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Fuzzy Synergetic Controller Based MPPT for Standalone Photovoltaic System

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Abstract

A hybrid control technique combining fuzzy logic control and synergetic control is proposed to extract maximum power of Standalone PhotoVoltaic System (SPV). The combined control law ensures the quick convergence of the SPV operating point towards the maximum power point without any chattering. The addition of fuzzy control makes the system robust under the presence of modeling uncertainties and external disturbances such as variable irradiance and temperature. The simulations results of the proposed hybrid control scheme are presented and performance comparison to individual control schemes i.e synergetic control and fuzzy control is studied under various atmospheric conditions. The MATLAB based simulation results show the effectiveness of presented scheme such as higher efficiency and quick convergence to MPP with reduced oscillations.

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1 Introduction

Rapid increase in the population and industrialization of the world is the prime cause of huge demand in the energy. The critical features of fissile fuels such as insufficiency, high prices and global warming, are the main driving force behind the search of other sources of energy. The solar energy became a major source in many parts of the world as a result of its ecological cordial characteristics, abundant in volume and easily accessible nature. In the solar energy conversion system, the photovoltaic (PV) cell is the fundamental element whose dynamics depends on the radiation and temperature. Essentially the SPV system consists of PV source, power electronic converter and load. The maximum power point tracking (MPPT) algorithm is an algorithm, which always extracts maximum power from PV source.

This paper presents a hybrid control scheme combining the features of fuzzy logic control with synergetic control to extract maximum power of photovoltaic system using boost converter as MPPT system. This combined control performs well and overcomes the disadvantage of the synergetic control.

The organization of this paper is as follows. Section 2 gives a concise review about the literature review on various MPPT techniques. Section 3, presents PV module modeling, working of the MPPT system, and modeling and design of boost converter. Section 4 explains the design procedure of proposed fuzzy synergetic control (FSC) technique. In section 5, simulations results analyzed in comparison to conventional P&O and synergetic control methods, and then the conclusions given in last section.

2 Literature Survey

The MPPT control is a challenging task, because the solar radiation is time dependent and also the model of PV system is highly non linear in nature. For these reasons, the design of an appropriate MPPT controller is hard to design. A wide choice of MPPT methods are presented in literature such as P&O, IC, fractional V_{oc}, fractional l_{sc} [1-2], AI based methods as neural networks(ANN), fuzzy logic (FL) and Sliding mode control (SMC) methods [3-4]. The choice of MPPT is highly application-dependent and unmistakably each MPPT technique has its own preferences and weaknesses. The P&O method fails in case of quick environmental changes, and in IC method the operating point oscillates around the MPP [5]. The ANN based technique MPPT algorithm needs a great amount of training data to acquire reasonable results, which limits its application [6]. The SMC based MPP tracking suffers from the drawback of chattering phenomenon [7].

Synergetic control (SC) is a nonlinear control strategy like sliding mode control utilizes the benefit of variable structure nature of the system and accomplishes the objective using switching control by changing structure form one state to another state continuously [8]. Contrasted with SMC the SC is more robust to load changes and parameter variations and improving the control performance with reduced chattering, finite time convergence and less steady state error [9]. However, the synergetic control alone cannot tackle the modeling uncertainties and disturbances completely. The fuzzy control is an intelligent control strategy utilizes the knowledge of human experience and performs well for the uncertain nonlinear systems. It overcomes the disadvantage of conventional control methods, which only can be applied to systems with the mathematical model [10-11].

3 Standalone Photovoltaic System

Standalone photovoltaic (SPV) systems are intended to work autonomously, without depending on the electric utility grid to supply simple electrical loads. The direct-coupled system is the basic SPV system without any energy storage system, i.e batteries operates only during daytime. The output of the PV panel through power converter is directly connected to the loads such as circulation fans, water pumps [12].

The schematic diagram of the Standalone Photovoltaic (SPV) system with PV panel and essential components is shown in figure. 1. The PV panel is a network of several PV cells interconnected in series and parallel to obtain desired output voltage and current.

