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Solar PV Transient Mitigation using Superimposed Sliding Mode-Perturb and Observe MPPT under Varying Irradiation Conditions

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Varying weather specifically temperature and irradiation have a significant impact on Solar Photo Voltaic (SPV) output performance and efficiency. Both the output voltage and power are unstable due to the unwanted solar fuel variation. Therefore, Maximum Power Point Tracking (MPPT) plays an important role in the case of SPV. Although different MPPT techniques are imposed to mitigate the above-said issues, the Perturb and Observe (P&O) is unique in its operation and simple to design. But when P&O comes under a sudden large variation of solar parameters, it fails to track and move away from the Maximum Power Point (MPP). A sliding mode controller superimposed with conventional P&O known as Superimposed Sliding Mode Controller-P&O (SISMC-PO) is proposed in this paper that improves the tracking accuracy and tries to minimize the transient disturbance during the rapid change in irradiation. Input side capacitor current and error in SPV voltage with reference voltage are taken as the input to the SMC whereas solar voltage and current are taken as the input to the P&O MPPT. SISMC-PO produces highly efficient and robust control of the switching frequency with a suitable step size that drives the switch of the DC-DC boost converter which is tested and verified by MATLAB/SIMULINK.

Keywords: Boost converter, Perturb & observe, Sliding mode control, Pulse width modulation, Solar fuel

Nomenclature

SMC	Sliding mode controller
MPP	Maximum power point
FOCV	Fractional open-circuit voltage
FSCC	Fractional short circuit current
SPV	Solar photo voltaic
S	Switch
P&O	Perturb and observe
SISMC-PO	Superimposed sliding mode controller-P&O
Temp	Temperature
Irr	Irradiance
PWM	Pulse width modulation
PV	Photo voltaic

Introduction

Motivation and Incitement

Electricity consumption is rapidly increasing which causes harmful emissions and environmental pollution. The Kyoto Agreement directs strict principles to bring down greenhouse gas emissions from the power sector for which power generation from sustainable energy resources is kept in high demand on a priority basis.[1] Solar power throughout the day can produce or fulfill the energy requirement for a year.[2]

Among the energy resources, solar energy is abundantly available and most suitable to generate electricity anywhere during the daytime. But the problem with the SPV is that its efficiency is very less around 17–20%[(3,4)] and Solar power is greatly affected by irradiation, ambient temperature, partial shading conditions, wavelength, reflection, and cloud coverage.[5] So we put stress on extracting the MPP which is possible only when a boost converter with an appropriate switching signal can dynamically match the impedance between the SPV and load under varying weather conditions.[6] Shading or cloudy weather is an unavoidable situation that produces local maximum points and a global maximum point which is hard to search quickly.[7] Application of SPV includes both power generation and heating of water whereas the tracking method follows sun-tracking, MPPT, and both simultaneously.[8] In sun-tracking, the position of the SPV changes accordingly to the way the sun moves whereas in MPPT the electronics circuit matches the impedance between the SPV and sink to deliver the optimal power.[9]

Literature Review

Apart from this, different MPPT techniques are implemented such as Fractional Open-Circuit Voltage (FOCV), Fractional Short Circuit Current (FSCC),

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fuzzy logic, neural network, Perturb and Observe (P&O), and incremental conduction algorithm.[10] The P&O method is very simple and easy to implement. However, it has certain limitations such as this method's failure to track MPP under rapid change of environmental conditions. The efficiency reduces due to power oscillations caused by changes in environmental conditions. It is difficult to control the step size in P & O method.

The SMC dominates other methods by its inherent robustness, flexibility, and ease of hardware implementation.[11] SMC can be applied directly to the nonlinear system which gives the MPPT tracking a much more effective manner.[12] Uncertainty of load and weather conditions, the SCM is the best fit for the nonlinearity of the SPV system function.[13] Proper control of SPV temperature, MPP can be operated without the MPPT algorithm.[14] Oscillation and response time depend on the step size.[15] When the weather changes, particle rearrange their position near to global maximum which results in time-saving.[16] The stand-alone system can extract the MPP using neural network-based and modified P&O MPPT control under changing weather conditions.[17,18]

Contribution and Paper Organization

This paper proposes SISMC-PO method-based MPPT which tracks the MPP under different weather situations. The chattering effects are not considered in this proposed controller. The control law for this proposed method improves the robustness. The sliding surface of the proposed SMC is designed to have insensitive to external disturbances and improves the steady state performances. The principle of the SMC control strategy is to force the initial conditions of the states to move towards the sliding surface during the reaching phase and helps the states to slide on the sliding surface to reach the desired location. The proposed SISMC-PO controller properly tracks the MPP under rapidly varying irradiation conditions.

