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ELECTRICAL & ELECTRONIC ENGINEERING | RESEARCH ARTICLE

Selection criteria of dc-dc converter and control variable for MPPT of PV system utilized in heating and cooking applications

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Abstract: This paper deals with the selection of dc-dc converter and control variable required to track the maximum power of photovoltaic (PV) array, to optimize the utilization of solar power. To reduce the maintenance cost and to simplify the model, the battery has not been used in the proposed PV system mainly used for cooking and heating applications. Since the battery has not been used, selection of dc-dc converter is an important consideration of the PV system in standalone applications. In the proposed system converter is selected based on maximum power transfer theorem which is dependent on load resistance. Different load resistance is considered for maximum power point tracking (MPPT) with different converter topologies, and it has been observed that buck-boost converter is suitable for any load resistance connected in the PV system. An effort has been taken to suitably choosing the control variable which is the output signal of the maximum power point (MPP) tracker. Control variable which is dependent on inputs of MPP tracker is decided based on the stability of the system. Two MPP trackers are designed based on neural-network (NN) controller and perturb and observe (P&O) algorithm. The tracking capabilities of

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PUBLIC INTEREST STATEMENT

In this paper, PV panel is utilized as a source of electrical energy for heating and cooking applications. For making the system cost effective and simple, the battery has not been used in the system. Since the battery has not been used, the selection of dc-dc converter for maximum power point tracking (MPPT) is an important consideration. The detailed mathematical analysis is provided based on maximum power transfer theorem for selecting the dc-dc converter. From the analysis, it is clear that a buck-boost converter is suitable for tracking maximum power for any load resistance connected to the PV system. Considering voltage at MPP (VMMP) and current at MPP (IMMP) as the control variable, two MPPTs are designed based on neural-network (NN) controller and perturb and observe (P&O) algorithm. From the obtained results it is clear that NN controller can track the MPP for both VMPP and IMMP as the control variable, but P&O algorithm fails to track the MPP considering VMPP as the control variable.

both NN controller and the P&O algorithm is compared with the variation of irradiation and found that tracking capability of NN controller is better than P&O method. The system is simulated using MATLAB/Simulink environment, and the results show that NN controller tracks MPP at a faster rate with reduced oscillation.

Subjects: Power & Energy; Renewable Energy; Power Electronics; Power Engineering

Keywords: photovoltaic power system; dc-dc converter; maximum power point tracking (MPPT); perturb and observe (P&O); neural network (NN)

1. Introduction

Out of the total daily energy requirement of a household, about 7% of energy is required for cooking and heating purposes. Fossil fuels have been the primary source of energy for cooking and heating. But fossil fuels are the major source of gaseous pollutants for the environment (Singh, Gupta, Kumar, & Kulshrestha, 2014). To avoid global warming, uses of fossil fuels must be reduced, and renewable energy resources must be utilized to a great extent (Zahnd & Mckay, 2009). Photovoltaic (PV) power generation system is the best alternative solution to meet the energy demand, because of its free availability and clean production (Panwar, Kaushik, & Kothari, 2011). There are two ways to use the solar energy for heating i.e. (i) Direct heating and (ii) Indirect heating. Direct heating requires the radiator to absorb the solar energy falling on it and are used for heating and cooking purposes. The best example is the solar cooker (Joshi & Jani, 2015; Panwar et al., 2011; Singh et al., 2014; Soria-Verdugo, 2015). The indirect method uses PV array for converting the solar energy into electrical energy, which can be utilized for any heating and cooking applications. The indirect method is expected to play an important role for cooking and heating application in the near future because the cost of the PV module is decreasing day by day and its efficiency is increasing. A major problem of the photovoltaic system is that its power output is not constant and fluctuates with weather conditions. To meet the constant voltage demand by the load and to manage the flow of power, the storage device like a battery can be used across the load (Chiang, Chang, & Yen, 1998; Gules et al., 2008; Koutroulis & Kalaitzakis, 2004). The functions of the battery are:

- To keep the voltage across the load constant.
- Depending on the availability of maximum power of PV, battery absorbs or discharges the power to keep the power demand by the load constant.

The additional cost of the battery, maintenance thereof and the concern of environment while disposing of are the major barrier to market the cooking PV module. However, for the heating purpose (mainly household cooking), the variation of the maximum power of solar array due to change of irradiation (*G*) and temperature (*T*) will not affect the efficiency and reliability of the system too much. Hence for cooking purposes, the solar power can be used without a battery. However, to harvest maximum solar power, PV panel must be operated at its maximum power point (MPP) with the help of a suitable MPP tracker (Esram & Chapman, 2007; Ishaque & Salam, 2013; Mohapatra, Nayak, Das, & Barada, 2017; Mohapatra, Nayak, & Mohanty, 2014; Salas, Olías, Barrado, & Lázaro, 2006). This requires selection of dc-dc converter, which is interfaced between the PV panel and heating load (Villalva, de Siqueira, & Ruppert, 2010). The duty ratio of the converter can be controlled in such a way that the input voltage of the converter must be equal to the voltage at maximum power point (V_{MPP}), which changes with a change of irradiation and temperature. To achieve the V_{MPP} point and to track the maximum power, the PV panel internal resistance at MPP must be equal to the equivalent load resistance (load resistance referred to an input side of the converter). Hence, the selection of dc-dc converter depends on load resistance. In standalone mode, the battery is essential for management of the power flow if the load demands a constant power. But in some application like heating and cooking where the change in the load power will not affect the reliability of the system too much. In those applications, the battery may not be used to avoid the cost, frequent maintenance

Table 1. Uses of PV panel in rural areas

Application	Power demand requirement	Battery requirement
Cooking	Constant power load is desirable but may operate at any load condition	May or may not required
Heating	Constant power load is desirable but may operate at any load condition	May or may not required
Illumination	Constant power load is essential	Must required for power management
Motor drive application (irrigation)	Constant power load is essential	Must required for power management

and environmental issues caused by battery usages. Table 1 depicts the usage of PV panel basically for rural areas for different applications.

