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Design of a maximum power point tracking-based PID controller for DC converter of stand-alone PV system

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Abstract

Stand-alone photovoltaic system (PV) produces a variance in the output voltage under variable irradiation and temperature, and variable load conditions, resulting in control challenges. The research scope is to maintain a constant output load voltage despite variations in input voltage or load. The use of a DC converter ensures that the output voltage of such systems remains constant regardless of changes in the production voltage and load. The control on a DC boost converter is employed to solve this problem. This paper presents the design of a maximum power point tracking-based (MPPT) DC converter controller for such a system. The MPPT-based PID has been proposed as a control approach and implemented to the system DC converter. Incremental Conductance (IC) algorithm has been employed as an MPPT in association with an optimized PID. The Particle Swarm optimization technique (PSO) has been used to optimize the proposed PID through selected cost function. The PV system with the loaded converter is modeled and simulated using the MATLAB/Simulink environment. The system performance is displayed using a family of curves under different operating conditions and disturbances.

Keywords: PV system, Stand-alone PV systems, DC–DC converter, Boost converters, MPPT algorithms, IC algorithm, PID optimization

Introduction

Recently, academics have focused on renewable energy assets such as wind turbines and solar panels to reduce the use of fossil fuels, which are the primary source of ecological natural contaminations. One of the most significant challenges in the creation of wind and solar energy is that, due to the stochastic nature of wind speeds and solar radiation, they usually include uncertainty. In this regard, the current uncertainty surrounding assets such as wind and solar units makes it important to evaluate the distribution system's arranging strategy to ensure a reliable execution. PV module power generation is primarily determined by solar irradiation, ambient temperature, and module characteristics [1].

Solar energy which can be directly generated from sun using photovoltaic (PV) installations is powerful enough to replace the need of conventional electricity sources, especially in urban or islanded areas. Such stand-alone energy sources operate under uneven lighting conditions. They represent the most conventional systems that produce a variance in the output voltage under variable irradiation and temperature, and also variable load conditions, resulting in control challenges. To achieve the peak efficiency, each PV array is connected in series through a DC–DC converter that performs per-array distributed maximum power point tracking [2].

A great attention has been paid to the control and robustness of the PV systems due to the change in either temperature, irradiation or even the connected load. Maximum Power Point Tracking (MPPT) has been used to improve and ensure that such systems are more efficient. PID controller for the DC converter of the stand-alone PV systems based on Maximum Power Point Tracking (MPPT) has been suggested in the literature. Mirza Fuad Adnan has presented in [3], the design and simulation of a DC–DC boost converter with PID controller to enhance the overall performance of the system. Their main aim was to achieve better conversion efficiency, minimizing the harmonic distortion and improving power factor while keeping size and cost of the converter within acceptable range. A PID controller has been applied to the boost converter achieving an improved voltage regulation considering only the variable irradiation and temperature. More research work has been introduced in the literature [4–7] discussing the same concept of implementing PID controller to PV systems either in stand-alone form or when being in grid connected form.

Improved model reference adaptive control scheme with PID controller is proposed in [8] to increase the stability and reliability of adaptive control. There are two loops in this upgraded version: an inner loop and an outer loop. With a PID controller, the inner loop acts as a typical feedback loop, while the outer loop acts as an adaptive control for parameter adjustment. This proposed method outperforms the standard model reference adaptive control method [8].

The PID controller generates a signal that consists of three terms: The proportional (P) action causes a direct proportionate change in the input (manipulated variable) to the error signal. The integral (I) action causes a change in the input proportionate to the integral of error, with the primary goal of removing offset. The derivative (D) action, on the other hand, is employed to speed up the reaction or to stabilize the system, and it produces a change in the input proportionate to the error signal's derivative [9].

In [10], simulations show that the FOPID controller outperforms the PID controller in terms of performance, but the PID controller outperforms the FOPID controller in terms of position tracking under disturbance [10].

In this paper, an optimal PID (OPID) and an MPPT-based PID controllers are designed to control the boost converter of a stand-alone PV system. This is the novelty in this work. Eberhart and Kennedy proposed PSO, a population-based stochastic search technique. The original inspiration for the PSO algorithm came from a concept of community behavior in animals like fish schooling and bird gathering. When birds or insects look for food or migrate in the search space, it is based on communication of individual knowledge and natural learning. The popularity of PSO in recent decades has been attributed to its simple structure and the fact that it just requires a few parameters to change the algorithm [11].

Performance of the two controllers in the presence of different operating points and disturbances is compared by carrying out simulation using the MATLAB/Simulink environment and displaying the system performance using a family of curves for the purpose of validating the proposed controllers.

The major contributions made by this research article are as follows:

1. MPPT-based PID controller for a DC–DC boost converter control scheme is formulated for a stand-alone PV system connected to a resistive load, using IC for real-time estimation of the MPP during the PV system operation.
2. The proposed control scheme has been figured out in such a way that it should be simple to understand and easy to implement.
3. Through PID controller, the MPPT is guaranteed with a superior performance to the proposed system and conventional PID and IC based MPPT techniques.

The system modeling

System modeling is perhaps an important phase in addition to the other forms of system control design work. The system model depends on the aims of the simulation. If the objective is to predict the behavior of a system before it is built, a good system model should support the designer with important information about the system dynamics, and so on. Because of the difficulty involved in solving nonlinear equations, all the governing equations will be put together in block diagram form and then simulated using MATLAB's Simulink environment. Simulink will solve these nonlinear equations numerically and provide a simulated response of the system dynamics [12]. The proposed system under study comprises a PV array, boost converter, an MPPT-based PID and PWM controller in addition to a resistive DC load. The model for each of the system elements is derived as follows:

PV system model

Figure 1 displays the stand-alone PV system to be considered in this work. The operation of the proposed system should operate at the strategies of: maximum power point operation, boosting the voltage of the PV array to the desired level of the load voltage, battery backup units with charge regulators and load matching.