Material and Methods

Solar Photovoltaic

1soltech15TH-215-P solar PV model with electrical characteristics is shown in Table 1. Two parallel string and two series-connected modules per string is used for the solar array for this proposed simulation study. The array has a maximum power capability of 852.6 Watts. The Short circuit current and open-circuit voltage of the array consisting of two modules is 15.68 A and 72.6 V respectively. At the maximum power point, the current and voltages are 14.7 A and 58 V respectively for the array.

Table 1 — Data per PV Module

Maximum power	213.15W
Open circuit voltage (Voc)	36.3 V
The voltage at maximum power point (Vmpp)	29 V
Cells per Module	60
Short circuit current	7.84 A
Current at maximum power point (Impp)	7.35 A

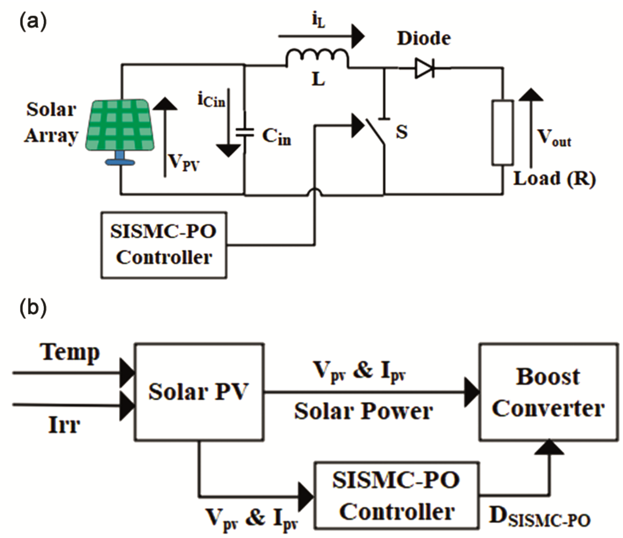

Fig. 1 — SISMC-PO: (a) Circuit diagram, and (b) Block diagram

The circuit diagram and structure are shown in Fig. 1(a) and Fig. 1(b) respectively.

DC-DC Boost Converter

This is an isolator between the SPV and load whose prime function is impedance matching between the sources and load to withdraw maximal power from the source. As the irradiation varies the switching signal is automatically adjusted to produce an appropriate switching frequency to operate the boost converter in such a way that will produce different impedance to match.

When the switch is on, the inductor starts charging and the part of the circuit gets separated from the load. The load gets the energy from the discharging capacitor and at the time of switch-off conditions, the load gets power from the SPV and the capacitor starts charging.

When the switch is closed, the state-space equation of the converter is:

Table 2 — Boost converter parameter

Input capacitor (Cin)	100 microfarads
Inductor (L)	2 milli-henry
Output capacitor (C)	100 microfarads
Load resistance (R)	20 ohms
Switching frequency	5000 Hz

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{RC_{in}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{PV} \quad \ldots (1)$$

The state-space equation while the switch is open

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC_{in}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{PV} \quad \ldots (2)$$

The average state-space model is shown in Eq. (3)

$$\dot{x} = \begin{bmatrix} 0 & \frac{-(1-D)}{L} \\ \frac{(1-D)}{C_{in}} & \frac{-1}{RC_{in}} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{PV} \quad \ldots (3)$$

where, $x_1 = I_{PV}$,$x_2 = V_{out}$,$L\frac{diL}{dt} = V_{PV}$ & $C_{in}\frac{dV_{out}}{dt} = \frac{V_{out}}{R}$. Here V_{PV} and V_{out} are the solar voltage and output voltage respectively $D = D_{SISMC-PO}$ is the duty cycle produced by the proposed controller that generates the gate signal for the switch and R is the load resistance. The parameter of the converter is shown in Table 2.

