High Performance MPPT Approach for Off-Line PV System Equipped With Storage Batteries and Electrolyzer

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ABSTRACT. The current publication is directed to achieve a high-performance stand-alone PV system having the capability of tracking maximum output power, providing fixed output DC voltage, and attaining efficient system utilization, under different irradiation levels. A new maximum power point tracking (MPPT) approach integrating the incremental conductance algorithm and fuzzy logic control, and enhanced with PI-controller, was proposed to track maximum power. To provide fixed output DC voltage and approaching full system utilization, the PV system is equipped with a battery bank, electrolyzer; as a dump load, and buck-boost converter, with two controllers. The results of the proposed MPPT technique; modified incremental conductance (MINC), are compared with the corresponding results of three prevalently implemented MPPT algorithms: perturbed and observed (P&O), modified variable step-size P&O (VSZ-PO) and the ordinarily incremental conductance (INC). The highest output power, best tracking efficiency and best output power response are achieved by utilizing the proposed MPPT method. The results of the output voltage response and electrolyzer on/off states confirm the ability of the PV scheme to provide fixed DC voltage and attain efficient system utilization, under varying irradiances.

Keywords: Photovoltaic, MPPT, Battery bank, Electrolyzer, Fuzzy logic.

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1. Introduction

People’s lifestyles and their comfort levels are changing drastically towards the increased demand for electricity consumption. This trend constitutes a great challenge for power system investors to invest in the power generation system which can meet the expected future demand expansions (Al-Refai, 2014). Unfortunately, most of the current power generation systems worldwide are based on conventional fossil fuel energy resources, like oil and natural gas (Bose, 2013). These resources are limited in nature which could be depleted in the near future. Moreover, their operation involves harmful emissions to the environment, and their prices are fluctuating depending on various political and economic issues (Bose, 2010). In contrast, renewable energy resources, like solar and wind, are abundant, sustainable, and environmentally friendly (Pazheri et al., 2014; Ahmadi et al., 2018; Bhukya and Kota, 2018).

Nowadays, photovoltaic (PV) generators are of great interest in many parts of the world due to the advantages of utilizing solar energy for power generation (Khatibi et al., 2019). The PV-based generation systems could be mainly divided into on-grid and off-grid schemes (Maleki et al., 2016). On-grid indicates that the PV system is connected to the grid, while the off-grid means that the PV system is operating solely (Blaabjerg et al., 2006; Pavlovic et al., 2010). Storage elements, like battery bank or supper capacitors, are usually required for off-grid PV configurations to ensure a continuous supply for the load (Li et al., 2009; Yokoyama et al., 2011). The main applications of stand-alone (off-grid) PV schemes are electrification of remote buildings, water pumping, transportation, mobile applications, and satellite systems (Mohammadnezami et al., 2015; Sebastian et al., 2016; Ahmadi et al., 2018).

A PV generator is an attractive electric energy source because of the solar energy merits. However, the efficiency of PV panels in converting solar energy to electric power is relatively low, typically in the range of 12% to 30% (Sera et al., 2007). In addition, the variations in the solar irradiation, panel temperature, and load are adversely affecting the PV system efficiency in a non-linear manner (Chandel et al., 2015). Therefore, tracking the maximum possible power from a PV generator, under the variations in atmospheric and load conditions, is highly demanded to improve the conversion efficiency. The system of maximum power point tracking (MPPT) is basically a DC chopper equipped with a control system to adjust the chopper duty-cycle Subudhi and Pradhan (2013). The behaviour of a MPPT technique can be assessed based on its tracking efficiency, which can be realized as the ratio of the practical tracked output power of the PV array to its theoretical output power, for the same time interval (Tafticht et al., 2007).
Over the last years, the issue of achieving maximum power extraction from the PV array has attracted the attention of many researchers worldwide. Therefore, a great number of papers deal with the implementation of various MPPT methods have been published Yeong-Chau et al. (2001); Pandey et al. (2008); Berrera et al. (2009); Mummadi (2010); Quang and Tong (2010); Revankar et al. (2010); Chim et al. (2011); Mei et al. (2011); Alajmi et al. (2013); Babaa et al. (2014). Maximum power point trackers are competing in terms of different factors such as simplicity, sensor requirements, cost, tracking efficiency, and convergence speed (Enrique et al., 2010). Perturbed and observe (P&O), Incremental conductance (INC) and modified variable step-size P&O (VSZ-PO) algorithms are the most utilized trackers in the PV based systems Metry et al., 2017; Naick et al. (2017); Bhukya and Kota (2018); Javed et al. (2018).