Several studies have been carried out for exact tracking of MPP (Liu, Meng, & Liu, 2016; Rajesh & Carolin Mabel, 2015), and the control procedures are explained in detail by developing a transfer function model assuming the load voltage is fixed when the battery is incorporated across the load. The above control procedures are based on controlling the duty cycle of the converter in such a manner that the PV panel voltage must be V_{MPP} with a fixed battery voltage. Since only one parameter that is V_{MPP} or current at maximum power (I_{MPP}) is to be controlled, the control technique is simple, and stability will not be affected whether V_{MPP} or I_{MPP} is chosen as the control command.

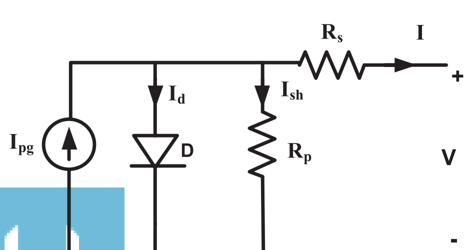
However, the control problem has not been considered earlier for tuning of maximum power point tracking (MPPT) in stand-alone mode without using the battery. The control issue is somewhat difficult if the battery has not been used across the load. In this case, both input voltage and load voltage are to be adjusted to track the V_{MPP} or I_{MPP} point. Since two parameters are to be adjusted by the controller duty cycle, the controller design should be carefully considered otherwise it may lead to instability.

There are large numbers of MPPT control techniques available till date (Rajesh & Carolin Mabel, 2015). Depending upon the inputs to MPP tracker, it can be classified as direct or indirect. In direct control MPPT, the PV voltage or current or both may be inputs to the controller. Direct control MPPT can be named as feed forward method because inputs to the model are system parameters. If inputs to the MPPT are not system parameters, but other external parameters such as irradiation and temperature, etc. then the MPPT controller is called indirect MPP tracker. Here both direct and indirect MPPT control is considered, and their performance is evaluated under varying environmental condition. The novelty of this paper is to improve the overall efficiency of heating and cooking system using a dc-dc converter with MPPT technique without using a battery. However, the capital cost of the proposed system is slightly more than the directly connected solar system used for cooking purposes as discussed in (Watkins et al., 2017). The major disadvantage of Watkins method is that its efficiency is less because MPPT has not been used, so it is difficult to extract maximum power from the solar panel at all environmental conditions.

2. Equivalent circuit model of PV module

The electrical characteristics of a single diode PV panel as shown in Figure 1 can be represented as (Villalva, Gazoli, Filho, & Ruppert, 2009):

Figure 1. PV panel equivalent circuit.



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$$I = I_{pg} - I_0\left[\exp\left(\frac{V + R_s I}{N_s V_t a}\right) - 1\right] - \frac{V + R_s I}{R_p} \tag{1}$$

where V and I are the PV panel output voltage and current respectively; I_{pg} represents the photo current; I_0 is the module saturation current. R_s represent the series resistance and appear due to contact losses, and R_p is due to leakage current loss. The quality factor of the diode is "*a*", and it represents the constituents of recombination and diffusion current. V_t is the thermal voltage of the p-n junction and N_s is the number of series cells in the panel.

If the internal parameters of the PV panel changes, then electrical characteristics of PV panel modified and it is also affected by the external parameter like temperature and solar irradiance (Mohapatra, Nayak, & Mohanty, 2016). The dependency of I_{pg}, panel voltage under open circuit condition (V_{oc}) and I_0 of the PV module on temperature and solar irradiation are represented by Equations (2)–(4) (Farivar & Asaei, 2010):

$$I_{pg} = \left[I_{pg,n} + K_I \times \mathrm{d}t\right]\frac{G}{G_n} \tag{2}$$

$$V_{oc} = V_{oc,n} + K_v \times \mathrm{d}t \tag{3}$$

$$I_0 = \frac{I_{sc,n} + K_I \times \mathrm{d}t}{\exp\left\{\frac{V_{oc,n} + K_V \times \mathrm{d}t}{N_s a V_t}\right\} - 1} \tag{4}$$

Change in temperature $\mathrm{d}t = T - T_n$ is the difference between operating temperature (T) and nominal temperature (T_n) of 25°C. K_I and K_v are temperature coefficients under short circuit and open circuit condition. The variation of current-voltage (I–V) and power-voltage (P–V) characteristics of KC200GT PV panel with change of irradiation is shown in Figure 2(a) and (b) and with temperature its variation is shown in Figures 3(a) and (b). The manufacturer electrical parameters of KC200GT PV panel at STC are given in Table 2. STC refers to temperature of 25°C and irradiation of 1,000 W/m².

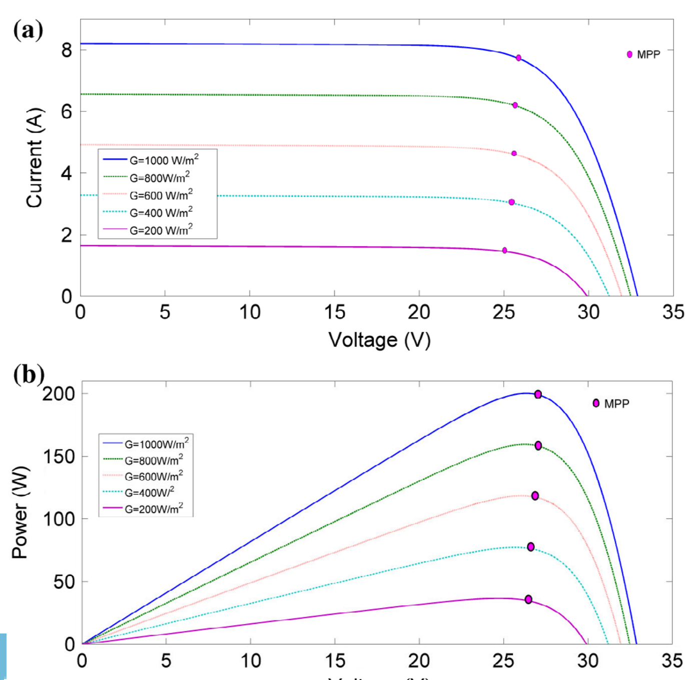

Figure 2. (a) I–V curve and (b) P–V curve of PV module at different irradiation at 25°C.