MPPT Technique

The MPPT algorithm is important to extract the MPP from the array by the P&O method and the SISMC-PO method of MPPT is as follows.

P&O Method

In the P&O method, the voltage is disturbed and the change in power is observed. If the change in power is positive, the same process repeats until the peak point is reached. After MPP point the change of power decreases in nature as compared to its previous value. So the voltage value is reduced to come near to the MPP. This makes the power oscillate near its MPP. Here the response time and oscillatory nature of conventional P&O methods are commendable that depend on the step size. Here the step size is "deltaD" of 0.000125 taken. The flow chart for P&O is shown in Fig. 2 (a).

To reduce the oscillation, if the step size is reduced, the response time increases and vice versa. For this reason, it is difficult to choose the optimal step size to give a better result. As the oscillation

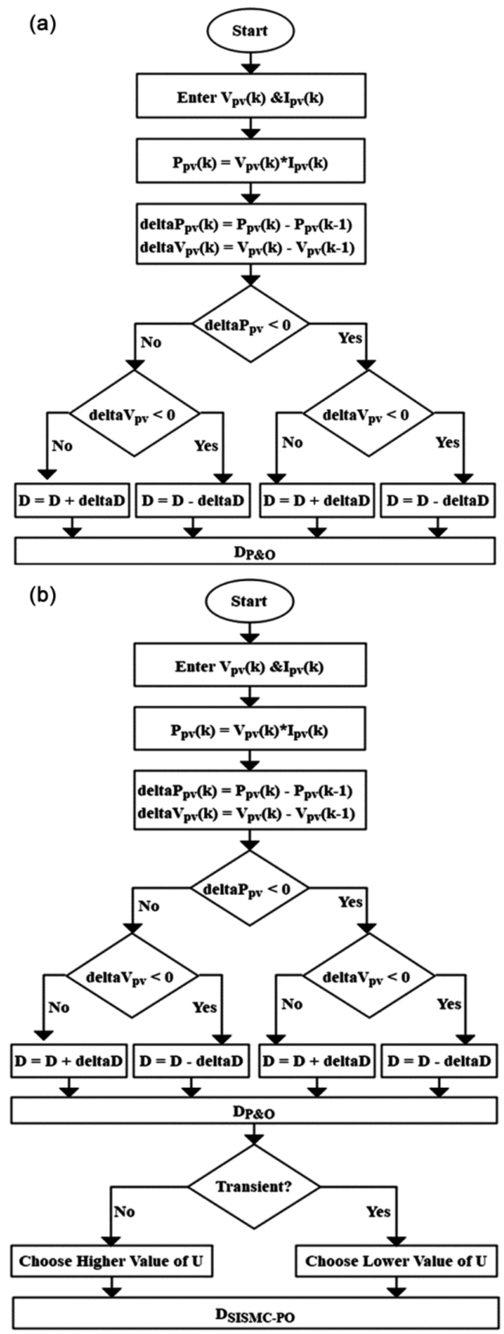

Fig. 2 — MPPT algorithm (a) P&O, and (b) SISMC-PO

persists, the loss of the system is increased and this condition reduces the system's performance and efficiency.

Although the P&O works well under gradually varying ambient irradiation and temperature, however, fails to track the peak point when the solar PV comes under sudden disturbances due to sharp changes in irradiation. Under uncertain disturbances, P&O suffers transient and, in some cases, it is seen it diverges from the global maximum point. So to overcome this issue, many methods have been proposed but their performance is not up to the mark.

SISMC-PO Method

The SMC is a very robust model that reduces the order of the compensated dynamics and provides robustness response with bounded disturbance in finite time. The overall system control law for SMC is shown in Fig. 2(b).

