Global MPP Tracking for Partial shaded PV System using Fractional Order Extreme Seeking controller

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Abstract. Renewable energy tends to replace natural resources like coal and fuel, nowadays research work is in progress on solar power utilization. To overcome the photovoltaic (PV) installation issue, building-integrated PV (BiPV) system has been introduced. Partial shading is major issue in BiPV system. In order to prevent this issue, an anti-parallel bypass diode is added across each panel/cell. But it results in multiple peaks p-v characteristics with respect to varying irradiations. To track global peak power among all other local peaks, a special control algorithm based on extreme seeking (ES) strategy with fractional order controller (FOC) is developed. The proposed control method increases the power generation and efficient tracking of maximum power at MPP.

Keywords – Maximum Power Point Tracking (MPPT); Integer Order Extreme Seeking (IOES); Fractional Order Extreme Seeking (FOES); DC-DC Converter; Photovoltaic Module.

1. Introduction

Due to swelling inhabitants and industries, electricity demand is increasing day by day. Hence, renewable energy plays a major role to satisfy this energy demand and also it tends to replace natural resources like coal and fuel, strong research work is being concentrated on power generation by solar because it is abundant in nature and inexhaustible. So, PV system with maximum energy conversion efficiency is gaining more responsibility [1]. A major issue in PV system is a large space requirement for the installation of photovoltaic (PV) system. Building-integrated PV (BiPV) system is used to overcome this issue, which becomes popular nowadays. However, BiPV model experience partial shading of PV array due to irradiation change [2]. The damage of PV cells/panels due to partial shading leads to power loss, which can be prevented by anti-parallel diode connected on sequence PV cells/panel [3]. This will prevent the panel damage, but causes multiple power curves in panel characteristics of proposed PV system, which makes critical problem to track maximum power point [4]. There are some special algorithms present in the literature to track global peak among all other local peaks [5-15]. Different techniques were implemented to improve the power generation efficiency.

In this work, to track extreme power of PV, FOES scheme is introduced. The mainstream developments in linear, nonlinear, and adaptive control seek to achieve the objectives of control issues...
to regulate the output PV system. However, in many control applications, the desired set point is unknown, it must be determined so that the output of the dynamic system reaches its maximum or minimum extreme point [16-20]. This type of control scheme is known as extreme seeking control (ESC).

Fractional order controller (FOC) is introduced in extreme seeking control to increase the conversion efficiency and stability of the system under variation in external conditions [21-30]. It is a non-model based gradient search scheme that dynamically seeks the optimal point of the output mapping of a system, which makes these methods robust to model [31-33]. By using maximum power point tracking algorithms (MPPT), the converter can adaptively control the voltage or current and consequently power, based on their control logic conditions. Figure 1 presents the blocks of proposed system with source and controller with load.

![Figure 1. Block diagram of partial shaded PV with FOES controller](image)

2. Fractional order controller

Nowadays in many applications fractional control technique is used rapidly. The main motive to use this controller is due to its increased performance. In this work, extreme seeking strategy based on a novel proposed control is established to enhance the output to improve the system performance.

2.1. Fractional Calculus

Integral and differential to non-integer order is represented as

\[
\begin{align*}
{aD^m}^t_{\tau} &= \begin{cases} 
\frac{d^m}{dt^m} & \text{Re}(m) > 0 \\
\int_0^t \frac{d^m}{d\tau^m} & \text{Re}(m) = 0 \\
\int_0^t d\tau^m & \text{Re}(m) < 0
\end{cases}
\end{align*}
\]

Where \( m \) is the derivative or integral order and \( \text{Re}(m) \) represents the real part. Many schemes are introduced with fractional order controller. In this paper, singularity function method proposed which is used as a fraction order controller.