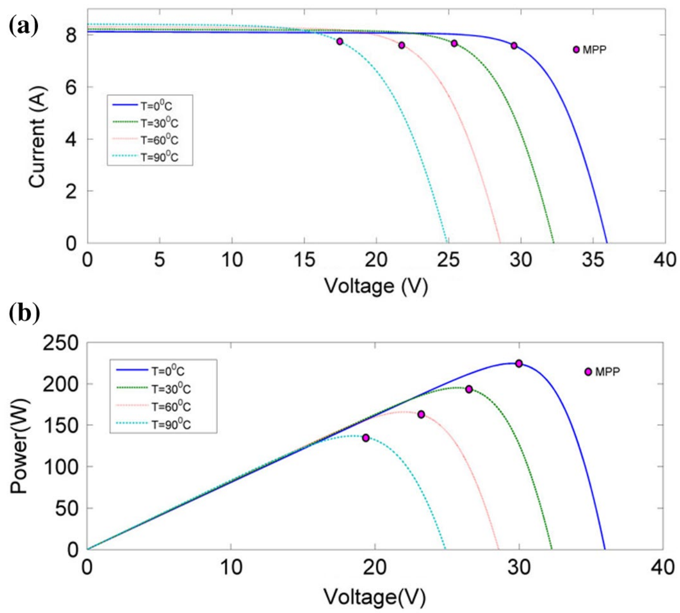

Figure 3. (a) I–V curve and (b) P–V curve of PV module at different temperature at 1,000 W/m².

Table 2. Parameters of Kyocera KC200GT PV panel at STC								
$V_{oc,n}$(V)	$I_{sc,n}$(A)	$V_{MPP,n}$(V)	$I_{MPP,n}$(A)	$P_{MPP,n}$(W)	FF	N_s	K_V(V/°K)	K_I(A/°K)
32.9	8.21	26.3	7.61	200.143	0.74	54	−0.1230	0.0032

3. Selection of dc-dc converter

Solar irradiation changes dramatically before it falls on PV array because of blocking and filtering nature of atmosphere and cloud cover. Change of irradiation with time shifts the maximum power point as shown in Figure 2(a) and (b). Besides irradiation, the variation of temperature also modifies the electrical characteristics of PV panel as shown in Figure 3(a) and (b). Irradiation varies at a faster pace as compared to temperature. Therefore, MPP tracker must be designed based on the faster dynamic behavior of irradiation in order to avoid the delay and failure in tracking of maximum power. MPPT demands the dc-dc converter in between PV array and load to keep the PV array voltage or current at MPP point for a particular condition of irradiation and temperature by controlling the duty ratio of converter (Villalva & Ruppert Filho, 2008).

3.1. Selection of dc-dc converter with battery

Selection of dc-dc converters such as buck, boost, or buck-boost converter depends on battery voltage if the battery is incorporated across the constant load. The boost converter is used to transfer the maximum available power on PV array to the load if the battery voltage (V_b) is higher than V_{MPP} in highest irradiation and lowest temperature condition. The buck converter is used when the battery voltage is lower than V_{MPP} in highest irradiation and lowest temperature condition. Buck-boost converter can be used at any level of battery voltage. Further, charging and discharging of the battery depends on the availability of maximum power of the PV panel. Table 3 presents the selection of dc-dc converter for different condition of battery voltage.

Table 3. Selection of converter with respect to battery voltage for MPPT			
Battery voltage	**Voltage at MPP**	**Condition**	**Selection of converter**
V_b	V_{MPP}	$V_b \geq V_{MPP}$	Boost
		$V_b \leq V_{MPP}$	Buck
		$V_b \geq V_{MPP}$ or $V_b \leq V_{MPP}$	Buck-Boost

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3.2. Selection of dc-dc converter without battery

Selection of dc-dc converter without battery across the load is decided using maximum power transfer theorem. For extracting maximum power from the PV panel, the equivalent load resistance referred to the input terminals of the dc-dc converter must be equal to the internal resistance of PV panel at MPP for a particular irradiation and temperature. The variation of internal resistance of KC200GT PV panel at MPP for different irradiation level with fixed temperature of 25°C is shown in Figure 4. The curve is approximately exponential decay in nature, and it has the lowest value at highest irradiation. Similarly, the variation of internal resistance of KC200GT PV panel at MPP for different temperature and fixed insolation of 1,000 W/m^2 is shown in Figure 5. It is a straight line, and internal resistance decreases with increase in temperature, but the rate of decrease is less as compared to the rate of decrease of internal resistance for the change of irradiation. This concludes that the internal resistance at MPP is lowest at highest insolation and highest temperature.

3.2.1. Buck converter

The relation between the output voltage (V_0) and input voltage (V) of a buck converter under ideal condition (without presence of parasitic elements) in steady-state can be expressed as:

$$\frac{V_0}{V} = D \tag{5}$$

According to the conservation of energy,

$$V_0 I_0 = VI$$

$$V_0 \frac{V_0}{R_L} = V \frac{V}{R_{el}} \text{ or, } \frac{V_0^2}{R_L} = \frac{V^2}{R_{el}} \tag{6}$$

Figure 4. Internal resistance of PV module at MPP at different irradiation.