The output voltage and power of a PV array are expected to vary due to natural variations in the atmospheric conditions. Therefore, off-grid PV systems are usually equipped with storage batteries to overcome the shortage in the generated power Thang et al. (2015); Bhattacharyya and Samanta (2018). To achieve fixed DC link voltage and proper power flow modes under the variations in atmospheric conditions, the PV system has to combine power conditioners, with the needed control Karthikeyan and Gupta (2017); Saxena et al. (2017).

In this paper, a new MPPT algorithm (MINC) is proposed for off-grid PV system. This MPP tracker combines both INC and Fuzzy Logic Control (FLC) algorithms and enhanced with PI controller. To confirm the validity of utilizing the MINC approach, a comparison with P&O, INC, and VSZ-PO has been made. The PV system performance is improved by maintaining the DC link voltage fixed and reaching efficient system utilization, even under rapid irradiation level changes. This improvement is achieved by enhancing the system with a battery bank, electrolyzer (dump load), and DC chopper, with two controllers.

2. Photovoltaic Generation System

This section provides the basic principles concern with the PV array including the mathematical model and the effects of the atmospheric variations (irradiance and temperature) on the I-V and P-V characteristics of the PV-generator. The second part of this section describes the investigated PV system in detail.

2.1 Principles of the Photovoltaic Array

The basic element of a photovoltaic array is the solar cell. It directly converts the sunlight to electricity (Vastav et al., 2016). To acquire more voltage and current, the cells are combined to form a panel (module). Panels are connected together either in series or in parallel to obtain an array, which can meet the electrical needs. The buildup structure of these components is presented in Fig. 1 (Vastav et al., 2016).

A Single-diode model or two-diode model is used to represent the behavior of a solar cell (Liu et al., 2005). The two configurations are shown in Fig. 2. Single-diode model has a simple configuration, which leads to less complex mathematical expression, and can provide accurate results Kim and Choi (2010); Bhukya and Kota (2018). Using the single diode model, the I-V relationship and the thermal potential \( V_T \) of a PV panel can be given in equations (1) and (2), respectively Liu et al., (2005); Khatibi et al. (2019); Premkumar et al. (2020).

The behavior of a PV-generator is strongly affected by the solar irradiation level and the ambient temperature (Premkumar et al. 2020). The current-voltage (I-V) and voltage-power (P-V) characteristics of the PV generator, under various irradiation levels and fixed temperature, are illustrated in Fig. 3. As can be observed, increasing the irradiation level causes the current to linearly increase, but the voltage is slightly increasing. As a result, the output power increases with irradiation level. The I-V and P-V characteristics, under different temperature settings and fixed irradiation level, are demonstrated in Fig. 4. It can be noticed that the increase in the ambient temperature causes a decrease in the open circuit voltage and very small increase in the current. Consequently, the array output power will decrease with an increase in temperature level.

\[
i = I_{ph} - I_0 \left( e^{\frac{V+I_n R_s}{a n T} - 1} - \frac{V+I_n R_s}{R_n a} \right)
\]

\[
V_T = \frac{\Delta K T q}{q}
\]

2.2 The Proposed PV generation Scheme

The main power source in the proposed PV generation system is the PV array. The PV system is equipped with a battery bank to feed the load if the generated power from the main source is insufficient to cover the load demand and at the same time the state of charge (SOC) of the battery bank is higher than 80%. To achieve the features of fixed DC link voltage and improved system utilization, under solar irradiation changes, a buck-boost DC/DC converter, with two controllers, and electrolyzer (dump load) are combined with the PV system.
Fig. 3. (a) The current-voltage relationship of the PV array for various irradiation levels and constant temperature level, (b) The Power-Voltage relationship of the Photovoltaic array for various irradiation levels and constant temperature settings.

Fig. 4. (a) The current-voltage relationship of the Photovoltaic array for variable temperature and constant irradiance, (b) The Power-Voltage relationship of the Photovoltaic array for variable temperature and constant irradiance

Fig. 5 The control scheme for the operation of the buck-boost converter

The control scheme for the operation of the buck-boost DC chopper is represented in Fig. 5 Berrera et al. (2009); Qiang and Tong (2010). The actual DC link voltage is subtracted from the reference set value to generate the deviation error signal, which is input to the PI-controller. The output control signal from the PI-controller represents the reference battery current signal. Subtracting the actual battery current from this reference signal will produce the error signal which is fed to the hysteresis controller. The output control signal from the hysteresis controller represents the switching command (duty cycle) for switch S1 or/and switch S2 of the converter, depending on the SOC of the battery bank.

