FAST-CONVERGING MPPT TECHNIQUE FOR PHOTOVOLTAIC SYSTEM USING SYNERGETIC CONTROLLER

Polamraju. V. S. Sobhan¹, M. Subba Rao², A. Sriharibabu³, N. Bharath Kumar⁴

¹,²,³,⁴ Vignan’s Foundation for Science, Technology and Research

https://doi.org/10.26782/jmcms.2019.12.00041

Abstract:

A robust nonlinear control technique based on synergetic control theory is presented to extract maximum power of standalone photovoltaic system (SPV). The synergetic control makes the controlled system robust under the presence of system uncertainties and external disturbances such as variable irradiance and temperature. The designed control law guarantees the fast convergence towards the maximum power operating point origin without any oscillations. The PV system comprises of a PV source, power converter, maximum power point tracking algorithm and load. The simulations results show effectiveness of proposed method in comparison with Perturb and Observe (P&O) method under different atmospheric conditions such as variable solar radiation and PV cell temperature.

Keywords : Synergetic control, Maximum power point, standalone PV system.

I. Introduction

The negative features of fossil fuels such as scarcity, high prices and global warming, are the main driving force behind the search of other alternative sources of energy. The solar energy is the major source in many parts of the world because of its environmental friendly characteristics, abundant in volume and easily accessible nature. In the energy conversion system from solar energy, the photovoltaic (PV) cell is the fundamental element and its voltage-current and voltage - power characteristics depends on the solar energy and atmospheric temperature. Basically the PV system consists of photovoltaic source, power electronic converter and load. The continuous transfer of maximum power to load is required an algorithm which always extracts maximum power from PV module called maximum power point tracking (MPPT) algorithm. The MPPT algorithm considers load changes, insolation variation and cell temperature, ensures maximum efficiency and smooth power transfer.

A broad range of MPPT methods are presented in literature such as Perturb and Observe (P&O), Incremental Conductance (IC), fractional open-circuit voltage (Voc), fractional short-circuit current control (Isc) [V], intelligent techniques like neural control, fuzzy logic control (FL) and nonlinear control method, Sliding mode
control (SMC)[III]. The method P&O fall shorts to follow the MPP under fast environmental changes, and IC method causes fluctuations around the MPP [VI]. The drawback of majority FL based MPPT methods is that the operating point shifts from MPP under fast changing ecological conditions. The ANN based MPPT algorithm needs a large samples of training data to train, which restricts computation time. The SMC is used for MPP tracking in photovoltaic systems suffers from the drawback of chattering phenomenon which causes high frequency oscillations around MPP [II].

Synergetic control (SC) is a non-linear control strategy similar to sliding mode control utilizes the advantage of variable structure nature of the system and achieves the objective using switching control by changing structure form one state to another state continuously [I][VII][VIII][IX]. Compared to 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.

This paper deals the design and analysis of a nonlinear control scheme based on synergetic control theory to extract maximum power of photovoltaic system using boost converter as MPPT system. This robust controller performs well for the systems with modeling uncertainties and external disturbances, and alsoovercomes the disadvantage of conventional MPPT methods which only can be applied to systems with negligible external disturbances.

The organization of the work is as per the following, the Section 2, presents PV array modeling, operation of MPPT system, boost converter. Section 3 explains the design of synergetic control (SC) technique. In Section 4, simulation results are analyzed to validate effectiveness of synergetic control (SC) in comparison to P&O technique. The conclusions are given in the last section.

II. PV System

The PV panel is a network of many PV cells. Series arrangement of cells increases the generated voltage level and parallel arrangement increases the current supplied by the PV source. Ideally the PV cell can be viewed as circuit with parallel branches of p-n junction diode and a current source. The model of an ideal PV cell with series and parallel resistances is shown in Fig. 1.

![Fig. 1. Model of a solar cell](image-url)
The mathematical model obtained from the model of PV cell is given in (1) and it also gives the current – voltage characteristic of PV array with \( n_p \) parallel and \( n_s \) series solar cells.

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

where \( V_{PV} \) and \( I_{PV} \) are generated voltage and current the PV array, \( R_s \) and \( R_{sh} \) are the parasitic resistances, and \( I_o \) is the diode dark current. Other quantities are \( q \) is electron charge \((1.6 \times 10^{-19} \text{ C})\), \( A \) is unit less factor depends on junction material, \( k \) is constant \((1.38 \times 10^{-23} \text{ J/K})\) and \( T \) is the cell’s temperature \((\text{K})\).

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

\[
I_{ph} = \frac{G}{G_{STC}} \left[ I_{ph,STC} + K_i (T - T_{STC}) \right]
\]

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 25oC, 1000W/m² from the datasheet are \( P_{max} = 120 \text{W}, V_{oc} = 22 \text{V}, I_{sc} = 7.06 \text{A}, V_{max} = 18 \text{V} \) and \( I_{max} = 6.67 \text{A} \).