Figure 2 displays the complete electrical equivalent circuit for PV cells which can be represented by two equations as:

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

$$V_{pv} = \frac{AkT_c}{e}\ln\left(\frac{I_{ph} + I_o - I_{pv}}{I_o}\right) - R_s I_{pv} \tag{2}$$

Based on Eqs. (1) and (2), the MATLAB Simulink block for the PV array has been considered in the system modeling by setting the array parameters in accordance with the selected data given in Appendix A. Figure 3 displays the I–V and P–V characteristics of the module and the array of the considered PV system.

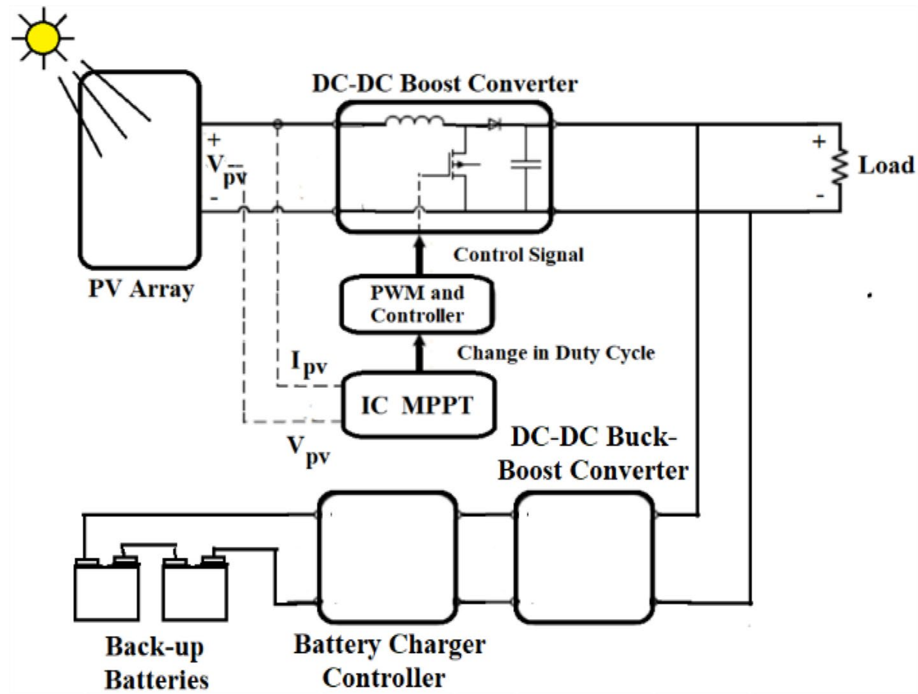


Fig. 1 Proposed PV stand-alone system with its load

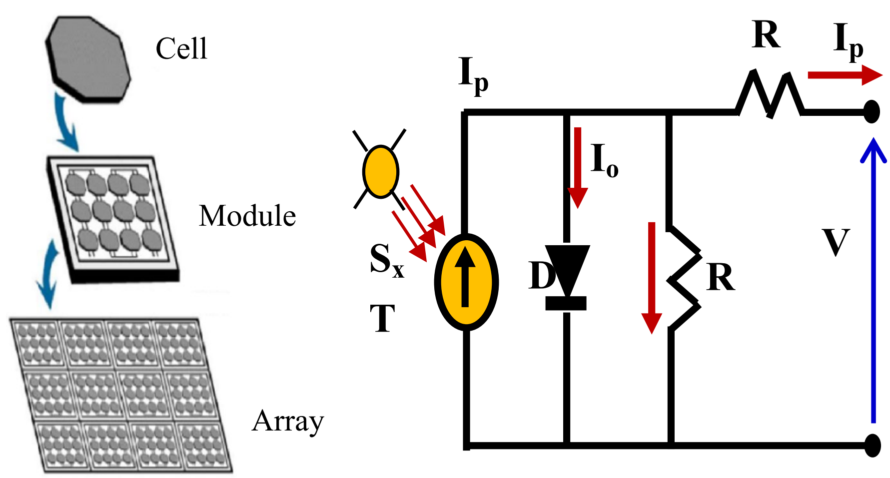
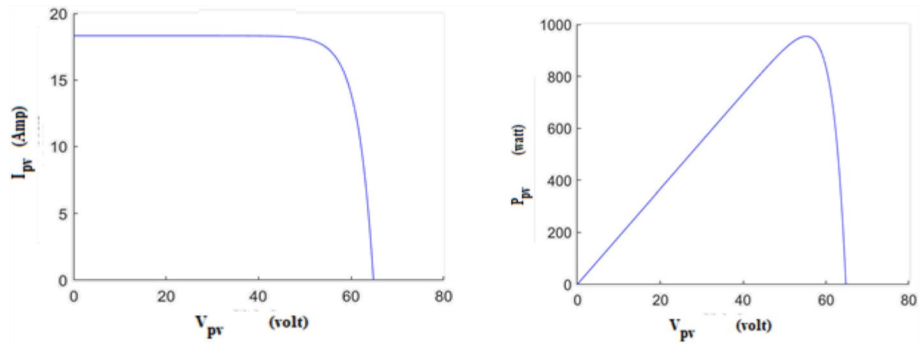


Fig. 2 Electrical equivalent circuit for PV cells

Boost converter model

The boost converter of Fig. 4 with a switching period of **T** and a duty cycle of **D** is considered as a part of the proposed stand-alone PV system. Assuming continuous conduction mode of operation, the state space equations when the main switch is ON are given by Eq. (3), [13].