2.2. Charef method

Various ideas can be carried out to implement fractional order operators in both time or frequency domain. Charef singularity function [8] is similar to Oustaloup’s method which allows the fractional order transfer function with the balanced one as given in Eq. (2)

\[ H(s) = s^m, \ m \in \mathbb{R}^+ \]

where \( m \) is the fractional number. Fractal dimension is represented in \( s \) function as in Eq. (3)
The coefficient of zeros and poles are calculated in time domain of $y$ in terms of dB as in Eqs. (4) – (6).

$$a = 10^{\left\lfloor \frac{v}{10} \right\rfloor (1-m)}$$

(4)

$$b = 10^{\left\lfloor \frac{v}{10} (m) \right\rfloor}$$

(5)

$$ab = 10^{\left\lfloor \frac{v}{10} m(1-m) \right\rfloor}$$

(6)

The poles and zeros are derived by,

$$p_0 = p_i 10^{\left\lfloor \frac{v}{20m} \right\rfloor}$$

(7)

$$p_i = (ab)^i p_0$$

(8)

$$z_i = (ab)^i ap_0$$

(9)

The number of poles and zeros can also be represented by band width $\omega_{\text{max}}$ as shown in Eq. (10)

$$N = \left\lceil \frac{\ln(\omega_{\text{max}})}{\ln(ab)} \right\rceil + 1$$

(10)

3. Fractional Order Extremum Seeking Control

An MPP seeker is also required to supply the controller an appropriate reference input. Fields in which the fractional order extreme seeking technique have been proved to be extremely powerful in the optimization process. The main issue on seeking the global optimum of $P(\cdot): \mathbb{R} \rightarrow \mathbb{R}$, where the input is varied by disturbance $d(t)$ is shown in Figure 2.

**Figure 2.** Schematic of the controller circuit

As in [7], we consider the following assumptions.

Assumption 1: $P(\cdot): \mathbb{R} \rightarrow \mathbb{R}$ is assumed to be Lipchitz and bounded. In extreme seeking problem it is assumed to achieve the probing signal $\theta(\cdot)$ which is controlled as the function of $P(\cdot)$ through a dynamic system by Eq. (11).

$$\varepsilon V = -V + \theta$$

(11)

Where $\varepsilon$ is a scalar. The unknown map signal is $P(\cdot)$ and shown in Fig. 2.

$$V_p = V(t) + d(t)$$

$$p'_p = P(V(t) + d(t))$$

(12)
Assumption 2: The disturbance $d$ is implicit to be bounded and contains first and second order time derivatives, $\ddot{d}$ and $\dot{d}$ as $|d(t)| \leq d_0$, $|\dot{d}_d| \leq \dot{d}_d$ for all values of $t \geq 0$. Let Eq. (11) be assumed to be available. The following Eq. (13) is known.

$$
\begin{align*}
\dot{z}_1(t) &= \ddot{v}(t) = \dot{v}(t) + \dot{d}(t) \\
\dot{z}_2(t) &= \dot{p}(t) = \frac{\partial P(V(t)+d(t))}{\partial P}(\dot{V}(t)+\dot{d}(t))
\end{align*}
$$

(13)

The signals in Eq. (13) are approximated to use in actual implementation. By introducing an integer order integral $1/s$ we obtain the controller strategy, which is explained in [9]. Block diagram of extremum seeking controller is represented in Fig. 3. $P$ is an input in which the signals are $V$ and $d$. Voltage and power measured from source is given as input to FOES algorithm. The schematic of closed-loop dynamic system is seen in Figure 3.

![Block diagram of extremum seeking controller](image)

Figure 3. Dynamic extremum seeking control blocks

Convergence speed of $V$ is set to $\theta$ by a parameter $\varepsilon > 0$, where $\varepsilon$ static gain. The signal $k_2 z(t) z_2(t)$ is fed with the saturation and is integrated by $1/s^m$ and then product to $k_1$, which results in plant reference $\theta$ along $k_1$ and $k_2$.