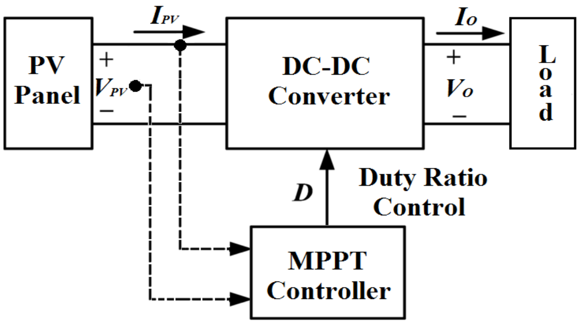


Figure 1 Block diagram of the SPV system

The dynamic equation obtained from the diode model of PV cell shown in figure 2 is given in (1) and it also gives the current – voltage characteristic of PV source.

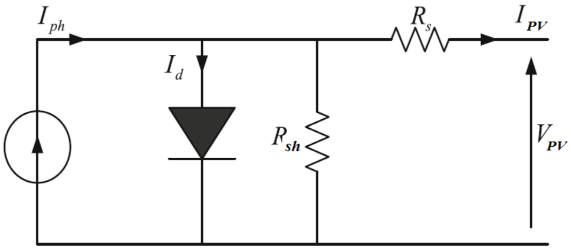


Figure 2 Model of a photovoltaic cell

$$I_{PV} = n_p \left(I_{Ph} - I_o \left[e^{\left(\frac{q(V_{PV} + R_s I_{PV})}{AkTn_s} \right)} - 1 \right] - \frac{(V_{PV} + R_s I_{PV})}{n_s R_{sh}} \right) \tag{1}$$

Where V_{PV} and I_{PV} are PV generated voltage and current. R_s and R_{sh} are the parasitic resistances, I_o is the diode dark current, n_p and n_s are the quantity of parallel and series solar cells. Other quantities are A is unit less factor depends on junction material, k is constant (1.38×10^{-23} J/K) and T is the cell's temperature (K).

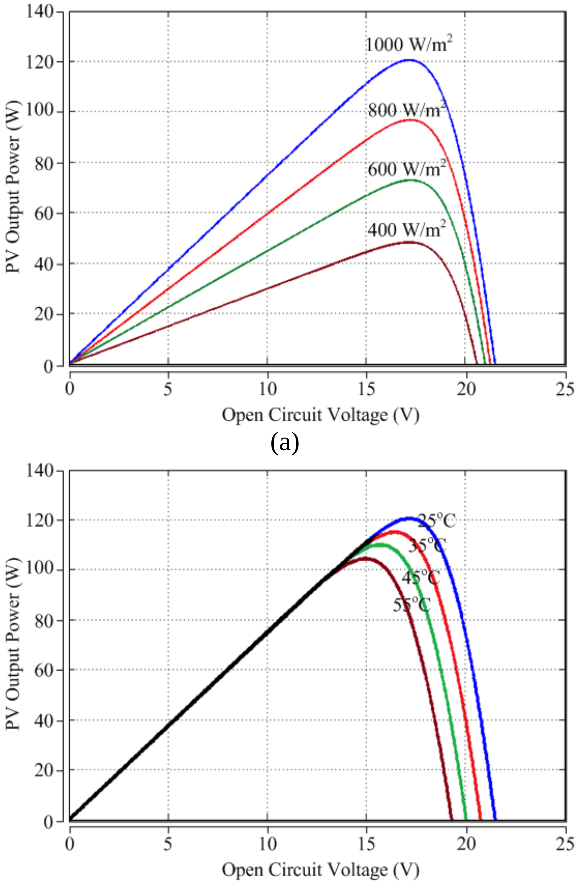
The dependence of the photo current, I_{ph} on the two important variables insolation G and temperature T, is expressed as,

$$I_{Ph} = \frac{G}{G_{STC}} \left[I_{Ph\_STC} + K_i (T - T_{STC} \right] \tag{2}$$

Where I_{Ph_STC} , T_{STC} and G_{STC} are the photo-current, temperature and insolation at STC. The K_i is a constant given by manufacturers.

The ratings of the PV module considered (CENTSYS 120W) at 25°C, 1000W/m^2 from the datasheet are P_{max}= 120W, V_{oc} = 22V, I_{sc}= 7.06 A, V_{max} = 18V and I_{max}= = 6.67 A.