Fig. 2 and 3 demonstrate the impact of differing climate conditions on the MPP locations in P-V characteristic. Figure 2 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. As shown in the Fig. 3, at the consistent insolation \((1000 \text{ W/m}^2)\) and rising temperature conditions, the \( V_{oc} \) decreases.

Schematic diagram of PV system with synergetic controlled MPPT is shown in fig.4., consist of PV array, power electronic converter, load and controller to extract the maximum power form PV source.
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 by controlling the duty cycle.

In the boost converter shown in fig. 5, the 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 switch S at a high frequency.
The dynamic equations when the duty cycle $D = 1$, switch $(S)$ is ON are given as,

$$\frac{dI_L}{dt} = \frac{1}{L} V_{pv}$$
$$\frac{dV_o}{dt} = -\frac{1}{RC} V_o$$

(3)

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

$$\frac{dI_L}{dt} = \frac{1}{L} V_{pv} - \frac{1}{L} V_o$$
$$\frac{dV_o}{dt} = \frac{1}{C} I_L - \frac{1}{RC} V_o$$

(4)

The complete model of the converter can be expressed as,

$$\frac{dI_L}{dt} = \frac{1}{L} V_{pv} - \frac{1}{L} (1-D) V_o = \frac{1}{L} (V_{pv} - V_o) + \frac{V_o}{L} D$$
$$\frac{dV_o}{dt} = \frac{(1-D)}{C} I_L - \frac{V_o}{RC} = \frac{1}{C} (I_L - \frac{V_o}{R}) - \frac{I_L}{C} D$$

(5)

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

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

(6)

The state space model is represented as,

$$\dot{x} = f(x,t) + g(x,t) D$$

(7)

Where

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

(8)

Table 1. Parameters of the boost converter

| Parameters          | Value     |
|---------------------|-----------|
| Inductance (L)      | 8.256 mH  |
| Capacitance (C)     | 268 µF    |
| Switching frequency ($f_{sw}$) | 10 KHz    |
| Input Voltage ($V_{pv}$) | 18 V      |
| Output Voltage ($V_o$) | 55 V      |
III. Synergetic MPPT controller

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

\[ \dot{x} = \frac{dx}{dt} = f(x, S, t) \]  

(9)

Where \( x \) is the \( nx \) state vector, \( S \) is the \( mx \) 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,

\[ \psi = \psi(x, t) \]  

(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

\[ T_s \dot{\psi} + \psi = 0, \quad T_s > 0 \]  

(11)

Where \( T_s \) is the time constant which specifies the speed of the convergence to the surface \( \psi = 0 \). The order of system on the specified manifold is \( n-m \).

The solution of this differential equation gives the following function for \( \psi \):

\[ \psi(t) = \psi_0 e^{-\frac{t}{T_s}} \]  

(12)

From the above equation, for any initial condition \( \psi_0 \), as \( t \) increases \( \psi(t) \) approaches to \( \psi = 0 \) i.e attracted to the surface \( \psi = 0 \). The parameter \( T_s \) determines the rate of convergence, smaller the value greater the rate of the transition processes.

Applying the chain rule of differentiation the derivative of \( \psi \) becomes,

\[ \dot{\psi} = \frac{d\psi}{dt} = \frac{d\psi}{dx} \frac{dx}{dt} = \frac{d\psi}{dx} \dot{x} \]  

(13)

From equations 9 and 13,

\[ T_s \frac{d\psi}{dx} f(x, S, t) + \psi = 0 \]  

(14)
Solving the equation 14 for $S$, the derived control law is expressed as,

$$ S = g[x, t, \psi(x, t), T_s] = 0 $$

From the equation 15, it can be observed that the control $S$ depends on the state variables as well as on the time constant $T_s$ and the macro variable $\psi$.

Similar to other MPPT techniques, the design of the synergetic MPPT controller depends on the 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 $\psi$ is expressed as a function of $I_L$,

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

(16)

The manifold in terms of PV variables,

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

(17)

For the considered boost converter, the manifold $\Psi$ is a function of $I_L$ only, which is the state variable $x_1$, the inductor current. Hence using the chain rule of differentiation

$$ \dot{\Psi} = \frac{d\Psi}{dt} = \frac{d\Psi}{dx} \frac{dx}{dt} = \frac{d\Psi}{dI_L} \frac{dI_L}{dt} = \left[ 2 \frac{\partial V_{PV}}{\partial I_L} + \frac{\partial^2 V_{PV}}{\partial I_L^2} I_L \right] \frac{dI_L}{dt} $$

(18)

From state space model

$$ \dot{\Psi} = \left[ 2 \frac{\partial V_{PV}}{\partial I_L} + \frac{\partial^2 V_{PV}}{\partial I_L^2} I_L \right] \left[ \frac{1}{L} V_{PV} - \frac{1}{L} (1 - D) V_o \right] $$

(19)