FO integration function Eq. (14) is obtained.

$$
\frac{d^m \theta}{dt^m} = -k_1 \text{sat}(k_2 z(t) z_2(t))
$$

(14)

Where $\text{sat}(\_)$ is the saturation function, the above function can be written as

$$
s^{-\theta} = -k_1 \text{sat}(k_2 z(t) z_2(t))
$$

(15)

the $\theta$ becomes with the control law as in Eq. (16)

$$
\theta = \frac{-k_1 \text{sat}(k_2 z(t) z_2(t))}{s^m}
$$

(16)

with gain $k_1$ & $k_2 > 0$. Eq. (16) involves iteration to solve.

The main objective to get the better stability control is done by regulating parameter $k_2$ sufficiently. The expression of $\theta$ in Eq. (16) assures that $\theta \leq k_1/s^m$, as it avoids high frequency dynamics. It is helpful in controlling the saturation rate constraints of the system.

The flow diagram shown in Figure 4 explains the operation of FOES algorithm to seek the global peak of photovoltaic array.
4. Photovoltaic System

The photovoltaic system is designed as in [6], [11]. Reference module for simulation is taken by SOLKAR 36 W peak power PV rated at 37.08 Wp; 16.56 V and 2.25 A at peak power. Three series connected PV panels are used in this work which results in necessary output current rating and voltage rating under ordinary conditions. The PV cell structure is represented in Figure 5.

![Figure 4. Fractional order extremum seeking operation flow](image)

4. Photovoltaic System

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The photo generated current $I_p$ of the photovoltaic module depends on the solar irradiation linearly and is also affected by the temperature as shown in the Eq. (17).

$$I_p = \left[I_{sc} + K(T_e - T_{ref})\right] \times \frac{\lambda}{1000} \quad (17)$$

Where $I_{sc}$ is the short circuit current in A taken from the datasheet, $K_i$ is the temperature coefficient (0.0017A/K), $T_e$ and $T_{ref}$ are the actual and reference temperatures in K and $\lambda$ is the insolation in W/m². Module reverse saturation current is expressed by Eq. (18)
Where $V_{oc}$ is the open circuit voltage, $q (=1.6 \times 10^{-19} \text{C})$ is the charge of electron, $K (=1.3805 \times 10^{-23} \text{J/K})$ is the Boltzmann constant and $A (=1.6)$ is the ideality factor. Module saturation current varies with temperature of cell shown by Eq. (19)

$$I_s = I_{sc} \left[ \frac{T}{T_1} \right] \exp \left[ \frac{qE_{g0}}{AK} \left( \frac{I}{T} - \frac{I}{T_1} \right) \right]$$

Where $E_{g0} (=1.1 \text{eV})$ is the semiconductor band-gap energy. The module current ($I_{mp}$) is given in Eq. (20).

$$I_{mp} = N_p I_p - N_s I_s \left[ \exp \left( \frac{q(V_{mp} + I_{mp} R_s)}{N_s AKT} \right) - 1 \right] - V_{mp} + \frac{I_{mp} R_s}{R_s}$$

Where $N_p$ and $N_s$ are the parallel and series connected cells numbers, $R_s$ and $R_{sh}$ is the equivalent series and shunt connected resistance. Generally, the value of $R_{sh}$ is high and hence neglected for model simplicity as in Eq. (21).

$$I_{mp} = N_p I_p - N_s I_s \left[ \exp \left( \frac{q(V_{mp} + I_{mp} R_s)}{N_s AKT} \right) - 1 \right]$$

5. Partial Shaded Model

Because of neighbour building, dirt, aging effect of PV module partial shading condition is taking place. PV module output power is affected by shaded cells and it is difficult to consider the shading of each and every cell, so the effect of shading is also considered in the module.

We have considered three modules with different illumination. When one cell is shaded, it becomes reverse bias, breakdown voltage will occur in these situations, which cause damage in the cell. So anti parallel diode connected in series to bypass the current.

