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Optimizing a Photovoltaic System and Tracking the Maximum Power Point

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ABSTRACT

Recently, hybrid systems combining photovoltaic systems, storage batteries, or wind power have attracted much attention with a focus on power deregulation and environmental protection. Although the photovoltaic system output density is very low and photovoltaic output is highly dependent on the surface temperature of the PV array and radiation conditions, this system is commonly used with battery storage systems. Despite the existence of several local maximum power points in current-power characteristic in the non-uniform irradiation, only one point can maximize the power incurrent-power characteristic of the photovoltaic system under the uniform radiation. Solar cells depending on the circumstances in which they are used such as weather conditions, radiation, etc. have a maximum power point (MPP). Therefore, there is a need for a method that can position solar cells in a MPP so that we can have maximum power and thus the maximum efficiency from solar cells. The solar energy absorbed by the solar cell should be transferred in a way that it can be moved easily to local and network loads. This can be done using power converters. The use of convertors with high efficiency and low initial and fixed costs seems essential. In this paper, a detailed model of the solar cells is presented and a control method to get the maximum power from solar cells will be studied.

KEYWORDS: renewable energy, tracking the maximum power output, solar cells, maximum power point (MPP).

1. INTRODUCTION

By connecting a p-type semiconductor to a semiconductor type n, electrons move from the zone *n* to zone p and holes move from zone p to zone n. When an electron is moved to zone p, a positive ion remains in in zone n and when a hole is moved to zone n, a negative ion remains in zone p. Positive and negative ions create an internal electric field that is directed from zone in towards zone p. The field with further transfer of porters (electrons and holes), become stronger and stronger until the net transfer of porters becomes zero. In these circumstances, the Fermi levels in the two zones are at an equal level and an internal electric field is formed. If in such a situation, the sun shines on links, photons with energy levels greater than those of semiconductor gap will generate electron-hole pairs and the pairs that have been generated in the empty area or around it are more likely to become separated by the internal field before recombination. The electric field transfers electrons to zone n and the holes to zone p. As such, the negative charge density in zone n and the positive charge density in zone p are high. This load density can be measured at both ends of the link in the form of voltage. If the two ends are short-circuited through a wire, the extra electrons in zone n are moved through the wire to zone p and form a short-circuit current. That's why higher semiconductor gap energy should be selected. Therefore, the open circuit voltage of a solar cell will increase with increasing the gap energy. However, as the gap energy increases, smaller numbers of photons are able to produce hole-electron pairs and thus less short circuit current is produced. As a result, increasing the gap energy has two conflicting effects on the open circuit voltage and short circuit current. There are many studies that have addressed the maximum power point tracking control method. These studies have been conducted through different methods such as mountain climbing, dV/dI, fuzzy theory, genetic algorithms, and so on.

Among MPPT controls, the fuzzy theory and genetic algorithms can be used to find out the actual maximum power point in relatively shady irradiation distribution. However, most of these control processes are fairly complex and sometimes the operational point is more likely to converge into the local maximum point, where the actual maximum power point is not located in the current-power curve of the photovoltaic system array. Based on what has been mentioned, this article describes a two-stage MPPT control method that enables the fast tracking of the actual maximum point in the current-power curve with a relatively simple process even in non-uniform radiation condition [2].

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MATERIAL AND METHODS

Figure (1) shows the equivalent diagram of the solar panels used in this study. Solar panels are made of several series or parallel photovoltaic cells with a number of external series-parallel connections [14, 15]. Eq. (1) shows the V-I characteristics of the solar panels.

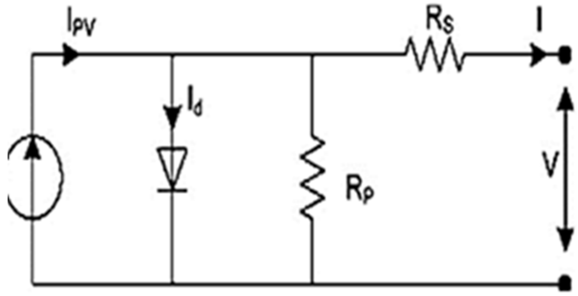

Figure (1): Equivalent circuit of the solar panels

$$I = I_{Pv} - I_o\left[exp\left(\frac{V + R_s I}{aV_t}\right) - 1\right] - \frac{V + R_s I}{R_P} \qquad (1)$$

Where, I_{PV} is photovoltaic current, Io is reverse saturation current, *a* the ideal diode constant, (V_t= $N_s KT\_q^{-1}$) is the thermal voltage, N_S stands for the number of serial cells, q is the electron charge, k is the Boltzmann's constant, p-n is the temperature in the connection point, and R_s and R_p are equivalent series and parallel resistances of solar panels, respectively [4]. Ipv has a linear relationship with light intensity and varies as the temperature changes. Io is als dependent on the temperature variations.