(a) Array I-V characteristics (b) Array P-V characteristics

Fig. 3 PV module characteristics for Ns = 36 and Np = 1 and array characteristics for Nss = 3 and Npp = 2

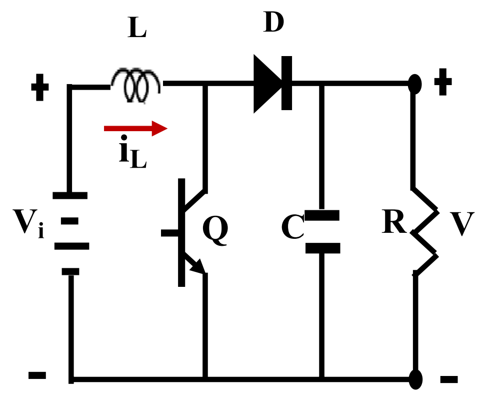


Fig. 4 Conventional boost converter

$$\begin{cases} \frac{\mathrm{d}i_L}{\mathrm{d}t} = \frac{1}{L}(V_{\mathrm{in}}) \\ \frac{\mathrm{d}v_0}{\mathrm{d}t} = \frac{1}{C}\left(-\frac{v_0}{R}\right) \end{cases}, \quad 0 < t < \mathrm{d}T,\ \underline{Q}:\ \mathrm{ON} \tag{3}$$

and when the switch is OFF are shown by Eq. (4):

$$\begin{cases} \frac{\mathrm{d}i_L}{\mathrm{d}t} = \frac{1}{L}(V_{\mathrm{in}} - V_{\mathrm{o}}) \\ \frac{\mathrm{d}v_0}{\mathrm{d}t} = \frac{1}{C}\left(i_L - \frac{v_0}{R}\right) \end{cases}, \quad \mathrm{d}T < t < T,\ \underline{Q}:\ \mathrm{OFF} \tag{4}$$

Figure 5 illustrates Eqs. (3) and (4) in MATLAB Simulink using a simulated boost converter circuit with a control signal applied to the gate of the switching element in order to get the desired switching operation of the converter and obtain the states $i_L(t)$ and $v_o(t)$ [14–16].

Maximum power point tracking (MPPT) algorithms

Maximum power point tracking MPPT is used in PV systems to maximize the output power of photovoltaic cells. MPPT can be achieved through the implementation of an electronic circuit, programmed algorithm, or it may be simulated in MATLAB Simulink

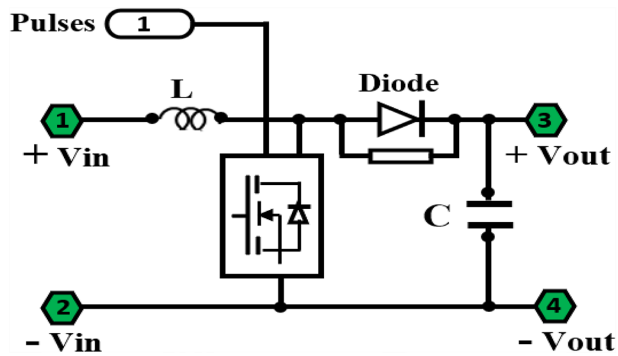


Fig. 5 Simulink model of the boost converter

environment. It varies the electrical operating point of the modules so that they are able to deliver maximum power [17]. Several algorithms for MPPT are proposed and introduced in the literature including: perturb and observe, open circuit voltage, short circuit current, incremental conductance algorithms, in addition to the neural networks and fuzzy logic [17]. The selection of the algorithm depends on the complexity of system and the time taken to track the maximum power point. In this work, the proposed method to track the maximum power for the stand-alone PV system is the incremental conductance **IC** algorithm using MATLAB/Simulink.

Incremental conductance algorithm

In this algorithm, it is needed to apply two voltages sensor and two current sensors for sensing both the output voltage and current of the PV array. The maximum power point is achieved when the slope of the P–V curve has a value of zero, this can be explained as:

$$\left(\frac{\mathrm{d}P}{\mathrm{d}V}\right)_{\mathrm{MPP}} = \mathrm{d}(VI)/\mathrm{d}V \tag{5}$$

$$0 = I + V\left(\frac{\mathrm{d}I}{\mathrm{d}v}\right)_{\mathrm{MPP}} \quad \text{or} \quad \left(\frac{\mathrm{d}I}{\mathrm{d}v}\right)_{\mathrm{MPP}} = -\frac{I}{V} \tag{6}$$

The Flow chart of the incremental conductance MPPT algorithm is displayed in Fig 6, [18].

MPPT-based PID controller

In most of the applications, it is needed to maintain the output voltage of converter as constant regardless the changes in the load or input voltage. The DC–DC power converters are sited in middle stage of most of electrical power systems; their input is connected to solar cells, and output is connected to the load. Both input and output sides are prone to sudden changes in values, slow transient response increase losses in the system and leads to reduction in efficiency.

Several methods have been proposed by researchers to control output voltage of DC–DC converters. This paper proposes an MPPT-based PID controller to be implemented to the converter as described in Figs. 7 and 8.