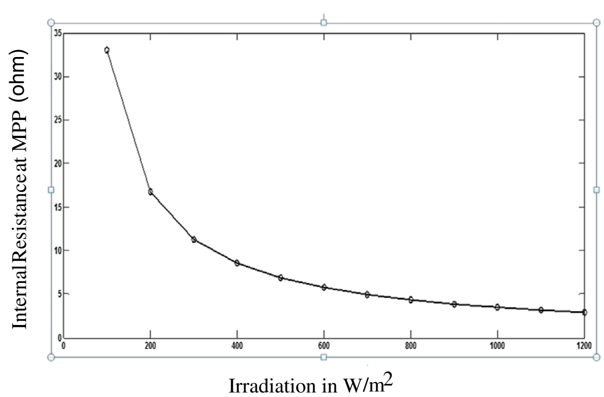
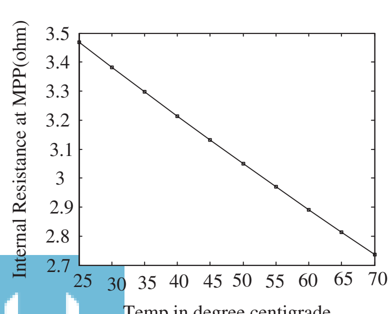


Figure 5. Internal resistance of PV module at MPP at different temperature.



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where I_0 and I are the output and input current of the converter respectively. R_L is the load resistance and R_{el} is the equivalent load resistance referred to input side of converter. From Equations (5) and (6), Equation (7) can be obtained.

$$R_{el} = \frac{R_L}{D^2} \tag{7}$$

Since the range of duty ratio D is from 0 to 1 therefore, $R_L \leq R_{el}$.

The above equation concludes that, buck converter must be used when the load resistance is less than or equal to the internal resistance of PV panel at MPP point at a particular environmental condition in order to track the maximum power. If the above condition is not fulfilled the MPPT fails to track the maximum power and tracking power at that time is the power of PV panel where the internal resistance of solar array is equal to load resistance by making duty ratio 1 (dc-dc converter is always connected to load).

3.2.2. Boost converter

The steady-state equation of boost converter under ideal condition in terms of load resistance and internal resistance can be expressed as:

$$R_{el} = R_L(1 - D)^2 \tag{8}$$

Since the range of duty ratio is from 0 to 1, therefore, $R_L \geq R_{el}$.

So, boost converter is used when the load resistance is greater than or equal to internal resistance of PV panel at MPP point at a particular environmental condition in order to track the maximum power. Like buck converter, the tracking of maximum power fails if the above condition is not satisfied and tracking power is the power of PV panel where the internal resistance of PV panel is equal to load resistance by making duty ratio 1.

3.2.3. Buck-Boost converter

Buck-boost converter is used for any load resistance to track the maximum power by maximum power point tracker. The above point can be easily explained using steady-state equation of buck-boost converter under ideal condition in terms of load resistance and internal resistance which is expressed as:

$$R_{el} = \frac{R_L(1 - D)^2}{D^2} \tag{9}$$

Equivalent load resistance at the input terminal of different dc-dc converters with respect to duty cycle for a load resistance of 1 ohm is shown in Figure 6. From the figure it is clear that for maximum power transfer from PV panel to the load is only possible if buck converter is used for MPPT control when equivalent load resistance which is equal to the internal resistance of the PV panel is greater

Figure 6. Equivalent load resistance of different types of dc-dc converter with duty ratio.

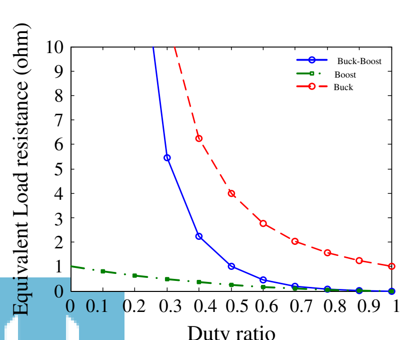


Table 4. Selection of converter based on internal resistance of PV panel for MPPT

Internal resistance of PV panel	Load resistance	Condition	Selection of converter
R_i	R_L	$R_i \le R_L$	Boost
		$R_i \ge R_L$	Buck
		$R_i \le R_L$ or $R_i \ge R_L$	Buck-Boost

than load resistance whereas boost converter is used for MPPT control when the equivalent load resistance is less than load resistance. Buck-boost converter is used to control when equivalent load resistance varies from 0 to infinity and is independent upon load resistance. Table 4 describes the selection of converter according to the relationship between load resistance and internal resistance of the PV panel.

4. Control aspects of MPPT

If the battery is incorporated in the system with battery voltage V_b, PV panel voltage V should be tracked to V_{MPP} by controlling the duty cycle of the converter. Here control of duty cycle posses one degree of freedom because V_b is fixed. It simplifies the design of control algorithms. In that case output of MPP tracker (control variable) may be current, voltage or power because all of the above parameters at MPP can represent the MPP. These variables are time variant as these are the function of insolation and temperature. The stability of the system is not dependent upon the control variable both in direct and indirect MPP tracker. So any control variables can be used to track the MPP. However, (Xiao, Dunford, Palmer, & Capel, 2007) explains the preferable control variable may be voltage compared to current and power because of following advantages.

- The voltage variation at MPP is usually bounded to 70–80% of the open circuit voltage as compared to wide range of current variation at MPP for wide change of insolation, which possess faster dynamic as compared temperature as shown in Figures 7 and 8. If current is the control variable of MPP tracker, then MPP tracker must have fast dynamic algorithm in order to match the fast dynamic of insolation. The delay of tracking response can be avoided using voltage as the control variable.