Figure 3 demonstrate the impact of differing climate conditions on the MPP locations in P-V characteristic. Figure 3(a) demonstrates the variation between open circuit voltage (V_{oc}) and the PV power generated when there is increase in the insolation. It is can be understood that the reduction in the insolation causes a decrease in the generated PV power. Figure 3(b), explains, at the consistent insolation (1000 W/m^2) and rising temperature conditions, the V_{oc} decreases.



(a)

(b)

Figure 3 Impact on P-V curves with (a) variable insolation (b) variable temperature

The operation of PV system is desired always at or close to maximum power point, which is ensured by MPPT controller. The continuous extraction of maximum power is accomplished through continuous switching of the boost converter shown in figure 4, by controlling the duty cycle [13].

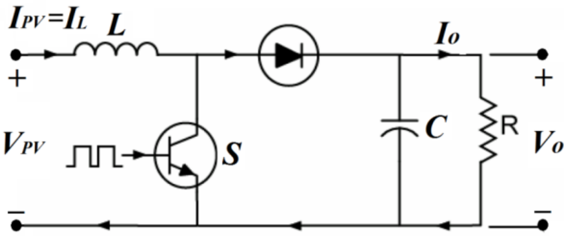


Figure 4 Circuit model of Boost converter

The converter output (V_o), which is the voltage across load is always greater than or equal to the input V_{PV} which is PV array voltage. The voltage level conversion is controlled by switching on and off of the swich S at a high frequency. The designed parameters are: Inductance, L = 8.256 mH, Capacitance, C = 26.8 F, Switching frequency, f_{sw} = 10 KHz, Voltages V_{PV} and V_o are 18V and 55V respectively.

The dynamic equations when the duty cycle D = 1, switch (S) is ON are given as [14],

$$\begin{aligned} \frac{dI_L}{dt} &= \frac{1}{L}V_{PV} \\ \frac{dV_o}{dt} &= -\frac{1}{RC}V_o \end{aligned} \tag{3}$$

The dynamic equations when the duty cycle D = 0, switch (S) is OFF are given as,

$$\begin{aligned} \frac{dI_L}{dt} &= \frac{1}{L}V_{PV} - \frac{1}{L}V_o \\ \frac{dV_o}{dt} &= \frac{1}{C}I_L - \frac{1}{RC}V_o \end{aligned} \tag{4}$$

The complete model of the converter becomes,

$$\begin{aligned} \frac{dI_L}{dt} &= \frac{1}{L}V_{PV} - \frac{1}{L}(1-D)V_o = \frac{1}{L}(V_{PV} - V_o) + \frac{V_o}{L}D \\ \frac{dV_o}{dt} &= \frac{(1-D)}{C}I_L - \frac{V_o}{RC} \qquad = \frac{1}{C}(I_L - \frac{V_o}{R}) - \frac{I_L}{C}D \end{aligned} \tag{5}$$

Let the three state variables are $x_1 = I_L\,; x_2 = V_o$, then the state vector x becomes,

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} I_L \\ V_o \end{bmatrix} \tag{6}$$

The state space model is represented as,

$$\dot{x} = \frac{dx}{dt} = f(x,t) + g(x,t)D \tag{7}$$

$$f(x,t) = \begin{bmatrix} \frac{1}{L}(V_{PV} - V_o) \\ \frac{1}{C}(I_L - \frac{V_o}{R}) \end{bmatrix}; g(x,t) = \begin{bmatrix} \frac{V_o}{L} \\ -\frac{I_L}{C} \end{bmatrix} \tag{8}$$

4 Proposed Fuzzy Synergetic Controller

The nonlinear system dynamics are expressed by the differential equation as follows,

$$\dot{x}(t) = f(x) + g(x)u \tag{9}$$

Where x is the n-dimensional state vector, u is the m - dimensional control input and t is time.

The design procedure of synergetic control for the nonlinear system involves the following steps.

Step 1: Selection of a macro variable which is a nonlinear function of state variables as,

$$\psi = \psi(x,t) \tag{10}$$

The synergetic control will drive the system to converge to the surface ($\Psi = 0$).

The selection of macro-variable is based on the specifications for example the settling time, the steady state error and constraints on control output.