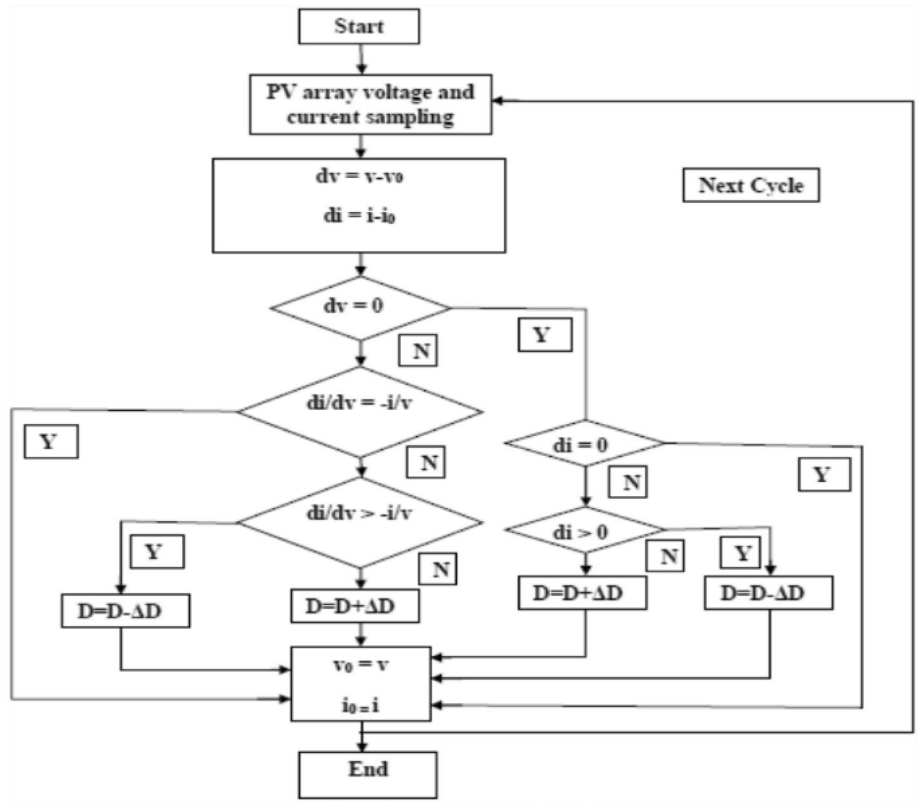


Fig. 6 Incremental conductance MPPT flowchart

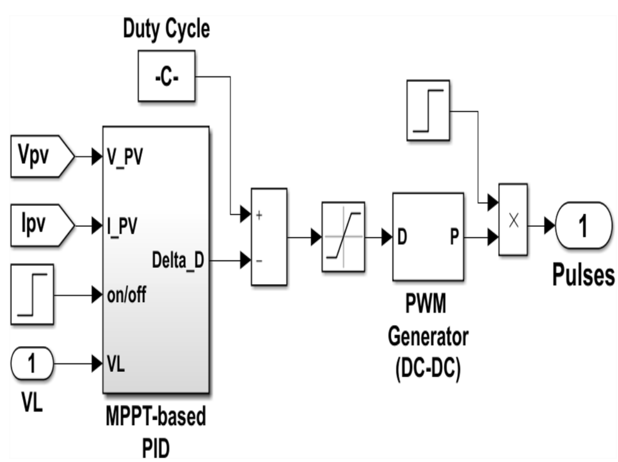


Fig. 7 MPPT-based PID controller block diagram

Nowadays, the PID controller is the most widely used, it is used to optimize the system performance like the stability, the voltage regulation, rapidity and the precision. The proposed PID controller is illustrated in Fig. 9 [19]. The PID tuning and optimization can be carried out by many algorithms Genetic, Ant Colony, Particle Swarm, Harmony, and other algorithms presented in the literature [20]. In this work,

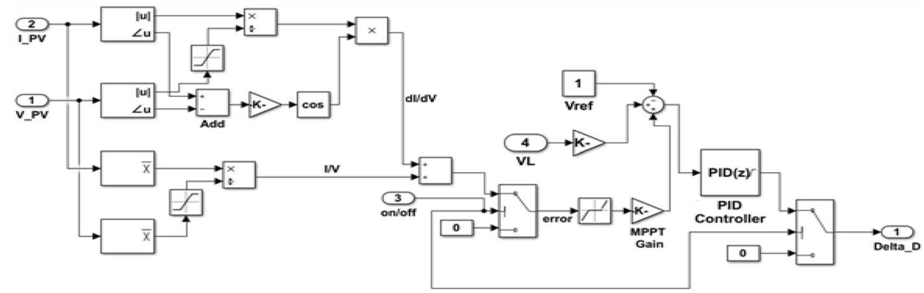


Fig. 8 MPPT-based PID Simulink blocks

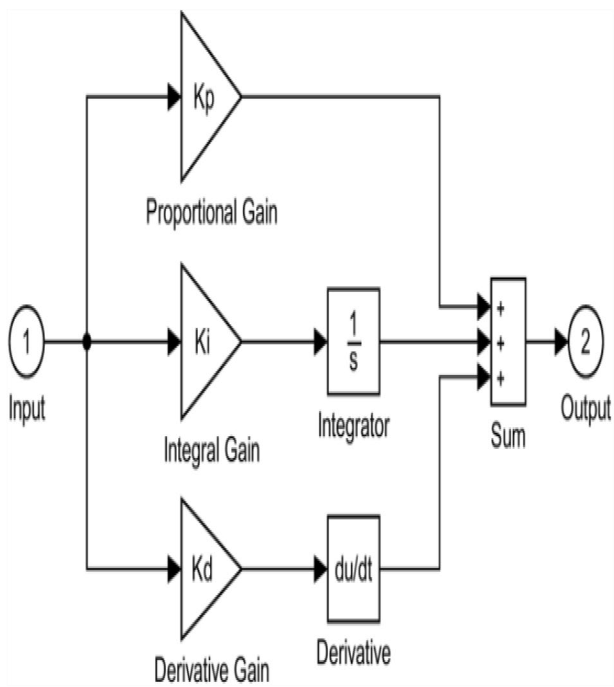


Fig. 9 PID controller Simulink blocks

the Particle Swarm Optimization (PSO) has been employed to get the gains of the optimal PID (OPID) and the MPPT-based PID proposed controllers. Figure 10 represents the flowchart of PSO algorithm [21].