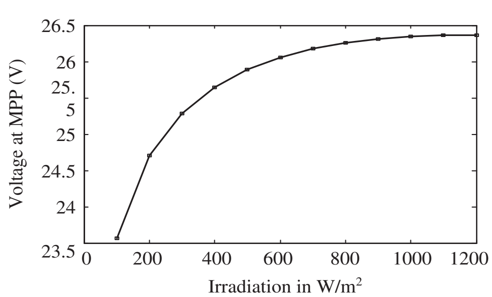


Figure 7. Variation of PV voltage at MPP with insolation.

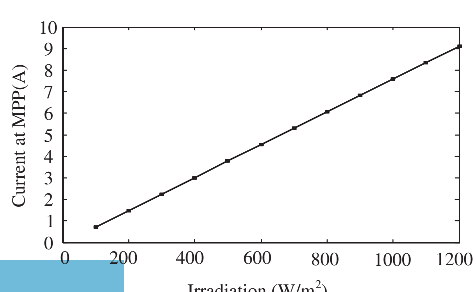


Figure 8. Variation of PV current at MPP with insolation.

- Saturation can be avoided by providing the lower and upper bound of voltage
- A good quality voltage sensor is cheaper than that of current sensor.

But unfortunately, stability analysis has not been taken into consideration before for the selection of control variable. However, it is found through simulation result that there is a failure of tracking of maximum power occurs when the voltage signal is chosen as control variable instead of current signal in direct control MPP tracker without connecting the battery in the system. The physical explanation without mathematical analysis is explained below to support the above statement. In direct control MPP tracker without battery, the duty cycle of dc-dc converter need to be regulated to fulfill the following desired conditions:

- The output signal (voltage, current or power) must be at the MPP which depends on operating condition.
- To extract the maximum power from the PV panel the equivalent load resistance must be equal to internal resistance of the PV panel at MPP.

Since, the input signals (voltage, current) of MPP tracker are the internal parameters of the solar array, the stability should be guaranteed before choosing the control variable otherwise incorrect choice may prone to instability of the system and the system will behave as if solar array connected directly to resistive load without converter and MPP tracker.

But, in the case of indirect MPP tracker, the duty ratio is controlled only to extract the maximum power from the solar array for a particular operating condition which is time variant. The output signal of MPP tracker is the mapping of input signals insolation and temperature provided by pyranometer and temperature sensor. The mapping is done through experimental datasheets. Since the input signals to MPP tracker are the external parameters, the stability guarantee is not required for choosing the control variables.

Further, when the battery is not used, the control of duty cycle possesses two degrees of freedoms because both V_0 and V are variables. In addition to that the matching of R_L and R_{el} is governed by the square of duty ratio as given in Equations (7)–(9). which is nonlinear. Therefore the control technique should be carefully considered; otherwise, the system may go to the unstable region. It has been verified that the photovoltaic current is a preferable control variable when the battery has not been used in the system because of stability and control design point of view.

- In direct MPP tracker, the stability should be guaranteed when the voltage is used as control variable because both V_0 and V are to be adjusted internally by controlling the duty ratio to track V_{MPP}. If the current is used as control variable the stability guarantee is not required as proved by simulation results. But, in indirect MPP tracker, both can be used as control variable.
- As shown in Figure 8, the variation of current at MPP due to change in insolation is linear in nature. Due to linearity, the design of control algorithm is simple as compared to voltage as control variable which has nonlinear behavior as shown in Figure 7.

5. MPPT comparison

This section provides a comparative study between direct and indirect MPP tracker. There are numerous research papers available for tracking of maximum power (Esram & Chapman, 2007). If the internal system information is used to track the MPP point, it is called direct MPP tracker. Perturb and observe method (P&O), Incremental conductance (IC), Current sweep, DC-link capacitor droop control and on- line MPP search algorithm are some of the methods of direct MPP tracker (Subudhi & Pradhan, 2013). In indirect MPP tracker, the control variable such as the voltage at MPP or current at MPP is generated from experimental knowledge based on the change of insolation and temperature. Neural Network (NN), Fractional open circuit voltage (FOCV), Fractional short circuit current (FSCI) and look-up table methods are the few methods of indirect MPP tracker. Here two mostly used P&O and NN methods have been taken for simulation study utilizing MATLAB/Simulation for comparison.

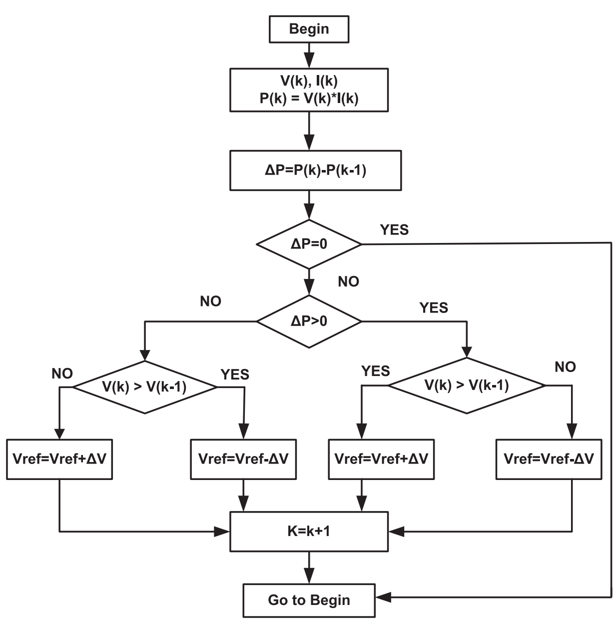
5.1. Perturb and observe method

In this method, the algorithm starts with a particular voltage and current value and corresponding power P_1 is measured. Considering small perturbation in voltage (ΔV) or duty cycle (Δd) of the dc-dc converter the new power P_2 is obtained. Then P_2 is compared with P_1 and if it is found $P_2 > P_1$ then perturbation is in the right direction, and more perturbation is given to reach the MPP. This is a simple and inexpensive technique to track maximum power from the PV panel (Abdelsalam, Massoud, Ahmed, & Enjeti, 2011; Femia, Petrone, Spagnuolo, & Vitelli, 2005; Killi & Samanta, 2015). The main drawback of this method is that it has slow tracking speed and output power oscillates around MPP. The flow chart of P&O method is shown if Figure 9. Small perturbation value reduces the oscillation, but the system becomes sluggish. To overcome this drawback artificial neural network is used to track maximum power rapidly with reduced oscillation.