The state-dependent sliding surface is given as

$$s = y_2 + cy_1 \quad \dots (4)$$

where, $y_1$and y_2 represents the states of the system

$$\dot{s} = \dot{y}_2 \quad \dots (5)$$

The state-space dynamics are given by

$$\dot{y}_1 = y_2 \quad \dots (6)$$

$$\dot{y}_2 = U + f(y,t)$$

Further, the control dynamic is modified as

$$\dot{s} = U + f(y,t) + cy_2 \quad \dots (7)$$

Assuming

$$U = -cy_2 + v$$

And

$$v = -Asgn(s)$$
$$\dot{s} = -Asgn(s) + f(y,t) \quad \dots (8)$$

Since,

$$|A| > |f(y,t)|$$

To converge the states at the desired location, the Lyapunov function is satisfied as

$$\dot{s}s < 0 \quad \dots (9)$$

However, the control law and voltage error for the proposed SISMC-PO designed based on SMC is shown in Eqs (10) & (11) respectively. The flow chart for the proposed controller is shown in Fig. 2 (b).

$$U = (V_{PV} - V_{ref})G_1 + i_{Cin} * G_2 \quad \dots (10)$$

$$V_{error} = (V_{PV} - V_{ref}) \quad \dots (11)$$

where, V_{PV} is the solar voltage, i_{Cin} is the capacitor current, V_{error} is the error between solar voltage (V_{PV}) and reference voltage (V_{ref}), and G_1, G_2 are the gains for the SMC as shown in Fig. 3(b).

Considering the two states of the boost converter in the proposed system,

$$y_1 = (V_{PV} - V_{ref}) \text{ and } y_2 = i_{Cin}$$

The flow chart of P&O is shown in Fig. 2(a), in which, the voltage V_{PV} and current I_{PV} samples are collected initially to calculate the corresponding power. Then change in voltage and change in power are calculated. The change in parameters is then compared with zero as shown in the flow chart. Based on the conditions, the duty ratio (D) is produced followed by "deltaD". The transient responses in responses are checked. The presence of transients is minimized by a suitable control law designed from the proposed SISMC-PO as illustrated in Fig. 2 (b).

The proposed SISMC-PO combines the output signals of the P&O and SMCin such a way as to produce a better switching signal to the converter. The duty cycle of SISMC-PO is given in Eq. (12).

$$D_{SISMC-PO} = U * D_{P\&O} \quad \dots (12)$$

$$D_{SISMC-PO} = (V_{error} * G_1 + i_{Cin} * G_2) * D_{P\&O} \quad \dots (13)$$

The output load voltage obtained using (14)

$$V_{out} = \frac{V_{PV}}{1 - D_{SISMC-PO}} \quad \dots (14)$$

Proposed controller decays the power oscillation and minimizes the settling time of the response with proper selection of the step size and optimizing the gain of SMC. The step size in the case of P&O:

$$deltaD = D(k) - D(k-1) \quad \dots (15)$$

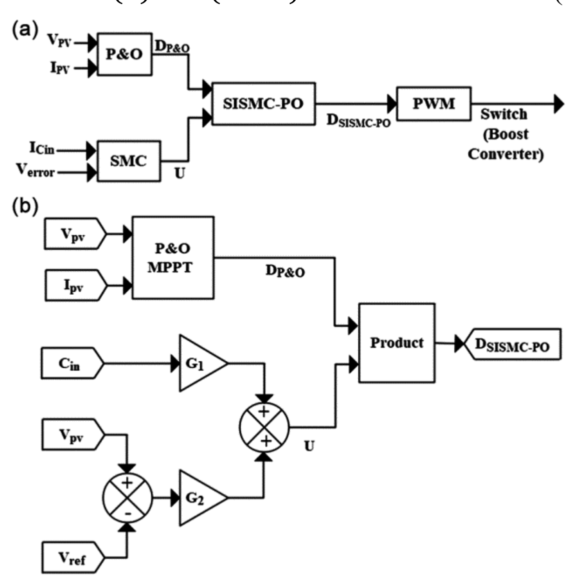

Fig. 3 — SISMC-PO, (a) Block diagram, and (b) Simulink diagram

where, D(k) and D(k-1) are the present and previous duty ratios.