3. The Proposed MPPT Approach

Incremental conductance (INC) algorithm is one of the well-known maximum power trackers and usually it runs with constant step size (Kharb et al., 2014). With fixed step size, it is very difficult to achieve fast transient response with minimized steady state oscillations (Javed et al. 2018). The proposed MPPT scheme integrates INC algorithm and fuzzy logic control to acquire proper adjustment for step size. Consequently, fast transient response and reduced fluctuations around the point of maximum power will be achieved. The proposed approach is enhanced with PI controller to accelerate the response and minimize the percentage overshoot. The PI-controller gains are adjusted using Zeigler-Nichols approach (Singh and Singh, 2014). the schematic diagram of the proposed MPPT is shown in Fig. 6.

The output current and voltage of the PV array are fed to INC block to produce the error (E), which is processed to provide the change of error (ΔE). This process is mathematically represented in equation (3). The two parameters E and ΔE are fed to the fuzzy-logic controller, which provides the modulation signal. This signal is compared with the reference signal to provide proper switching command for the boost chopper. As a result, fast speed response in tracking the maximum power point, with minimized fluctuations around this attained point, will be achieved. Detailed description of the INC method and fuzzy logic control approach are given in next subsections.

\[ ΔE = E(n) - E(n - 1) \]  

(3)
3.1 Incremental Conductance (INC) Algorithm

Incremental conductance algorithm is based on the concept that maximum power point (MPP) is attained when the rate of change of the power output with respect to the output voltage is zero (Yun et al., 2004). This condition can be mathematically represented by the following equation:

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} = 0$$  \hspace{1cm} (4)

On the array power-voltage characteristic, the slope is zero (dP/dV=0) at the MPP, positive on its left-hand side (LHS) and negative on the right-hand side (RHS) (Subudhi and Pradhan, 2013). From equation 4, ∆I / ∆V may be given by:

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V}$$  \hspace{1cm} (5)

Equation 5 represents the case at the MPP. For all operating points located on the LHS of the MPPT, (∆I/∆V) > (-IV). On the other hand, (∆I/∆V) < (-IV) for all operating points located to the RHS of the MPP. Consequently, the MPP can be tracked by comparing the instantaneous conductance (IV) with the incremental conductance (∆I/∆V). The INC algorithm is demonstrated by the flowchart shown in Fig. 7 (Diva and Kavitha, 2013). The Simulink model of the INC algorithm given in Fig. 8 which can be explained through two stages. In the first stage, the current and voltage of the PV array are fed to the model to produce the conductance IV and the incremental conductance ∆I/∆V. In the next stage, IV is compared with ∆I/∆V to give the error signal. This signal is then subjected to two consecutive comparison via two cascaded switches to provide the output.

3.2 Fuzzy Logic Control

Fuzzy logic control (FLC) has been widely used in various applications due to its several advantages. First, the controller can be tuned to control complicated nonlinear system having several inputs. Second, an exact system mathematical model is not required to implement FLC (Esram and Chapman, 2007). There are various techniques which can be used to perform fuzzy interface process. Mamdani method is widely utilized for control engineering applications because it is the most computationally efficient approach (Bai et al., 2006). Mamdani method performs the fuzzy interface process in four steps: Fuzzification, knowledge base, interface engine and defuzzification (Mobaied, 2008; Iancu, 2012; Ocran et al., 2005).

The general structure of the fuzzy interface system is demonstrated in Fig. 9. The first process in FLC is fuzzification. During this stage, the fuzzifier transforms crisp input variables into fuzzy inputs through membership functions. These inputs are then represented using linguistic rules, for example “if x and y, then z”. The fuzzy inference engine processes these data to obtain the desired fuzzy outputs (Soufi et al., 2014). The last interface process to achieve the desired FLC objective is defuzzification. It is accomplished through the defuzzifier which converts the fuzzy outputs into numerical values.