![Figure 6. Partial shaded PV module](image)

PV array in partial shading condition is in need to simulate with MPPT controller because P-V curve had multiple peaks, so MPPT should be good enough to track the global peak among all other local peaks. The circuit diagram of partial shaded PV module is shown in Figure 6.
6. Converter Modelling

The MPPT is applied to regulate the voltage and the duty cycle of converter. The PV module is designed to supply desired maximum power. The basic blocks of the dc-dc converter are illustrated in Figure 7.

The output of designed converter is controlled by switching ON/OFF the controllable switch with constant frequency. Signal produced by the MPPT is compared with constant switching frequency triangular signal which will produce a square wave and is fed to DC-DC converter. The current flow in the inductor \( L \) is given in Eq. (22), as in [12].

\[
\begin{align*}
\text{Turn on time : } L &= \frac{V_i}{I_{\text{max}} - I_{\text{min}}} t_{\text{on}} \\
\text{Turn off time : } L &= \frac{V_o - V_i}{I_{\text{max}} - I_{\text{min}}} t_{\text{off}}
\end{align*}
\]

The control signal duty ratio is expressed as in Eq. (23).

\[
D = \frac{T}{t_{\text{on}} - t_{\text{off}}}
\]

By neglecting the difference of \( I_{\text{max}} - I_{\text{min}} \), the output voltage of the converter can be obtained as

\[
V_o = V_i \left( \frac{t_{\text{on}} + t_{\text{off}}}{t_{\text{off}}} \right) = \frac{V_i}{1 - D}
\]

7. Simulation Results

The specifications of the various parameters of the partial shaded connected PV model are as follows. Irradiation levels at three panels are considered as, \( G_1 = 1000 \text{ W/m}^2 \), \( G_2 = 200 \text{ W/m}^2 \), \( G_3 = 600 \text{ W/m}^2 \) and temperature is kept at \( T = 25^\circ\text{C} \). The MatLab schematics for varying irradiation condition are shown in Fig. 8. The power loss due to partial shaded PV is more. To overcome from this issue, bypass diodes are added across each module in series connected system as shown in Figure 8 and the output characteristics of the partial shaded PV system is shown in the below Figure 9.
Figure 8. Partial shaded PV array with bypass diodes

Figure 9. V-I and P-V characteristics of partial shaded PV

From the Figure 9, it is observed that the bypass diode introduced each series connected panel causes multiple peaks in characteristics, however it improves the power. To track the global peak among all other peaks, the developed FOES algorithm is used and also the convergence time is increased.

Figure 10. Developed system in MatLab/Simulink
The developed FOES algorithm tracking global peak among all other local peaks can be seen from the characteristic Figure 11.

![Figure 11. MPPT at global maximum](image1)

Maximum power point curve for three different level of irradiation at particular instance is shown in following Figure 12.

![Figure 12. MPP curve for varying irradiation](image2)

Converter output power for different fractional values are inferred in Figure 13, in which the convergence period is comparatively high at fractional value \( m = 0.7 \). For fractional value \( m = 1 \) FOES controller acts similar like normal Integer Order ES controller.

![Figure 13. Convergence time comparison plot](image3)
8. Hardware Results

An electronic load is modelled to study the characteristics of PV module shown in Figure 14.

![Electronic load schematic](image)

**Figure 14.** Electronic load schematic

The circuit is connected such that the IPV is proportional to voltage at the amplifier terminal. The MOSFET gate terminal is triggered by triangular signal such that the current swings between zero and short circuit value. When the IPV varies from zero to maximum and vice versa, the characteristic curve is drawn. DSO has been used to trace the characteristics of without shading effect and also under partial shaded conditions. The traced characteristics under shading conditions are shown in Figure 15. The hardware prototype of the partial shaded PV interfaced with conventional boost converter with the developed MPPT algorithm is shown in Figure 16. The input and output voltage for boost converter with developed algorithm, gate pulse for MOSFET switch and load current waveforms for un shaded and under shaded conditions are shown in Figure 17 and Figure 18.