During oscillation, the magnitude of both D(k) and D(k-1) are nearly the same but the movement is in opposite direction, so the (deltaD = 0), and during non-oscillatory conditions, the value of deltaD is nonzero. During normal operating situations, the value of the SMC gain is kept as high as near 1, so the large step size of the convention P&O reduces the settling time. But at the time of oscillation, to reduce the step size, the control law U of SMC is kept low, to reduce the oscillation. The optimal value of G_1 and G_2 decides the value of U. By using fsolver G_1 and G_2 are obtained as 1 and 2 respectively shown in Fig. 3(a). The complete control structure for SISMC-PO is shown in Fig. 3(b). It is shown that the duty ratio $D_{P\&O}$ is developed from the MATLAB coding which is multiplied with control signal$U$ from the sliding mode control structure.The product of U and $D_{P\&O}$ is passed through a PWM generator for generating a PWM signal which is the triggering pulse to the boost converter.

Results and Discussion

The simulation study for both the conventional P&O method and the proposed SISMC-PO method is carried out using MATLAB/SIMULINK with a solar array (array type: 1soltech 1STH-215P) of two series modules and two parallel strings. Both aforesaid methods are conducted for 1.5 sec simulation time. MPPT tracking and solar PV parameter variations are observed under both slow and quick-changing irradiation conditions. The irradiation values are taken such as 0, 300, 500, 1000, 500 and 0 w/m^2 respectively.

The traditional P&O Power tracking is indicated in Fig. 4(a), whereas Fig. 4(b) shows the proposed SISMC-PO simulation result. It is seen that the change in irradiation from one value to another, there exists a transient for the transition state. The P&O in Fig. 4(a) takes 0.025 sec to settle down the steady-state value whereas SISMC-PO in Fig. 4(b) does not take any time to approach the final value. Transient oscillation happens in the P&O method when the irradiation changes rapidly from 1000w/m^2 to 500w/m^2. There survive an overshoot and damped oscillation at the P&O method which is reduced significantly in the SISMC-PO method. The solar voltage of both methods is shown in Fig. 4(c) and Fig. 4(d). The same disturbance point is considered for the productivity analysis and comparative study of the new method with the conventional method. The value of G_1 and G_2 are obtained by using the f-solver optimization technique in MATLAB which are found to be 1 and 2 respectively. The transient in voltage and current is high in the P&O method as compared