The PID controller can be described as illustrated in Eq. (7) [22]:

$$
\begin{aligned}
u(t) &= K_t e(t) + K_i \int_0^t e(t)\mathrm{d}t + K_d \frac{\mathrm{d}}{\mathrm{d}t} e(t) \text{ or} \\
u(s) &= K_t E(S) + K_i \frac{E(S)}{D} + K_d \cdot sE(s)
\end{aligned}
\tag{7}
$$

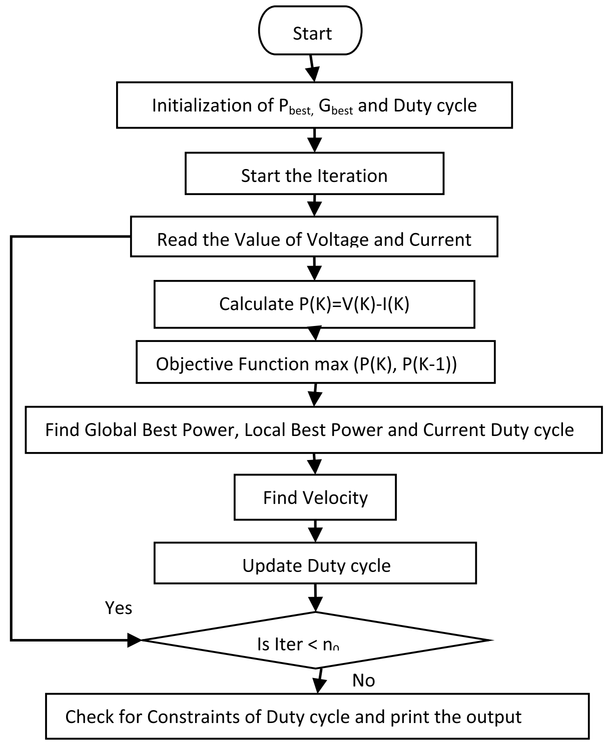


Fig. 10 Flowchart of PSO algorithm

The parameters of OPID and MPPT-based PID controllers have been designed and optimized using the PSO technique with the objective function that is chosen to be the Integral Time Square Error (ITSE) which can be defined as in Eq. (8) to minimize the squared error:

$$\text{ITSE} = \int t \cdot e^2 \mathrm{d}t \tag{8}$$

In addition, among the evolutionary computation, the updated velocity and position for each particle in the swarm can be calculated using the current velocity and the distance from the particle best solution $\mathbf{p}_{\mathbf{besti}}$ and the global best solution $\mathbf{g}_{\mathbf{besti}}$ by employing Eqs. (9) and (10) [23, 24]:

$$v_i^{k+1} = w * v_i^k + c_1 * rand_1 * \left(x_{pbesti}^k - x_i^k\right) + c_1 * rand_1 * \left(x_{gbesti}^k - x_i^k\right) \tag{9}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{10}$$

Initialization parameters used for PSO are: population size = 30, maximum number of iterations = 2000, minimum and maximum velocities are 0 and 2, cognitive and social acceleration coefficient C1 = 2, C2 = 1.4, minimum and maximum inertia weights are 0.6 and 0.9.

Results and discussion

Maximum power point tracking-based PID controller for DC converter of stand-alone PV system is employed to maintain a constant output voltage despite variations in load and input voltage due to the variable of irradiation and temperature. With the parameters of the OPID and MPPT-based PID controllers have been designed using PSO technique and the above-mentioned objective function, the proposed system simulation has been carried out using MatLabR2017b. The parameters of the PV array model are given in the appendix. Figure 11 displays the Simulink model for the system under study. To validate the effectiveness of the proposed controllers, the system has been tested and disturbed under three case studies:

- Running the system under constant converter input voltage, i.e., constant temperature and irradiance for the PV array.
- Running the system under variable converter input voltage, i.e., variable temperature and irradiance for the PV array.
- Running the system under load change disturbance.

For each case study, the converter output voltage, current and power responses are displayed in the form of families of curves for the purpose of validation the proposed controllers under the above-mentioned condition as elaborated in the following:

