results show that the PV power generation system reaches the desired voltage and maximum power point at 0.1s for alghorithm in [18] and 0.12s for algorithm in [19]. Contrariwise, the proposed FSMC achieved the MPP at 0.01s which means that our controller track the MPP rapidly and provides high robustness to parameter uncertainties. Furthermore, the FSMC reduces the oscillation around the MPP.

6. CONCLUSION

In this paper, a fuzzy sliding mode controller based MPPT technique was developed and tested. The proposed controller is designed by combining the fuzzy logic and sliding mode control to guarantee the stability and the tracking performance and also to avoid the drawbacks of the traditional SM and FL controllers. A Matlab/Simulink based simulation of a stand-alone PV system under varying climatic conditions and two levels of load was carried out to validate the proposed controller. Simulation results demonstrate that the designed FSMC-MPPT exhibits good responses as it successfully and accurately achieved the maximum power point with a significantly higher performance than the P&O, SM and FLC strategies. The proposed approach provides a feasible approach to control PV power systems.

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