![Characteristics of PV array](image)

**Figure 15.** VI characteristics of PV array with and without shading Conditions
9. Conclusion
In this research, the proposed control method is developed with abusing external disturbance produced in the system. Three PV panels connected in series have been characterized under partial
shaded condition with bypass diodes. The developed FOES controller results in efficient performance and robustness on tracking maximum global peak of the PV system. Performance analysis has been carried out with developed FOES algorithm for partial shaded PV system. FOES controller increases the time of convergence which is proven by comparison plot for different fractional values. The proposed system has also been validated experimentally.

References

[1] Sitharthan R, Geethanjali M and Pandy TKS 2016 Adaptive protection scheme for smart microgrid with electronically coupled distributed generations Alexandria Engineering Journal 55(3) 2539-2550
[2] Fathima AH, and Palanisamy K 2014 Battery energy storage applications in wind integrated systems—a review IEEE International Conference on Smart Electric Grid 1-8
[3] Prabaharan N and Palanisamy K 2015 Investigation of single-phase reduced switch count asymmetric multilevel inverter using advanced pulse width modulation technique International Journal of Renewable Energy Research 5(3) 879-890.
[4] Jerin ARA, Kaliannan P and Subramaniam U 2017 Improved fault ride through capability of DFIG based wind turbines using synchronous reference frame control based dynamic voltage restorer. ISA transactions 70 465-474
[5] Sitharthan, R, Sundarabalan CK, Devabalaji KR, Nataraj SK and Karthikeyan M 2018 Improved fault ride through capability of DFIG-wind turbines using customized dynamic voltage restorer Sustainable cities and society 39 114-125
[6] Prabaharan N and Palanisamy K 2016 A single-phase grid connected hybrid multilevel inverter for interfacing photo-voltaic system Energy Procedia 103 250-255
[7] Palanisamy K, Mishra JS, Raglend IJ and Kothari DP 2010 Instantaneous power theory based unified power quality conditioner (UPQC) IEEE Joint International Conference on Power Electronics, Drives and Energy Systems 1-5
[8] Sitharthan R and Geethanjali M 2017 An adaptive Elman neural network with C-PSO learning algorithm-based pitch angle controller for DFIG based WECS Journal of Vibration and Control 23(5) 716-730
[9] Sitharthan R and Geethanjali M 2015 Application of the superconducting fault current limiter strategy to improve the fault ride-through capability of a doubly-fed induction generator–based wind energy conversion system Simulation 91(12) 1081-1087
[10] Sitharthan R, Karthikeyan M, Sundar DS and Rajasekaran S 2020 Adaptive hybrid intelligent MPPT controller to approximate effectual wind speed and optimal rotor speed of variable speed wind turbine ISA transactions 96 479-489
[11] Sitharthan R, Devabalaji KR and Jees A 2017 An Levenberg–Marquardt trained feed-forward back-propagation based intelligent pitch angle controller for wind generation system Renewable Energy Focus 22 24-32
[12] Sitharthan R, Sundarbalaban CK, Devabalaji KR, Yuvaraj T and Mohamed Imran A 2019 Automated power management strategy for wind power generation system using pitch angle controller Measurement and Control 52(3-4) 169-182
[13] Sundar DS, Umamaheswari C, Sridarshini T, Karthikeyan M, Sitharthan R, Raja AS and Carrasco MF 2019 Compact four-port circulator based on 2D photonic crystals with a 90° rotation of the light wave for photonic integrated circuits applications Laser Physics 29(6) 066201
[14] Sitharthan R, Parthasarathy T, Sheeba Rani S and Ramya KC 2019. An improved radial basis function neural network control strategy-based maximum power point tracking controller for wind power generation system Transactions of the Institute of Measurement and Control 41(11) 3158-3170
[15] Rajesh M and Gnanasekar JM 2017 Path observation based physical routing protocol for
wireless ad hoc networks Wireless Personal Communications 97(1) 1267-1289