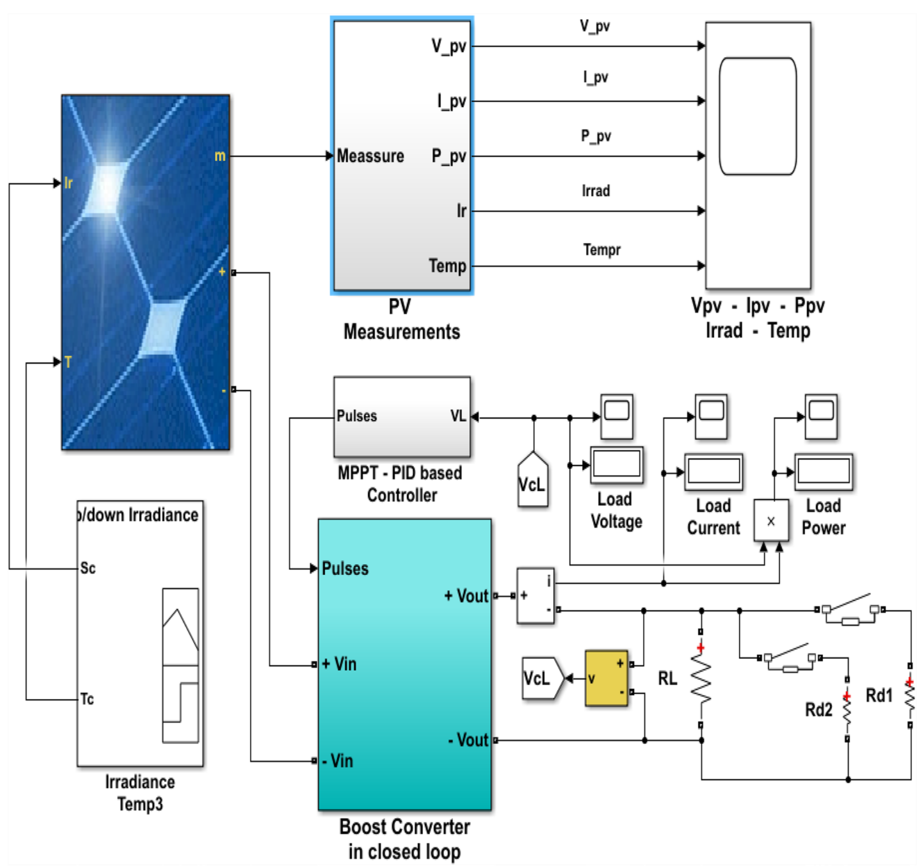


Fig. 11 Simulink model for the stand-alone PV system with MPPT-based PID controller

Simulation of the PV system with MPPT-based PID controller under constant input voltage

In this case, the PV stand-alone system has been considered to be running under constant converter input voltage, i.e., constant temperature and irradiance for the PV array. The responses of the converter output voltage, current, and power responses associated with this case are displayed in Fig. 12b–d. From these responses, it is clear that MPPT-based controller succeeded in reducing overshoot and minimizing the settling time.

Simulation of the PV system with MPPT-based PID controller under variable input voltage

In this case, the PV stand-alone system has been considered to be running under variable converter input voltage, i.e., variable temperature and irradiance for the PV array as shown in Fig. 13a. The responses of the converter output voltage, current and power responses associated with this case are displayed in Fig. 13b–d. From these responses, it is clear that MPPT-based controller succeeded in reducing overshoot and minimizing the settling time.

Simulation of the PV system with MPPT-based PID controller under load change disturbance

In this case, the PV stand-alone system has been considered to be running under a load change disturbance, where the load current and power have been increased in two steps by adding a parallel load to the main system load using two C. Bs as shown in Fig. 14a. The responses of the converter output voltage, current and power responses associated with this case are displayed in Fig. 14b–d. From these responses, it is clear that MPPT-based controller succeeded in reducing overshoot and minimizing the settling time.

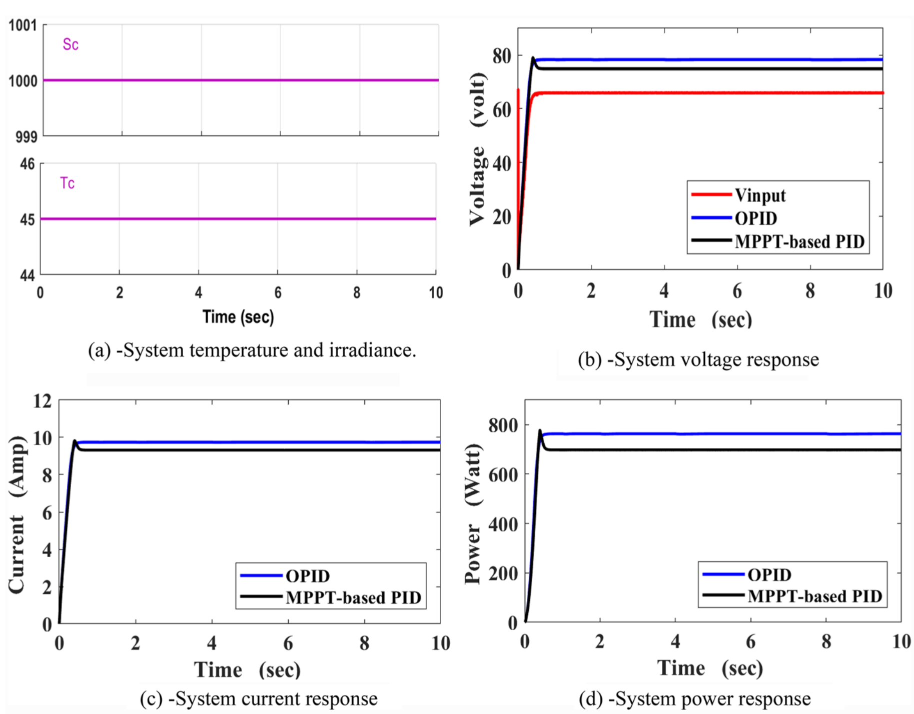


Fig. 12 The system responses associated with the system running under constant converter input voltage (constant array temperature and irradiance)