Step 2: Selection of the desired dynamics of the macro-variable as

$$T_s\,\dot{\psi} + \psi = 0,\ T_s > 0 \tag{11}$$

Where T_s is the time constant, which determines the rate of convergence, smaller the value greater the rate of the transition processes.

Applying the chain rule of differentiation the derivative of ψ becomes,

$$\dot{\psi} = \frac{d\psi}{dt} = \frac{d\psi}{dx}\frac{dx}{dt} = \frac{d\psi}{dx}\dot{x} \tag{12}$$

From equations 9 and 12,

$$T_s \frac{d\psi}{dx}\left(f(x) + g(x)u\right) + \psi = 0 \tag{13}$$

Solving the equation 13 for u, the derived control law is expressed as,

$$u_{SC} = -[\psi_x(x)g(x)]^{-1}\psi_x(x)f(x) - [T_s\,\psi_x(x)g(x)]^{-1}\psi(x) = u_{eq} + u_{sy} \tag{14}$$

Where $u_{eq} = -[\psi_x(x)g(x)]^{-1}\psi_x(x)f(x)$ and $u_{sy} = -[T_s\,\psi_x(x)g(x)]^{-1}\psi(x)$ (15)

From the equation 15, it is observed that the control u depends on the state variables as well as on the time constant T_s and the macro variable Ψ.

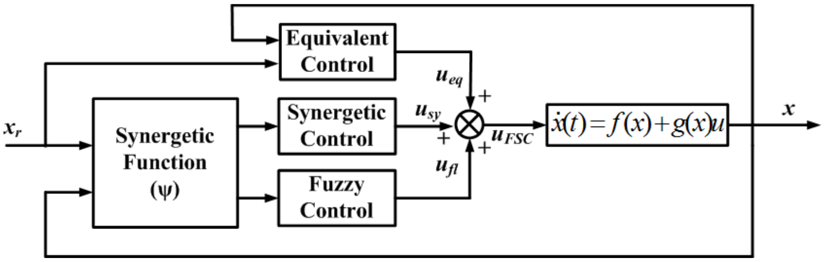


Figure 5 Schematic diagram of Fuzzy Synergetic Controller (FSC)

The combined fuzzy synergetic control is the sum of synergetic control and fuzzy control [15].

$$u_{FSC} = u_{eq} + u_{sy} + u_{fl} \tag{16}$$

The fuzzy controller takes the synergetic function Ψ as input and produces u_{fl} as output as u_{fl} = Fuzzy(Ψ).

Similar to other MPPT techniques, the design of the fuzzy synergetic MPPT controller depends on condition that at the MPP the ratio of change in generated PV power to the change in current should be zero. Accordingly the selected manifold Ψ is expressed as a function of I_L,

$$\psi = \frac{\partial P}{\partial I_L} \tag{17}$$

For the considered boost converter, the manifold Ψ is a function of I_L only, which is the state variable x_1, the inductor current.

The manifold in terms of PV variables,

$$\psi(x) = \frac{\partial P_{PV}}{\partial I_L} = \frac{\partial (V_{PV} I_L)}{\partial I_L} = I_L \frac{\partial V_{PV}}{\partial I_L} + V_{PV} \tag{18}$$

Hence using the chain rule of differentiation

$$\dot{\psi}(x) = \frac{d\psi}{dt} = \frac{d\psi}{dx_1}\dot{x}_1 = \psi_{x_1}\dot{I}_L = \left[2\frac{\partial V_{PV}}{\partial I_L} + \frac{\partial^2 V_{PV}}{\partial I_L^2} I_L\right]\dot{I}_L \tag{19}$$

$$\frac{d\psi}{dx_1} = \psi_{x_1} = \left[2\frac{\partial V_{PV}}{\partial I_L} + \frac{\partial^2 V_{PV}}{\partial I_L^2} I_L\right] \tag{20}$$

The derived control law is

$$D_{SC} = D_{eq} + D_{sy} = -[\psi_{x_1}(x) g_1(x)]^{-1} \psi_{x_1}(x_1) f_1(x) - [T_s \psi_{x_1}(x) g_1(x)]^{-1} \psi(x) \tag{21}$$

$$D_{eq} = -\left(\frac{V_{PV}}{V_0}-1\right); \quad D_{sy} = -\left(\frac{V_{PV}\dfrac{\partial I_L}{\partial V_{PV}}+I_L}{T_s.\dfrac{V_o}{L}.\left[2\dfrac{\partial V_{PV}}{\partial I_L}+\dfrac{\partial^2 V_{PV}}{\partial I_L^2}I_L\right]}\right) \tag{22}$$