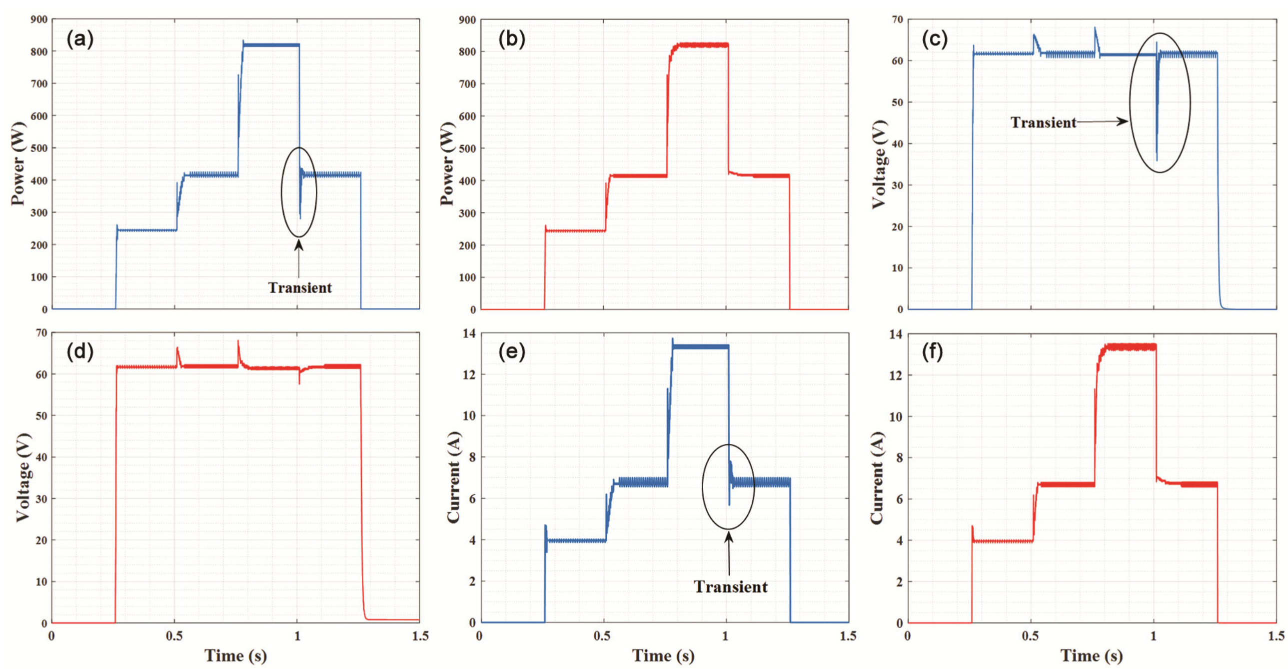

Fig. 4 — Comparison of methods for power, voltage and current: (a) Power (P&O), (b) Power (SISMC-PO), (c) Voltage (P&O), (d) Voltage (SISMC-PO), (e) Current (P&O), and (f) Current (SISMC-PO)

to the proposed method from 1.01 to 1.02 sec as shown in Fig. 4(e) and Fig. 4(f). In both mentioned methods, it is seen that the duty cycle is continuously varying to adjust the irradiation change to operate the system optimally. It is observed that the duty ratio is very sensitive in the proposed SISCM-PO method during disturbances of irradiation and works satisfactorily to minimize the transients which are indicated whereas the duty ratio is less sensitive in the conventional P&O method. The duty cycle of SISMC-PO varies from 0.5 to 0.3 under transient conditions adopting SMC control law. However, the duty ratio of P&O remains almost constant which is 0.3 due to the fixed step size. Hence SISMC-PO improves the sensitivity to the parameter variation that helps in transient mitigation.

In each step of irradiation variation, there is a transient, but at t = 1 sec, the transient appeared as severe and significant. The power loss due to transient at t = 1 sec is considered in this study to validate the efficacy of the proposed model. The transient power loss in P&O is 160 W and 5 W in SISMC-PO which is reduced by 96.87%. Similarly, the voltage and current transient are reduced by 86.66% and 90% respectively by the proposed controller.

In an ideal case, the maximum power of 852.6 W can be tracked under 1000 w/m^2 irradiance. However, the simulation result shows the SISMC-PO tracks 830 W under 1000 w/m^2 irradiance. This indicates that a 2.65% loss appears in the simulation from the ideal case. The efficiency is found to be 97.34% for the proposed controller.

Conclusions

A new MPPT algorithm SISMC-PO has been implemented in this work to show its superiority over P&O algorithm. The concept behind the algorithm is to start with a basic P&O method with a fixed step size and once oscillation occurs; it tried to reduce the step size by providing a lower value of the SMC control law. This finds the appropriate $D_{SISMC-PO}$ to operate the switch which helps to reduce oscillation significantly and improve convergence. The chattering effects are not considered in the proposed work which can be considered to get better result. The proposed work helps the researcher to pick a suitable control method for MPPT tracking with greater efficiency. This study is carried out under a solar power-based island mode test model which can be extended to the grid-connected mode with multiple power resources like solar, wind, etc.

References

1 ALQahtani A H & Utkin V I, Control of photovoltaic system power generation using sliding mode control, *IEEE Int Conf on Power Sys Technol* (Auckland, New Zealand) 2012, 1–6, doi: 10.1109/PowerCon.2012.6401325.

2 Darab C & Turcu A, Internal model control for MPPT of a solar PV system, *IEEE Int Conf on Modern Power Sys* (Cluj-Napoca, Romania), 2017, 1–4, doi: 10.1109/MPS.2017.7974464.

3 Jain P, Joshi S N, Gupta N & Sharma K G, Analysis of MPPT techniques in grid-connected PV System, *3rd Int Conf and Work on Recent Advan and Innov in Engg* (Jaipur, India) 2018, 1–4, doi: 10.1109/ICRAIE.2018.8710412.

4 Ali H G, Vilanova R & Pelez-Restrepo J, Perturb & observe based adaptive sliding mode MPPT control of solar photovoltaic system, *IEEE Int Conf on Env and Elect Engg and IEEE Indus and Commer Power Sys* (Europe, Madrid, Spain) 2020, 1–6, doi: 10.1109/EEEIC/ICPSEurope49358.2020.9160539.