5.2. Artificial neural network

Artificial neural networks have potential to construct the global approximation model for mapping of input-output nonlinear dynamic relation. This constructional property of artificial neural network can be used to generate the voltage, current, and power at MPP of PV array. In this paper, the global approximation model is constructed by considering the irradiation and temperature as input variables. The data of voltage at MPP and current at MPP are collected through model based equation of KC200GT using different insolation and temperature. The range of insolation varies from 100 to 1,200 W/m^2 with an increment of 100 W/m^2 and temperature range is from 25 to 70°C with an increase of 5°C. Therefore, the total data of voltage at MPP and current at MPP is 120 each. The data are tabulated for input–output matching using NN. The NN used for creating the approximate model has a three layer structure, i.e. input layer, hidden layer and output layer. This NN consist of two input layer for insolation and temperature, 150 hidden layers considered for accurate tracking and two output layer for generation of voltage and current at MPP depending upon insolation and

Figure 9. Flowchart of P&O algorithm.



temperature as shown in Figure 10. All neurons in the hidden layer are connected to weight, and also bias signals are coupled to all the neurons through weight. Hidden layer has a tangent sigmoid transfer function, and output layer has a pure linear transfer function. Back-propagation algorithm is used for training to adapt the weight and bias for mapping the input and output relation. This method uses a gradient descent technique to minimize the error function. The learning rate taken for training is fixed value of 0.1. For training back—propagation NN, the error goal has set to 1×10^{-5} and maximum epochs of 500. The neural network is trained using MATLAB toolbox. The unmasked simulation diagram of NN is shown in Figure 11. Error goal is met within 105 epochs as shown in Figure 12. Since the error goal is achieved it can be used for generating the voltage at MPP or current at MPP for any value of temperature and insolation (Hiyama & Kitabayashi, 1997; Lin, Hong, & Chen, 2011; Liu, Liu, Huang, & Chen, 2013).

Figure 10. Schematic diagram of the utilized neural network.

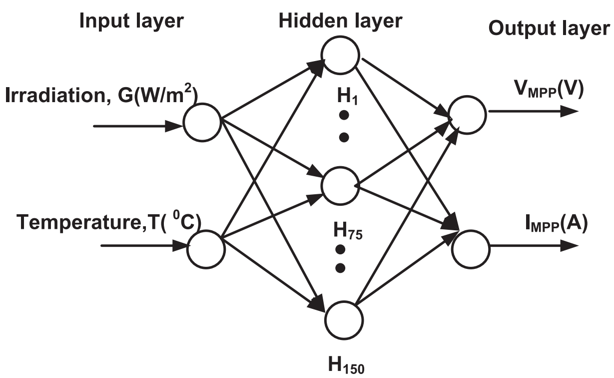


Figure 11. Unmasked simulation diagram of neural network.

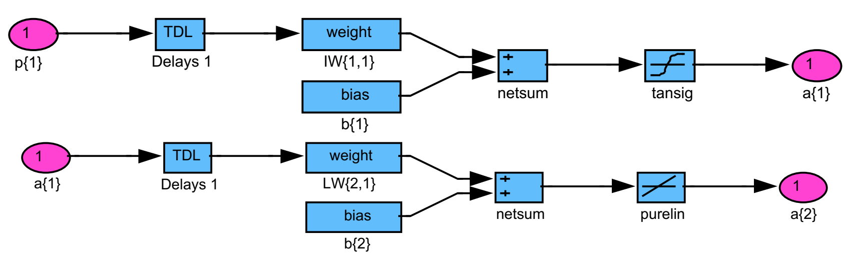
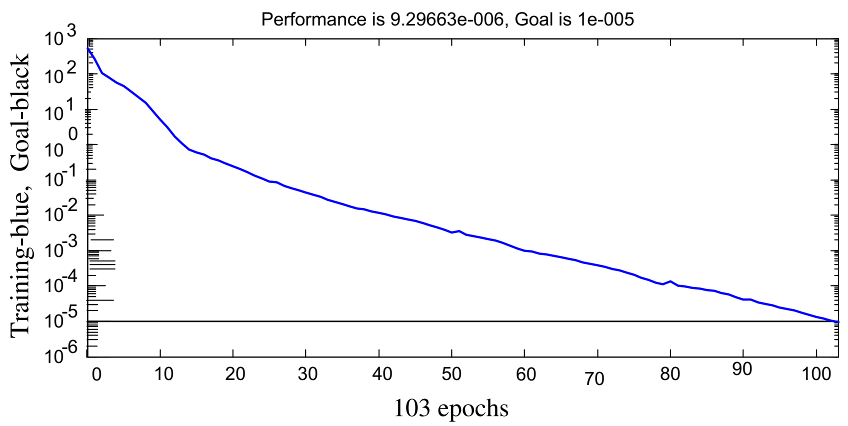


Figure 12. Training of neural network.