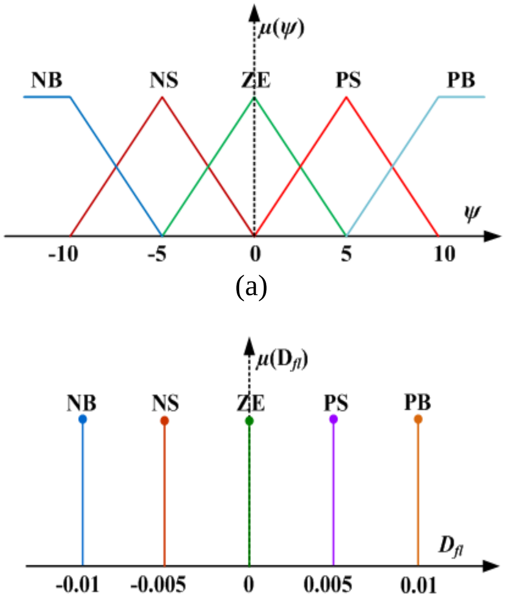
$$D_{SC} = -\left(\frac{V_{PV}}{V_0}-1\right)-\left(\frac{V_{PV}\dfrac{\partial I_L}{\partial V_{PV}}+I_L}{T_s.\dfrac{V_o}{L}.\left[2\dfrac{\partial V_{PV}}{\partial I_L}+\dfrac{\partial^2 V_{PV}}{\partial I_L^2}I_L\right]}\right) \tag{23}$$

The overall output of combined fuzzy logic and synergetic controller is

$$D_{FSC}(k+1) = D_{SC}(k)+D_{fl}(k) = D_{eq}(k)+D_{sy}(k)+D_{fl}(k) \tag{24}$$

The design of fuzzy control involves four major operations as following: the fuzzification converts crisp input into proper fuzzy value, continuous interaction with rule base, the fuzzy inference to decide which rule has to fire based on the current input, and the final stage is the defuzzification, which converts the fuzzy values to crisp output.

The input Ψ and output D_{fl} of the fuzzy controller are partitioned into five fuzzy variables, NB, NS, ZE, PS and PB respectively as shown in figure 6.



(a)

(b)

Figure 6 Fuzzy membership functions (a) Ψ (b) D_{fl}

The operating range of Ψ is determined from the simulation studies of P-V and V-I characteristic curves which results as [−10,10]. The range of output variable D_{fl} is considered as [−0.01; 0.01]. The five fuzzy rules are shown in table 1

Table 1 Rule base of FSC MPPT controller

Rule	Statement
1	IF Ψ is PB, then u_{fl} is NB
2	IF Ψ is PS, then u_{fl} is NS
3	IF Ψ is ZE, then u_{fl} is ZE
4	IF Ψ is NS, then u_{fl} is PS
5	IF Ψ is NP, then u_{fl} is PB

5 Result Analysis

The figure 6 and 7 demonstrates the simulation results of PV output power variation and corresponding duty cycle variation of designed boost converter for the considered PV system using the two MPPT controllers at temperature = 25^{o}C and solar insolation =1000W/m^{2}. Clearly, it very well may be reasoned with the Fuzzy Synergetic controller, the generated PV power reaches the maximum value quicker than the synergetic controller and P&O algorithm. However, with the P&O method the duty cycle variation is much higher.