In the present work, the error and change of error (E, ∆E) are the input variables to FLC. After the accomplishing of all required processes, the desired output from the final interface process is the duty cycle (AD). The membership functions of the inputs (E, ∆E) and output (AD) are presented in Fig. 10. The implemented fuzzy rules in the present work are given in Table 1. The triangular shape is chosen to represent the membership functions because it is the most popular and widely used shape. The degree of membership function lies in the range of [0 1]. As can be noticed in Table 1, the selected number of membership functions for each input is five and consequently the inference rules of the fuzzy logic controller are twenty-five rules.
4. Results and Discussion

The parameters of the implemented PV array in the proposed standalone photovoltaic system are presented in Table 2. The integrated system components, including a MPPT algorithm, have been simulated in Matlab/Simulink platform. The system performance with MINC (the proposed approach), P&O, INC or VSZ-PO algorithm, under the same conditions, is investigated. The assessment is carried out under the operation of fixed irradiation level as well as variable irradiation level. The capability of the proposed PV scheme in achieving fixed DC voltage and reaching efficient system utilization, under various irradiation levels, is also tested.

The obtained output power results using P&O, INC, VSZ-PO and MINC (the proposed approach) MPPT methods are presented in Fig. 11. The system output power without MPPT is also shown in the figure. The PV generator is assumed to operate under fixed irradiance of 1000 W/m², constant temperature of 25°C, and feeding a resistive load of 48 Ω. It can be observed that VSZ-PO has better dynamic performance and less oscillations, compared with P&O or INC method. This improvement is due to the use of variable step size, which is not the case for P&O or INC approach. However, INC method provides the highest steady output power compared with P&O and VSZ-PO methods. It is suitable to say that none of the three methods can provide high output power with minimized oscillations.

Based on the comparison made between the proposed MINC method in one hand and P&O, INC or VSZ-PO on the other hand, tremendous improvements in the PV system behaviour during both transient and steady-state situations has been achieved with MINC approach. It provides fast and smooth dynamic response, minimized steady-state oscillations and high steady-state output power. The computed tracking efficiency of the proposed MPPT technique reaches 99.3%, which is higher compared with that of P&O, INC or VSZ-PO.

To assess the behaviour of the output power for each of the four mentioned MPPT algorithms under rapid irradiation changes, the irradiance profile with great changes shown in Fig. 12 is considered. This profile is fed as input to the Simulink model of the proposed PV scheme and an individual simulation is run for each MPPT algorithm. The results of the output power tracked by P&O, INC, VSZ-PO and MINC MPPT algorithms are presented in Fig. 13. It can be observed that the MINC (proposed MPPT approach) possess the best performance features compared with P&O, INC and VSZ-PO techniques. It can respond very fast, under the rapid change in solar irradiation, to reach the steady state final value with no oscillations.

Table 2
The parameters of the tested solar array

| Parameter                        | value | Unit |
|----------------------------------|-------|------|
| Maximum Power                    | 230   | W    |
| Open circuit voltage             | 37    | V    |
| Short circuit current            | 8.3   | A    |
| No. cells per module             | 60    | -    |
| No. parallel strings             | 5     | -    |
| No. series strings               | 6     | -    |
| Current at maximum power point   | 7.72  | A    |
| Voltage at maximum power point   | 29.8  | V    |
The proposed algorithm also provides the highest steady-state output power, compared with other three algorithms. The other assessment criteria used to evaluate the performance of proposed MPPT method in comparison with the three commonly used MPPT approaches is the tracking efficiency. It is ratio of the real tracked PV output power, by a MPPT technique, to the theoretical computed one, under the same irradiation level. The irradiation levels used in the current investigation are 1000, 650 and 250 W/m². The obtained theoretical power output results for these irradiances are 6583, 3180 and 1085 W, respectively. The results of the tracking efficiency for the algorithms are given in Table 3. As can be noticed, the maximum tracking efficiency is achieved when implementing the proposed MPPT approach. The results presented in Fig. 11 and Fig. 13 as well as those given in Table 3 confirm the validity of the proposed MPPT approach in achieving high performance PV system.

| Irradiance (W/m²) | MINC | P&O | INC | VSZ-PO |
|-------------------|------|-----|-----|--------|
| 1000              | 99.3%| 44.1%| 84.5%| 73.4%  |
| 650               | 98.1%| 73.9%| 73.9%| 94.8%  |
| 250               | 97.7%| 65.4%| 36%  | 33%    |

Two attractive features in the performance of the proposed PV scheme are also examined. These features are the system capability to maintain the DC link voltage fixed and the ability to approach efficient utilization of the system components, under varying irradiation level. The assessment is carried out by feeding the irradiance profile of Fig. 12 to the PV system model and then SIMULINK simulations are run for the examined cases.