From the desired dynamic equation of the macro-variable,

$$ \dot{\Psi} = -\frac{1}{T_s} \psi $$

(20)

$$ \left[ 2 \frac{\partial V_{PV}}{\partial I_L} + \frac{\partial^2 V_{PV}}{\partial I_L^2} I_L \right] \left[ \frac{1}{L} V_{PV} - \frac{1}{L} (1 - D) V_o \right] = -\frac{1}{T_s} \left[ \frac{V_{PV}}{\partial V_{PV}} \frac{\partial I_L}{\partial V_{PV}} + I_L \right] $$

(21)

$$ D_{sc} = 1 - \frac{V_{PV}}{V_o} = \frac{V_o}{T_s \frac{V_o}{L}} \left[ 2 \frac{\partial V_{PV}}{\partial I_L} + \frac{\partial^2 V_{PV}}{\partial I_L^2} I_L \right] $$

(22)

Asymptotic stability is obtained using a positive definite Lyapounov function given as,

$$ V_{Ly} = \frac{1}{2} \psi^2 $$

---

Copyright reserved © J. Mech. Cont.& Math. Sci.
Polamraju. V. S. Sobhan et al
The derivative of $V_{Lia}$ becomes,

$$\frac{dV_{Lia}}{dt} = \psi \left( \frac{d\psi}{dt} \right) = \psi \left[ \left( -\frac{1}{T_s} \right) \psi \right] = \left( -\frac{1}{T_s} \right) \psi^2 \leq 0 \quad (22)$$

IV. Result Analysis

The fig. 6 and 7 demonstrates the simulation results of PV output power variation and corresponding change in duty cycle of designed boost converter for the considered PV system using the two MPPT controllers at temperature = 25°C and solar insolation = 1000 W/m$^2$. Clearly, it very well may be reasoned with the Synergetic controller, the generated PV power reaches the maximum value quicker than the P&O controller. However with the P&O method the duty cycle variation is much smoother with less oscillations in the steady state i.e when the power reaches maximum value.

![Fig. 6. The PV power under standard climatic conditions](image)

![Fig. 7. The duty cycle of boost converter under standard climatic conditions](image)

The figs. 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 1000 W/m$^2$ at time 2 sec. From fig. 9, with the synergetic controller the photovoltaic system has reacted accurately by generating power quickly.
and reaches the maximum value without any undershoots when compared to P&O MPPT algorithm under condition of sudden change in irradiance. The corresponding variation in the duty cycle of designed boost converter is shown in fig.9.

![Fig. 8. The power under variable irradiance](image1)

![Fig. 9. The duty cycle under variable irradiance](image2)

The fig. 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 synergetic controller maintains the generated PV power at maximum value without any interruption when compared to P&O algorithm. The variation in duty cycle using synergetic controller is limited to ±5 % of 0.67 when compared to the variation ±20 % of 0.67 using P&O method.
V. Conclusions

The design and analysis of a nonlinear MPPT controller based on synergetic control theory is presented in this paper. The synergetic control sustains the PV output power at its maximum under the disturbance conditions such as sudden change in irradiance and load when compared to the conventional P&O algorithm. The variation in duty cycle is also less using synergetic controller. The superiority of proposed controller is shown by comparing the simulation results with standard P&O MPPT algorithm.
References

I. A. A. Kolesnikov, "Synergetic Control Theory", Energoatomizdat, Moscow, 1994.

II. A. Sriharibabu and G. Srinivasa Rao, “DSPACE real time implementation of maximum power point tracking method for photovoltaic system using neural network”, Jol. of Advanced Research in Dynamical and Control Systems, vol.10, no.9, pp. 2005-2010, 2018.

III. L.V S Kumar and 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.

IV. Mitra, Indranil, Gopa Roy Biswas, and Sutapa Biswas Majee. "Effect of Filler Hydrophilicity on Superdisintegrant Performance and Release Kinetics From Solid Dispersion Tablets of A Model BCS Class II Drug." International Journal 4.1 (2014): 87-92.

V. M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Comprehensive approach to modeling and simulation of photovoltaic arrays,” Power Electron., IEEE Trans., vol. 24, no. 5, pp. 1198–1208, May 2009.

VI. M. Subba Rao, Dr. Ch.SaiBabu, and Dr.S.Satyanarayana, “1-phase Integrated Buck- Boost PFC LED Driver ” in the Jol. of Advanced Research in Dynamical and Control Systems, vol. 9, no.1, pp. 283-292, Oct 2017.

VII. Maheswararao, Ch Uma, YS Kishore Babu, and K. Amaresh. "Sliding mode speed control of a DC motor." 2011 International Conference on Communication Systems and Network Technologies. IEEE, 2011.

VIII. Sukumar, Durga, JayachandranathJithendranath, and Suman Saranu. "Three-level inverter-fed induction motor drive performance improvement with neuro-fuzzy space vector modulation." Electric Power Components and Systems 42.15 (2014): 1633-1646.

IX. Yadlapalli, Ravindranath Tagore, and Anuradha Kotapati. "A fast-response sliding-mode controller for quadratic buck converter." International Journal of Power Electronics 6.2 (2014): 103-130.