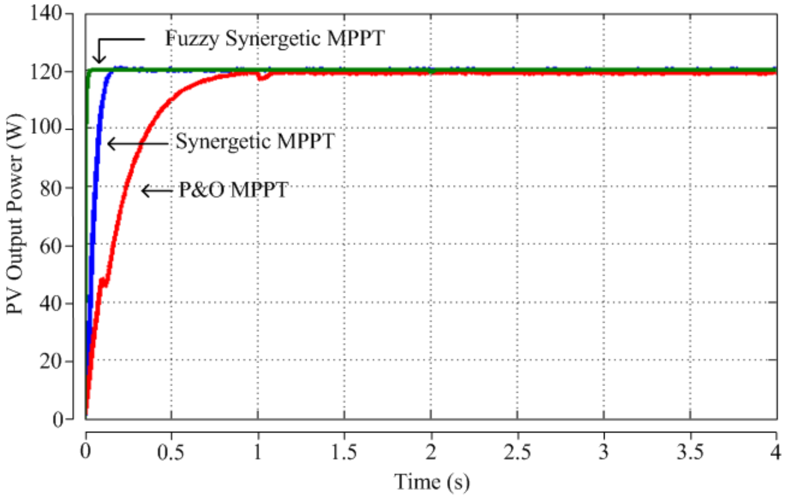


Figure 6 The PV power under standard climatic conditions

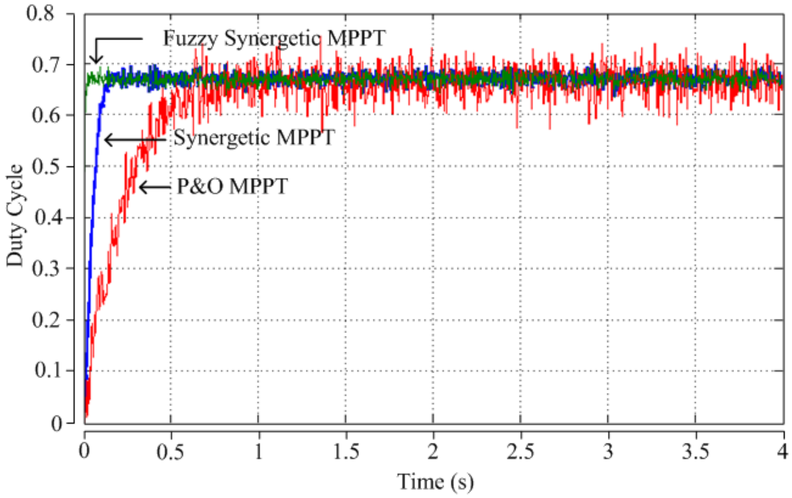


Figure 7 The duty cycle of boost converter under standard climatic conditions

The figures 8 and 9 shows variation in the generated PV power and corresponding duty cycle under variable irradiance conditions i.e the irradiance is varied from 600 W/m^2 to 1000W/m^2 at time 2sec. From figure 9, with the fuzzy synergetic controller the photovoltaic system has reacted accurately by generating power quickly and reaches the maximum value without any undershoots when compared to Synergetic controller and P&O algorithm under condition of sudden change in irradiance. The corresponding variation in the duty cycle of designed boost converter is shown in figure 9. Using the P&O method the duty cycle variation is very high and the oscillations present in the initial stage continue throughout the operation.