6. Results and discussion

To check the effectiveness of the choice of the control variable, two MPPT algorithms such as P&O and NN controller are considered for comparison. KC200GT PV panel is used for simulation using a dc-dc buck converter. A step change in insolation is considered which changes from 1,000 W/m^2 to 600 W/m^2 after one second at a fixed temperature of 25°C. Table 5 presents the MPP parameters of the PV panel at the above-said condition. A dc-dc buck converter is interfaced between the PV panel and the load resistance as shown in Figure 13. The value of load resistance is taken 1 Ω which is less than the internal resistance of PV panel at MPP for highest insolation and lowest temperature considered here to be 1,200 W/m^2 and 25°C. From both the MPP tracker the MPP current command is generated which depends on insolation and temperature at that instant. I_{MPP} current command is compared with the actual PV current sensed by the current sensor by a hysteresis band current controller to generate the pulse to control the converter. The band width of hysteresis band controller is taken 0.002 units for both the MPP trackers for running of simulation in MATLAB environment. The control unit incorporating hysteresis band controller is shown in Figure 14.

Tracking capability of both the algorithms considered taking I_{MPP} as the control variable. Tracking response of P&O algorithm is shown in Figure 15 and for NN controller is shown in Figure 16. For P&O algorithm the tracking response is sluggish in nature, and it takes approximately 0.7 s to reach the steady state value. But it is seen that NN controller tracks the MPP very quickly with elapsed time of 0.01 s as shown in magnified subplot of Figure 16.

Table 5. MPP parameter of the KC200GT PV panel at different irradiation

Irradiation (W/m^2)	Temperature (°C)	V_{MPP} (V)	I_{MPP} (A)	P_{MPP} (W)
1,000	25	26.348	7.5956	200.1301
600	25	26.057	4.5408	118.3229

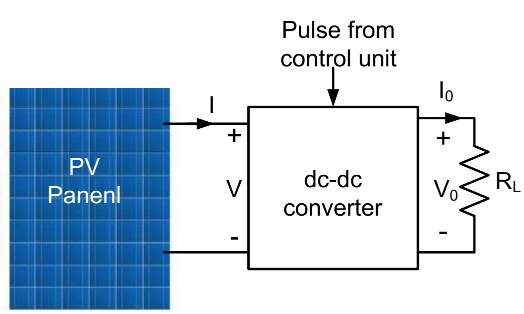


Figure 13. Block diagram of simulation model.

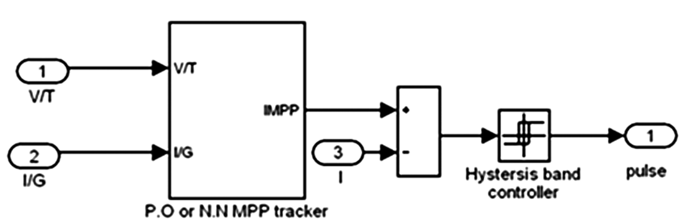


Figure 14. Block diagram of control unit using hysteresis band controller for generation of pulse.

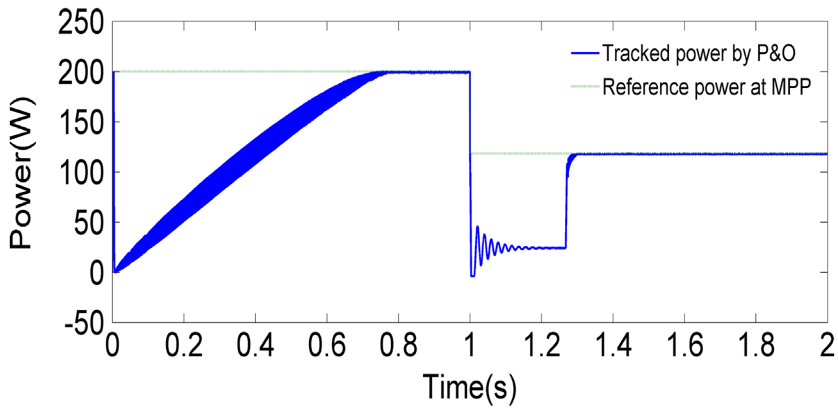


Figure 15. MPPT using P&O algorithm with I_{MPP} as control variable.

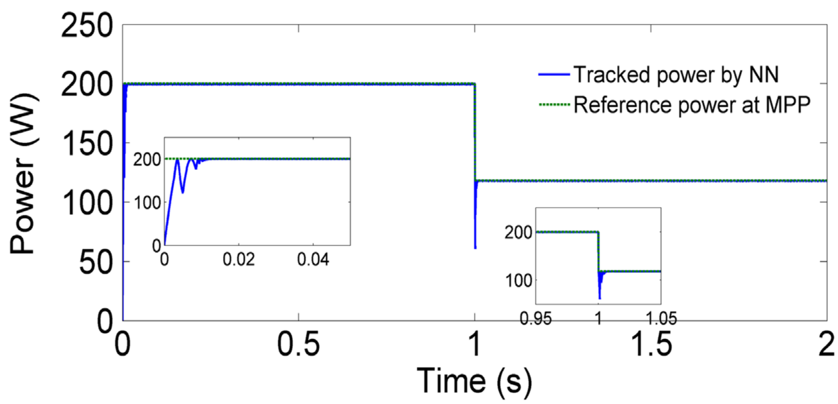


Figure 16. MPPT using NN controller with I_{MPP} as control variable.

The delay of tracking is the further drawback of P&O MPP tracker due to sudden fall of insolation. As shown in Figure 15, P&O MPP tracker fails to track the new maximum power point for some period, here, it is 0.3 s due to sudden fall of insolation from 1,000 W/m^2 to 600 W/m^2. During this period the PV panel is directly connected to load, and the extracted power is the power of PV panel whose internal resistance is equal to the load resistance. Insolation variation has faster dynamic and may be the order of millisecond compared to temperature variation. Since P&O MPP tracker possess slow dynamic (0.3 s delay), it may fail to track the rapid variation of insolation level which depends on climatic condition. The delay time of NN MPP tracker is negligible and mainly depends on dynamics of pyranometer.