The output DC voltage of the PV scheme when excluding the storage means and the controllers is shown in Fig. 14. As can be seen the output DC voltage is changing in response to the variations in solar irradiation. Therefore, feeding most of the load types could be impossible or the solution to adjust the voltage will not be an easy task. The results of this test confirm the importance of the proposed PV system structure to achieve fixed output DC voltage under the variation in solar irradiation.

The output DC voltage of the proposed PV scheme under different solar irradiation levels is shown in Fig. 15. As can be observed the output DC voltage remains fixed for the whole solar profile period. Moreover, it possesses the features of fast dynamic response, with reduced percentage overshoot, and no oscillations during the steady state condition.

![Fig. 11 The system output power using P&O, INC, VSZ-PO and MINC algorithms under fixed irradiation level operation](image1)

![Fig. 12 The considered irradiance profile](image2)

![Fig. 13 Output power of the P&O, INC, VSZ-PO and MINC MPPT methods under different irradiation levels](image3)

![Fig. 14 The output DC voltage of PV system when excluding the storage means and the controllers](image4)

![Fig. 15 The DC link voltage of the PV system enhanced with storage battery bank and ON/OFF controller](image5)

Table 3
The computed tracking efficiency of MPPT techniques

| Irradiance (W/m²) | MINC  | P&O  | INC  | VSZ-PO |
|-------------------|-------|------|------|--------|
| 1000              | 99.3% | 44.1%| 84.5%| 73.4%  |
| 650               | 98.1% | 73.9%| 73.9%| 94.8%  |
| 250               | 97.7% | 65.4%| 36%  | 33%    |
confirm irradiation level, and attain efficient system utilization
dynamic and steady state to a high
highest output
bank standalone P&O and INC and enhance
power point tracking (MPPT) approach
The implementation of a new high performance maximum
5.
interval, the solar irradiation level is moderate
power is insufficient to supply the load
generated power enables the electrolyzer to turn ON again.
the electrolyzer to turn ON again. In the third
interval, the solar irradiation level is moderate enabling
the PV array, with the help of the battery bank, to produce
power exceeds the load demand. The excess power causing
the electrolyzer to turn ON again. It can be stated that the
proposed PV scheme has the capability to manage the
mores of power flow between the system components
reaching efficient system utilization, under varying solar
irradiation level.

5. Conclusion
The implementation of a new high performance maximum
power point tracking (MPPT) approach, which integrates
P&O and INC and enhances with PI controller, for
standalone photovoltaic system, enhanced with a battery
bank and electrolyzer, has been evaluated. Based on the
comparison made with P&O, INC and VSZ-PO, the
highest output power and maximum tracking efficiency,
even under rapid changes in solar irradiation, are
acquired with the proposed algorithm. In addition, it leads
to a high-performance output power response during
dynamic and steady state conditions. The capability of
the proposed PV configuration to achieve fixed DC link voltage
and attain efficient system utilization, under varying solar
irradiation level, was also assessed. The obtained results
confirm the attainment of these two features properly.

Nomenclature

| Symbol | Description |
|--------|-------------|
| A      | The diode quality factor, usually 1<A<2 |
| DC     | Direct current |
| ΔE    | Change of error |
| E(n)  | Error of the current sample |
| E(n-1) | Error of the previous sample |

Fig. 16 The ON/OFF states of the electrolyzer under the
different solar irradiation levels

The results presented in Fig. 16 shows the electrolyzer
on/off states under the variation in the solar irradiation
(Fig. 12). It can be noticed that the electrolyzer is ON in the
first intervals (0 – 0.78) s, OFF in the second interval
(0.78 – 1.54) s and again ON in the third interval (1.54 –
2) s.

During the first interval, the solar irradiation is high
efficient enough to extra PV generated power exceeds the
load demand and the power for charging the batteries, if
the SOC of the battery bank is less than 80%. The excess
generated power enables the electrolyzer to turn on. In the
second interval, the electrolyzer is OFF because the solar
irradiation level is low and therefore the PV generated
power is insufficient to supply the load. In the third
interval, the solar irradiation level is moderate enabling
the PV array, with the help of the battery bank, to produce
power exceeds the load demand. The excess power causing
the electrolyzer to turn ON again. It can be stated that the
proposed PV scheme has the capability to manage the
mores of power flow between the system components
reaching efficient system utilization, under varying solar
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