5 Merry M, Shaman M B, Balog R S & Abu-Rub H, MPPT of photovoltaic Systems using Sensorless current-based model predictive control, *IEEE Trans on Ind Appli*, **53(2)** (2017) 1157–1167, doi: 10.1109/TIA.2016.2623283.

6 Kolluru V R, Sahu G, Mahapatra K & Subudhi B, Design and simulation of a modified sliding mode controller evaluated with a conventional P&O MPPT controller for solar applications, *IEEE Int Conf Sig Process Info Commun Energy Syst* (Kozhikode, India) 2015, 1–5, doi: 10.1109/SPICES.2015.7091473.

7 Mohanty S, Subudhi B & Ray P K, A Grey Wolf-Assisted Perturb & Observe MPPT Algorithm for a PV System, *IEEE Trans on Ener Conv*, **32(1)** (2017) 340–347, doi: 10.1109/TEC.2016.2633722.

8 Kumar Roy S, Hussain S & Bazaz M A, Implementation of MPPT technique for solar PV system using ANN, *Recent Dev Control Auto & Power Eng* (Noida, India) 2017, 338–342, doi: 10.1109/RDCAPE.2017.8358293.

9 Nayak B P & Shaw A, Design of MPPT controllers and PV cells using MATLAB Simulink and their analysis, *Int Conf Nas Technol Eng* (Navi Mumbai, India) 2017, 1–6, doi: 10.1109/ICNTE.2017.7947932.

10 Gaga A, Errahimi F & Es-Sbai N, Design and implementation of MPPT solar system based on the enhanced P&O algorithm using Labview, *Renew Sust Energy Conf* (Ouarzazate) 2014, 203–208, doi: 10.1109/IRSEC.2014.7059786.

11 Pradhan R & Subudhi B, Double Integral Sliding Mode MPPT Control of a Photovoltaic System, *IEEE Trans on Control Sys Technol*, **24(1)** (2016) 285–292, doi: 10.1109/TCST.2015.2420674.

12 Touil S, Boudjerda N, Boubakira A & Boudouda A, Sliding mode control of a grid-connected photovoltaic source via a three-phase inverter using incremental conductance MPPT, *5th Int Conf Elect Eng* – (Boumerdes, Algeria) 2017, 1–6, doi: 10.1109/ICEE-B.2017.8192220.

13 Farhadi P, Seda H M, Sharifi S & Taheri B, Power point tracking in photovoltaic systems by sliding mode control, *10th Int Symp Adv Topics Electr Eng* (Bucharest) 2017, 781–785, doi: 10.1109/ATEE.2017.7905097.

14 Martins da Rocha N M, Martins D C & Passos J C, MPPT method based on temperature control of the photovoltaic

cells, *12th IEEE Int Conf Ind Appl*, (Curitiba) 2016, 1–8, doi: 10.1109/INDUSCON. 2016.7874451.

15 Saxena V, Kumar N, Singh B & Panigrahi B K, A rapid circle centre-line concept-based MPPT algorithm for solar photovoltaic energy conversion systems, *IEEE Trans on Circ and Sys I: Regular Papers*, **68(2)** **(**2021) 940–949.

16 Koad R B A, Zobaa A F & El-Shah A, A Novel MPPT algorithm based on particle swarm optimization for photovoltaic systems, *IEEE Trans on Sust Ener*, **8(2)** **(**2017) 468–476, doi: 10.1109/TSTE.2016.2606421.

17 Lin W, Hong C & Chen C, Neural-network-based MPPT control of a stand-alone hybrid power generation system, *IEEE Trans on Power Electronics*, **26(12)** (2011) 3571–3581, doi: 10.1109/TPEL.2011.2161775.

18 Mohanty A & Rout B, Modified P&O MPPT boost converter and voltage control inverter based island solar PV with power quality analysis under the varying load and changing weather condition, *IEEE Int Symp Sust Energy Sign Process Cyber Secur* (Gunupur Odisha, India) 2020, 1–6, doi: 10.1109/iSSSC50941.2020.9358852.