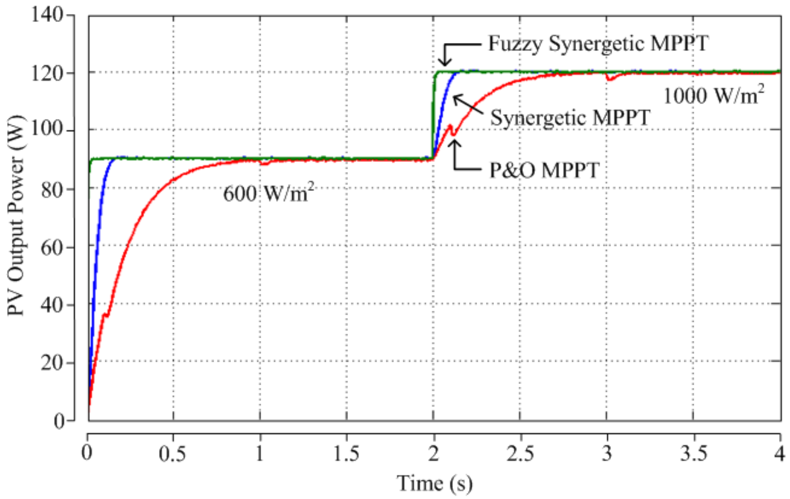


Figure 8 The power under variable irradiance

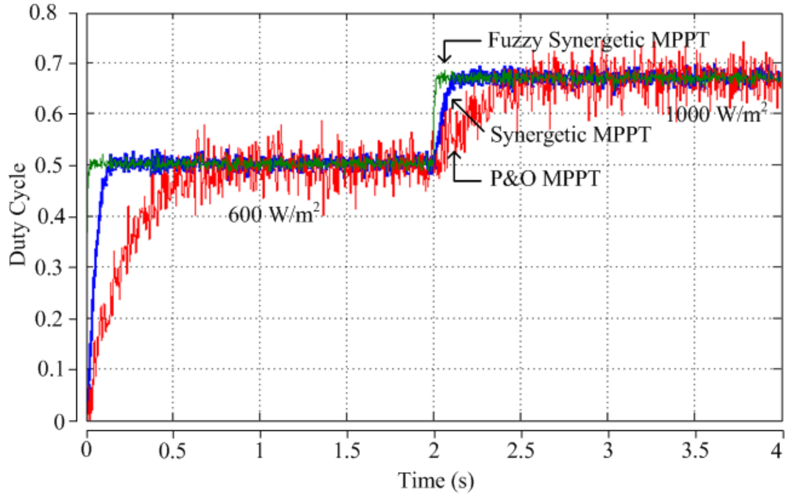


Figure 9 The duty cycle under variable irradiance

The figure 10 and 11 shows variation in the generated PV power and corresponding duty cycle under variable load conditions i.e the load resistance is abruptly varied from 50 to 100 Ω at 2 sec. The fuzzy synergetic controller maintains the generated PV power at maximum value without any interruption when compared to Synergetic controller and P&O algorithm. The variation in duty cycle using fuzzy synergetic controller is limited to ±3 % of 0.67 when compared to the variation ±10 % of 0.67 using synergetic controller and ±20 % of 0.67 using P&O method.