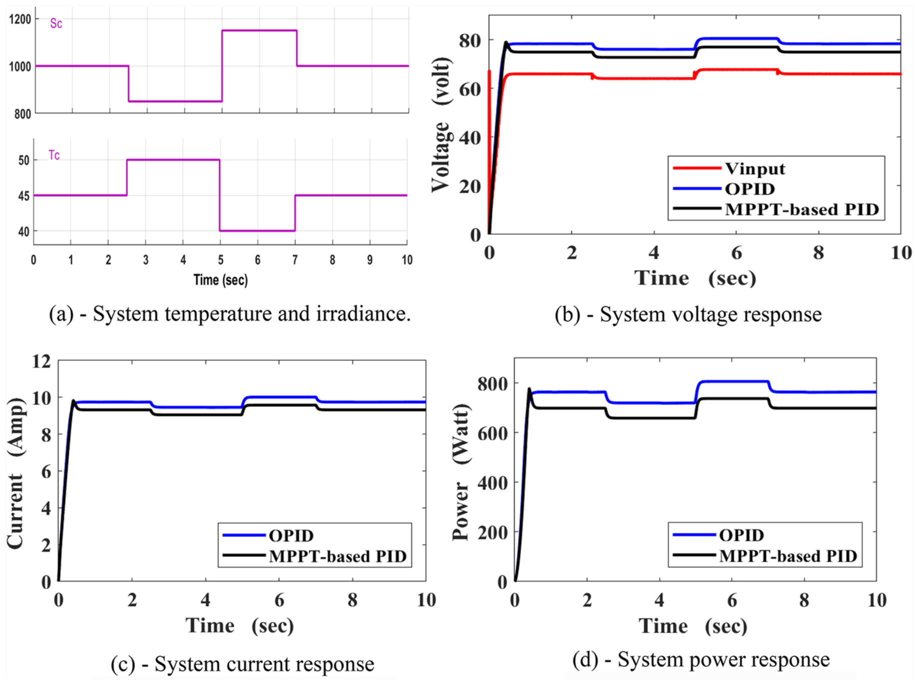


Fig. 13 The system responses associated with the system running under variable converter input voltage (variable array temperature and irradiance)

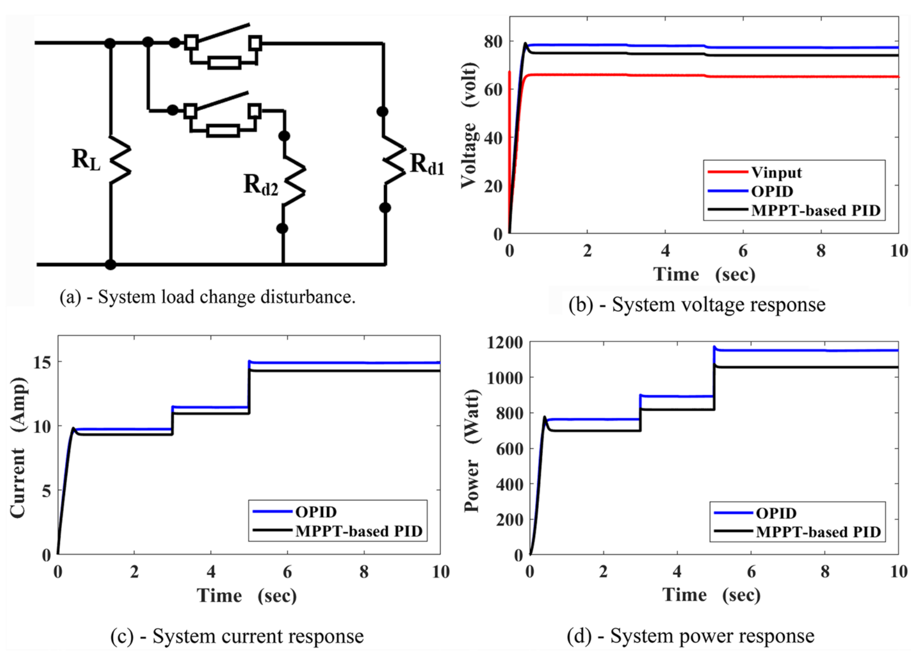


Fig. 14 The system responses associated with the system running under load change disturbance

Conclusion

One of the most promising sources of electricity is renewable green energy. It is a free source that does not have a reserve amount. Aside from other renewable green energy sources, photovoltaic solar energy is another major option for reducing emissions. PV solar cells are a versatile energy source since they can be deployed practically everywhere there is sunlight.

The novelty of this paper is to present a design of an MPPT-based PID controller for a DC–DC boost converter control of a stand-alone PV system to maintain a constant output voltage at different disturbances. Incremental conductance MPPT and Particle Swarm Optimization algorithms have been used. The results illustrated that the voltage, current and power system responses with the proposed controller under different disturbances had less overshoot, lower steady state error, and smaller settling time compared with optimized PID controller noticing that the results were obtained by using the same optimization technique for the two controllers. The effectiveness of the proposed controller has been tested by implementing different disturbances including variable temperature, variable irradiation, and load change disturbances.

Scope of future

Future research directions could include the following:

- Designing of Fuzzy controller and Fuzzy PID controller.
- Under partial shading conditions, compare the proposed control strategies to alternative MPPT algorithms (PSC).

Appendix: Selected PV module to supply the practical system

Model	100 WPV module
Maximum power (Wp)	100 Wp
Maximum power voltage (V)	18
Maximum power current (A)	5.55
Open circuit voltage (V)	21.6
Short circuit current (A)	6.11
Number of series cells (Ns)	36
Number of parallel cells (Np)	1
Temperature coefficients of Isc (%)	+0.002/℃
Temperature coefficients of Voc (%)	−0.2355/℃
Cell series resistance Rs (Ω)	0.0001
Cell shunt resistance Rsh (Ω)	1000
Temperature Range	− 40°℃ to +80°℃
Standard Test Conditions	1000 w/m^2 AM1.5 25°℃

To form an array by specifications of: 800 W—75 V, it is needed to have Nss = 3 and Npp = 2.