Using V_{MPP} as the control variable, same step variation of insolation is considered to check the tracking capabilities for both of the above MPP trackers. The control unit and tracking capabilities for both of the algorithms are shown in Figures 17–19. As shown in Figure 18, NN controller tracks the

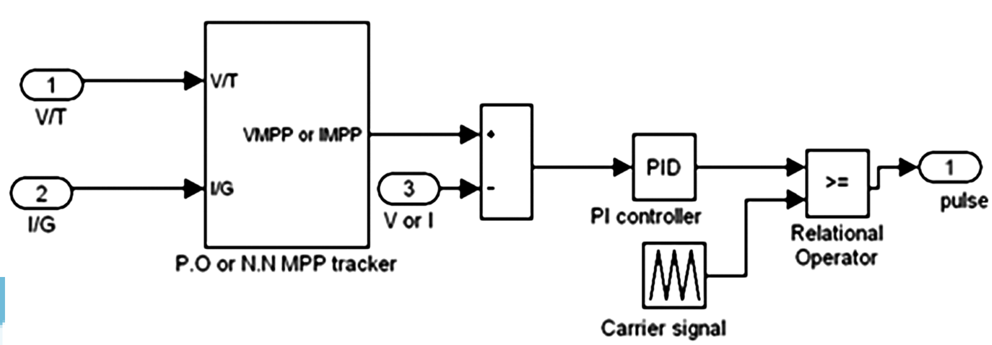


Figure 17. Block diagram of control unit using fixed gain controller for generation of pulse.

https://doi.org/10.1080/23311916.2017.1363357

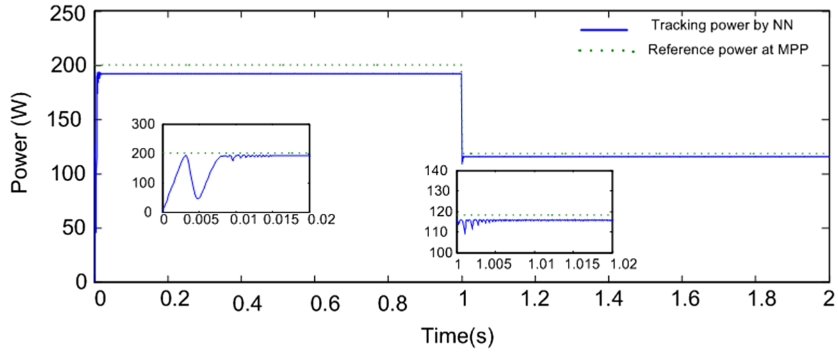


Figure 18. MPPT using NN controller with V_{MPP} as control variable.

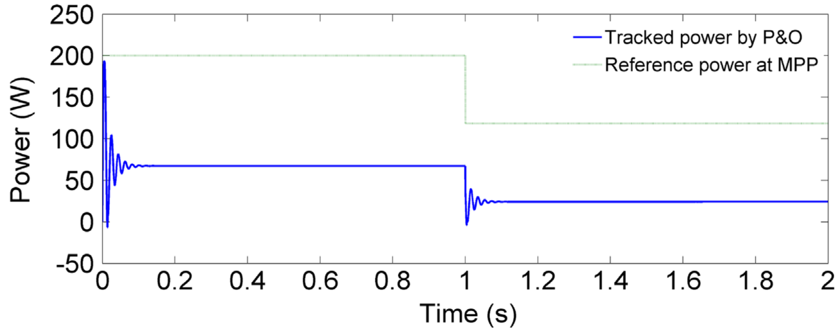


Figure 19. MPPT using P&O algorithm with V_{MPP} as control variable.

Table 6. Comparative analysis for both the MPPT controller

Control variable	MPPT technique	Controller	Tracking factor	Tracking speed	Oscillation present
I_{MPP}	P&O	HCC	0.979	Slow	Yes
	NN		0.986	Fast	No
V_{MPP}	P&O	PID	Failed to track the MPP	–	–
	NN		0.949	Fast	No

maximum power just like I_{MPP} as control variable whereas P&O MPP tracker fails to track the maximum power which needs special attention for stability analysis before V_{MPP} used as control variable. The simulation result of P&O MPP tracker taking voltage as the control variable is shown in Figure 19 which confirms the analysis discussed in control aspects of MPPT. A comparative analysis of both the MPPT techniques is presented in Table 6.

$$\text{Tracking factor} = \frac{\text{Tracked power by MPPT technique}}{\text{Maximum power avilable at a given condition}} \quad (10)$$

7. Conclusion

The variation of the power of PV panel due to the change of irradiation and temperature because of climatic change is analyzed by developing the mathematical model of PV panel. It is observed that failure of tracking of maximum power occurs if chosen dc-dc converter is not matched with the load resistance connected directly to converter without a battery in the system. A mathematical analysis is provided based on maximum power transfer theorem for selecting dc-dc converter. From the analysis, it is clear that a buck-boost converter is suitable for tracking maximum power for any load resistance connected to the PV system. Buck converter is used when the load resistance is smaller than the internal resistance of PV array at MPP and boost converter is used in the vice versa condition. Selection of control variables (voltage or current) as the output of the MPP tracker is an important factor for generating pulses to control the dc-dc converter, otherwise the system becomes unstable mainly in direct MPP trackers. Therefore, it is desirable that the stability should be guaranteed if the voltage is chosen as the control variable in direct MPP tracker. Two MPP trackers, NN (indirect) and P&O (direct) are considered here to compare the tracking capabilities of the PV system. It has been seen that NN MPPT can track the maximum power for either V_{MPP} or I_{MPP} considered as the control variables whereas P&O fails to track the maximum power when V_{MPP} is taken as the control variable. Another drawback of P&O method is that the delay of tracking due to sudden falls of irradiation is eliminated using NN MPPT. Tracking capabilities of both the controller is compared and is seen that for considering I_{MMP} as control variable the tracking factor for both the controller is satisfactory. But considering V_{MPP} as control variable the tracking factor of NN controller is acceptable whereas P&O technique fails to track the maximum power.

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