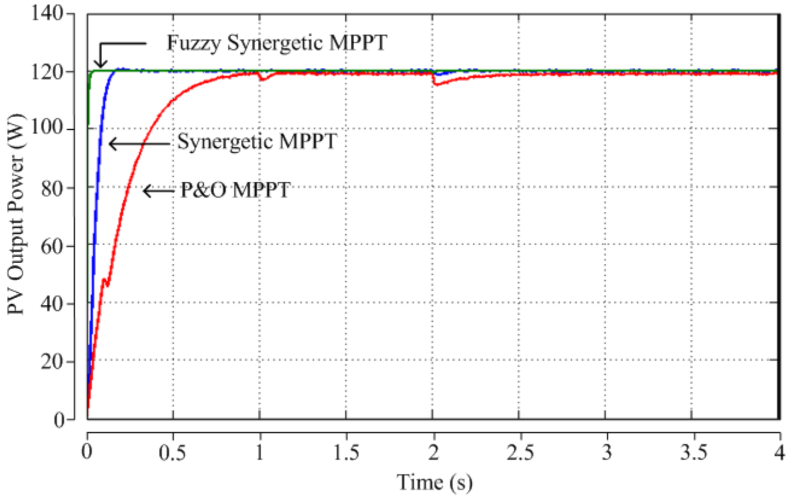


Figure 10 The generated power under load change

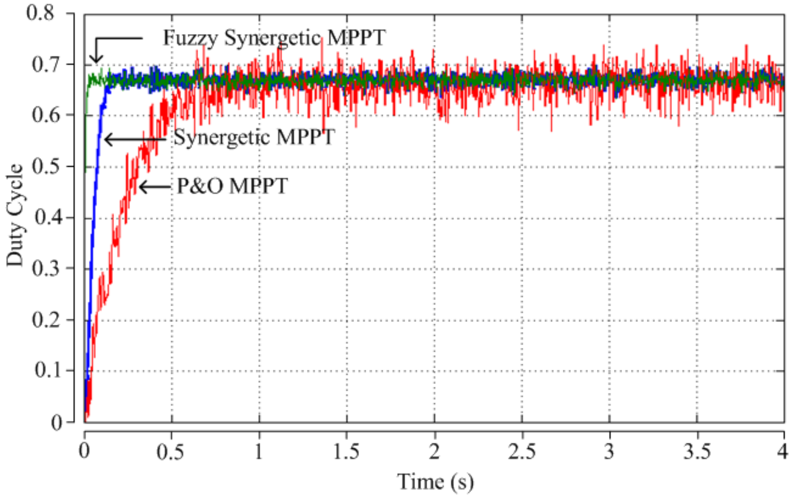


Figure 11 The duty cycle under load change

6 Conclusions

The design and analysis of a hybrid MPPT controller combining intelligent fuzzy logic control and nonlinear synergetic control theory is presented in this paper. The fuzzy synergetic MPPT controller drives boost converter such that the PV output power is always at it's the maximum under the disturbance conditions such as sudden change in irradiance and load when compared to the synergetic controller and P&O algorithm. The variation in duty cycle is also less using fuzzy synergetic controller. The superiority of proposed controller is shown by comparing the simulation results with the synergetic controller and standard P&O MPPT algorithm.

References

[1] T. Esram, P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," IEEE Transactions on Energy Conversion, Vol. 22, no. 2, pp. 439–49, 2007.
[2] L.V.S Kumar, G.V.N. Kumar,"Power conversion in renewable energy systems: A review advances in wind and PV system", International Journal of Energy Research , vol. 41, no. 2, pp.182- 197, 2016.
[3] D. P. Hohm, M. E. Ropp, "Comparative study of maximum power point tracking algorithms," Progress in Photovoltaics: Research and Applications, Vol. 11, no. 1, pp. 47–62, Jan. 2003.
[4] Polamraju.V.S.Sobhan, M.Subba Rao, N. Bharath Kumar, A.Sriharibabu, "Design of Fuzzy Logic Based Photovoltaic Fed Battery Charging System", Journal of Green Engineering, Vol. 9, no.2, pp. 270-281, 2019.
[5] Abdelsalam, A.K , Massoud, A.M, Ahmed, S, Enjeti. P, High-Performance Adaptive Perturb and Observe MPPT Technique for Photovoltaic-Based Microgrids. IEEE Transactions on Power Electronics, Vol.26, no.2, pp.1010–1021, 2011.
[6] Zaki, A.M., Amer, S.I., Mostafa, M., "Maximum power point tracking for PV system using advanced neural networks technique," Int. Jol of Emerging Tech. and Advanced Engg , Vol. 2, no.12, 58–63, 2012.
[7] S. C. Tan, Y. M. Lai, C. K. Tse, "Sliding mode control of switching power converters: Techniques and implementation", CRC Press, 2017.
[8] A.A. Kolesnikov, "Synergetic Control Theory", Energoatomizdat, Moscow, 1994.
[9] E. Santi, A. Monti, D. Li, R. A. Dougal, "Synergetic control for dc-dc boost converter: Implementation options", IEEE Transactions on Industrial Applications, Vol. 39, No. 6, pp. 1803-1813,2003.
[10] Rebai, A., Guesmi, K., Hemici, B., "Adaptive fuzzy synergetic control for nonlinear hysteretic systems", Nonlinear Dynamics, Vol. 86, No. 3, pp.1445–1454, 2016.
[11] M. A. Hannan, Z. A. Ghani, M. M. Hoque, P. J. Ker, A. Hussain A. Mohamed, "Fuzzy Logic Inverter Controller in Photovoltaic Applications: Issues and Recommendations", IEEE Access, vol. 7, pp. 24934-24955, 2019.
[12] W.Ali, H.Farooq, A.U.Rehman, M. Jamil, A.Noman,"Design Considerations of Stand-Alone Solar Photovoltaic Systems",

International Conference on Computing, Electronic and Electrical Engineering, ICE Cube 2018, pp. 1–6, February, 2019.

[13] Khatib, T. E., Wilfried Mohamed, Azah, "Simplified I-V characteristic tester for photovoltaic modules using a DC-DC boost converter", Sustainability, Vol. 9, no.4, pp. 66-77, 2017.

[14] Z. R. Labidi, H. Schulte, A. Mami, "A model-based approach of dc-dc converters dedicated to controller design applications for photovoltaic generators", Engineering, Technology & Applied Science Research, Vol. 9, No. 4, pp. 4371-4376, 2019.

[15] K. Behih, Z. Bouchama, K. Saoudi, "Finite-time fuzzy synergetic power system regulator", Soft Computing and Electrical Engineering, Vol. 4, No. 1, pp. 69-78, 2019.

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