Abbreviations

PV: Photovoltaic; MPPT: Maximum power point tracking-based; IC: Incremental Conductance; PSO: Particle Swarm optimization technique; OPID: Optimal PID; T: Switching period; D: Duty cycle; ITSE: Integral Time Square Error; $\mathbf{p}_{\mathbf{besti}}$: Particle best solution; $\mathbf{g}_{\mathbf{besti}}$: Global best solution; C1: Cognitive coefficient; C2: Social acceleration coefficient.

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Author contributions

FAM made the initial preparations for writing the research and doing the Simulink of model. MEB made adjustments in writing, correcting it, and reducing the citation rate, the final results of Simulink of model were produced. SS and SM did the final review. All authors read and approved the final manuscript.

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Ethical approval and consent to participate

I agree.

Consent for publication

I agree.

Competing interests

The authors declare that they have no competing interests.

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References

1. Ansari MM, Guo C, Shaikh M, Chopra N, Yang B, Pan J, Zhu Y, Huang X (2020) Considering the uncertainty of hydrothermal wind and solar-based DG. Alex Eng J 59:4211–4236
2. Ali HG, Arbos RV (2020) Chattering free adaptive sliding mode controller for photovoltaic panels with maximum power point tracking. Energies 13:5678
3. Adnan MF, Oninda MAM, Nishat MM, Islam N (2017) Design and simulation of a DC–DC boost converter with PID controller for enhanced performance. Int J Eng Res Technol (IJERT). https://doi.org/10.1757/IJERTV6IS090029
4. Dwivedi LK, Sake RK (2017) Improve efficiency of Photovoltaic (PV) system based by PID controller. Int Res J Eng Technol (IRJET) 4(5):2273–2277
5. Deveci O, Kasnakoğlu C (2015) Control of a Photovoltaic system operating at maximum power point and constant output voltage under different atmospheric conditions. Int J Comput Electr Eng 7(4):240–247
6. Guerrero-Ramire E, Martinez-Barbosa A, Contreras-Orda MA, Guerrero-Ramire G (2020) FPGA-based active disturbance rejection control and maximum power point tracking for a Photovoltaic system. Int Trans Electr Energ Syst 30:e12398
7. Abdel rassoul R, Ali Y, Zaghloul MS (2016) Genetic algorithm-optimized PID controller for better performance of PV system. In: World Symposium on Computer Applications & Research (WSCAR)
8. Rajesh R, Hari Krishnan P (2018) Effects of adaption gain in direct model reference adaptive control for a single conical tank system. Int J Digit Signal Process 10(5):77–82
9. Rajesh R, Baranilingasen I (2017) Modeling and analysis of different tuning methodologies of PID controller for a linearly parameterized non-linear system. IJSART 3(5):615–620
10. Ramakrishnan R, Nachimuthu DS (2021) Design of state feedback LQR based dual mode fractional-order PID controller using inertia weighted PSO algorithm: for control of an under actuated system. J Inst Eng India Ser C 102(6):1403–1417
11. Rajesh R, Deepa SN (2020) Design of direct MRAC augmented with 2 DoF PIDD controller: An application to speed control of a servo plant. J King Saud Univ Eng Sci 32:310–320
12. Sigalo MB, Osikibo LT (2016) Design and simulation of DC–DC voltage converters using MATLAB/Simulink. Am J Eng Res (AJER) 5(2):229–236
13. Mahdavi J, Emadi A, Toliyat HA (1997) Application of state space averaging method to sliding mode control of PWM DC/DC converters. IEEE Industry Applications Society
14. Pires VF, Silva JFA (2002) Teaching nonlinear modeling, simulation, and control of electronic power converters using MATLAB/SIMULINK. IEEE Trans Educ 45(3):253–261
15. Su J-H, Chen J-J, Wu D-S (2002) Learning feedback controller design of switching converters via MATLAB/SIMULINK. IEEE Trans Educ 45(4):307–315
16. Logue D, Krein PT (2000) Simulation of electric machinery and power electronics interfacing using MATLAB/SIMULINK. In: 7th Workshop Computer in Power Electronics, pp 34–39

17. Kumar R, Choudhary A, Koundal G, Singh A, Yadav A (2017) Modelling/simulation of MPPT techniques for Photovoltaic systems using MATLAB. Int J Adv Res Comput Sci Softw Eng. https://doi.org/10.23956/ijarcsse/V7I4/0129
18. Visweswara K (2013) An investigation of incremental conductance based maximum power point tracking for Photovoltaic system. Energy Procedia. https://doi.org/10.1016/j.egypro.2014.07.245
19. Rebhi M (2013) Comparative study of MPPT controllers for PV system implemented in the South-west of Algeria. Energy Procedia 36:142–153
20. Nagaraj B, Murugananth N (2010) A comparative study of PID controller tuning using GA, EP, PSO and ACO. In: International conference on communication control and computing technologies
21. Kalaiarasi N, Dash SS, Padmanaban S, Paramasivam S, Morati PK (2018) Maximum power point tracking implementation by Dspace controller integrated through Z-source inverter using particle swarm optimization technique for Photovoltaic applications. Appl Sci 8:145
22. Mahammad AK (2013) Development of optimum controller based on MPPT for Photovoltaic system during shading condition. Procedia Eng 53:337–346
23. Kathpal S, Vohra R, Singh J, Sawhney RS (2012) Hybrid PSO–SA algorithm for achieving partitioning optimization in various network applications. Procedia Eng 38:1728–1734
24. Khunkitti S, Watson NR, Chatthaworn R (2019) An improved DA-PSO optimization approach for unit commitment problem. Energies 12:2335

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