[16] Palanisamy K, Varghese LJ, Raglend IJ and Kothari DP 2009. Comparison of intelligent techniques to solve economic load dispatch problem with line flow constraints IEEE International Advance Computing Conference 446-452

[17] Sitharathan R, Ponnusamy M, Karthikeyan M and Sundar DS 2019 Analysis on smart material suitable for autogenous microelectronic application Materials Research Express 6(10) 105709

[18] Rajaram P, Palanisamy K, Ramasamy S and Ramanathan P 2014 Selective harmonic elimination in PWM inverter using fire fly and fireworks algorithm International Journal of Innovative Research in Advanced Engineering 1(8) 55-62

[19] Sitharathan R, Swaminathan JN and Parthasarathy T 2018 March. Exploration of wind energy in India: A short review IEEE National Power Engineering Conference 1-5

[20] Karthikeyan M, Sitharathan R, Ali T and Roy B 2020 Compact multiband CPW fed monopole antenna with square ring and T-shaped strips Microwave and Optical Technology Letters 62(2) 926-932

[21] Sundar D Sridharshini T, Sitharathan R, Madurakavi Karthikeyan, Sivanantha Raja A, and Marcos Flores Carrasco 2019 Performance investigation of 16/32-channel DWDM PON and long-reach PON systems using an ASE noise source In Advances in Optoelectronic Technology and Industry Development: Proceedings of the 12th International Symposium on Photonics and Optoelectronics 93

[22] Sitharathan R and Geethanjali M 2014 Wind Energy Utilization in India: A Review Middle-East J. Sci. Res. 22 796–801 doi:10.5829/idosi.mejsr.2014.22.06.21944

[23] Sitharathan R and Geethanjali M 2014 ANFIS based wind speed sensor-less MPPT controller for variable speed wind energy conversion systems Australian Journal of Basic and Applied Sciences 814-23

[24] Jerin ARA, Kaliannan P, Subramaniam U and El Moursi MS 2018 Review on FRT solutions for improving transient stability in DFIG-WTs IET Renewable Power Generation 12(15) 1786-1799

[25] Prabaharan N, Jerin ARA, Palanisamy K and Umashankar S 2017 Integration of single-phase reduced switch multilevel inverter topology for grid connected photovoltaic system Energy Procedia 138 1177-1183

[26] Rameshkumar K, Indragandhi V, Palanisamy K and Arunkumari T 2017 Model predictive current control of single phase shunt active power filter Energy Procedia 117 658-665

[27] Fathima AH and Palanisamy K 2016 Energy storage systems for energy management of renewable energy and distributed generation systems Energy Management of Distributed Generation Systems 157

[28] Rajesh M 2020 Streamlining Radio Network Organizing Enlargement Towards Microcellular Frameworks Wireless Personal Communications 1-13

[29] Subbiah B, Obaidat MS, Sriram S, Manoharn R and Chandrasekaran SK 2020 Selection of intermediate routes for secure data communication systems using graph theory application and grey wolf optimisation algorithm in MANETs IET Networks doi:10.1049/iet-net.2020.0051

[30] Singh RR and Chelliah TR 2017 Enforcement of cost-effective energy conservation on single-fed asynchronous machine using a novel switching strategy Energy 126 179-191

[31] Amalorpavaraj RAI, Palanisamy K, Umashankar S and Thirumooorthy AD 2016 Power quality improvement of grid connected wind farms through voltage restoration using dynamic voltage restorer International Journal of Renewable Energy Research 6(1) 53-60

[32] Singh RR, Chelliah TR, Khare D and Ramesh US 2016 November. Energy saving strategy on electric propulsion system integrated with doubly fed asynchronous motors IEEE Power India International Conference 1-6

[33] Singh RR, Mohan H and Chelliah TR 2016 November. Performance of doubly fed machines
influenced to electrical perturbation in pumped storage plant-a comparative electromechanical analysis IEEE 7th India International Conference on Power Electronics 1-6