Ip and Ip values are calculated using the following equations:

$$I_{Pv} = \left(I_{PV,n} + k_I \Delta T\right)\frac{G}{G_n} \qquad (2)$$

$$I_o = \frac{I_{sc,n} + K_I \Delta T}{\frac{\exp\left(V_{oc,n} + K_v \Delta T\right)}{aV_t} - 1} \qquad (3)$$

Where $V_{OC,\ n,}$ $I_{PV,n}$, and $I_{SC,n}$ are photovoltaic current, short-circuit current, and open circuit voltage at standard conditions (Tn=25, C and Gn=1000Wm^{-2}), respectively. KI is the short-circuit current to the temperature coefficient, ΔT=T-Tn is the temperature deviation from standard temperature, G is the light intensity, and KV is the ratio of the open circuit voltage to the temperature. Open circuit voltage, short circuit current, and current-voltage related to the maximum power are three important points of I-V profile of solar panels which vary due to changing atmospheric conditions [6]. Using equations (4) and (5) that are derived from the PV model equations, the short circuit current and open circuit voltage can be calculated for different weather conditions:

$$I_{sc} = \left(I_{sc,n} + K_I \Delta T\right)\frac{G}{G_n} \qquad (4)$$

$$V_{oc} = V_{oc,n} + K_v \Delta T \qquad (5)$$

RESULTS AND DISCUSSION

Maximum power point tracking and control include sensors, wave manufacturer, and maximum power point tracking implementer. Depending on the MPPT method and having the existing control system; PWM is calculated by measuring parameters needed for the suitable operating point (the maximum output power point) in solar cell [13]. The relationship between operating point and the light intensity is calculated through the following equation [16].

$$\mathrm{V_{PVmpp}} = \mathrm{f_1}\left(\mathrm{L}\,, \mathrm{g_\sigma}(\mathrm{L}, \mathrm{V_{PV}}, \mathrm{T_{Env}})\right) \quad \rightarrow \quad \mathrm{V_{PVmpp}} = \mathrm{f_2}(\mathrm{L}\,, \mathrm{T_{Env}}) \qquad (6)$$

Given that the ambient temperature does not change significantly in a short interval (one hour), it is considered fixed in this interval and thus Eq. (1) can be rewritten as follows:

$$V_{PVmpp} = f_3(L) \qquad (7)$$

Eq. (7) is reliable if the ambient temperature or its impact *f* is present in Eq. (3). In this case, Eq. (8) can be written as follows. Vmpp can be used for the maximum power point voltage compared to the derived voltage and it is set as zero. In this case, the voltage calculated from the following equation is the maximum power voltage:

$$\frac{\partial \mathrm{P_o}}{\partial \mathrm{V_{pv}}} = 0 \quad \rightarrow V_{PVmpp} = f_1(L\ , T_{cell}\ ) \qquad (8)$$

Appropriate conditions for installation and operation of PV systems

The efficiency of photovoltaic panels depends on their orientation, location, and weather conditions [6]. The most important factors for an ideal material to be used for photovoltaic cells are stated as follows:

- A bandwidth between 1.1 eV to 1.8 eV.
- The availability in the market and the non-toxicity of the materials
- Recyclability and suitability for mass production
- Good photovoltaic conversion efficiency
- Long-term sustainability

A) The orientation of PV panels is of high importance to ensure the maximum efficiency. Fixed panels compared with tracking panels that track the sun to provide maximum radiation, a southward orientation in the northern hemisphere is the best direction to collect the maximum solar radiation.

B) In addition to orientation, the panel deviation angle is an important factor that must to be considered when designing solar systems. The deviation angel is an angle of solar panels with the horizon level and it ranges from 0 to 90 degrees.

C) The latitude, longitude, and the height of the installation place of solar systems are important factors that need to be taken into account when calculating the solar irradiation power. Usually 80% to 85%of the sunlight (1000w/m^2) is absorbed in a sunny day.

D) The efficiency og all of modules decreases to a certain degree at high temperatures. So it is not a serious matter as far as the ambient temperature does exceed 80 ºF. The location of modules should be determined in a manner that it allows perfect ventilation. The free circulation of the airflow around the modules will increase their efficiency. It also prevents the accumulation of solid wastes and the increased humidity under solar modules, maiming the roof corrosion and damages made to the electrical connections.

The proposed MPPT algorithm contains two parts including the adjustment point and fine tuning component. In the first stage, the maximum power point voltage (VMPP) is calculated based on the open circuit voltage using Eq. (5). Afterwards, in the second stage, the exact maximum power point is tracked using dv/dI with a small fixed range and multiple disturbances [7, 8]. In this procedure, in addition to KI, KV, VOC, n values which are provided by the manufacturer, RS and RP are taken with their initial values. These three values are determined by replacing the three points of (0, ISC, n), (VOC, n, 0), and (VMPP, n, IMPP, n) under standard conditions (Gn=100Wm^{-2}, Tn = 2500°c) in Eq. (1) and the solution of the following equations is found:

$$\mathrm{I_{sc,n}} = \mathrm{I_{PV,n}} - \mathrm{I_{o,n}}\left(\exp\left(\frac{\mathrm{I_{sc,n}R_s}}{\mathrm{aV_{T,n}}}\right) - 1\right) - \frac{\mathrm{I_{sc,n}R_s}}{\mathrm{R_p}}\mathrm{K_I\Delta T)}\frac{\mathrm{G}}{\mathrm{G_n}} \qquad (9)$$

$$0 = I_{PV,n} - I_{o,n}\left(\exp\left(\frac{V_{oc,n}}{aV_{T,n}}\right) - 1\right) - \frac{V_{oc,n}}{R_p} \rightarrow a, R_s, R_p \qquad (10)$$

$$I_{Mpp,n} = I_{PV,n} - I_{o,n}\left(\exp\left(\frac{I_{Mpp,n}R_s}{aV_{T,n}}\right) - 1\right) - \frac{I_{Mpp,n}R_s}{R_p} \qquad (11)$$

The instantaneous values of voltage, current, and temperature of solar panels are measured and in addition to the temperature, IPV which is the only variable dependent variable to light intensity is calculated using Eq. (11) [9], where, VT and IO are dependent on the temperature and V_t= $N_s KT\_q^{-1}$ can be used in Eq. (1).

$$I_{PV} = I - I_o\left(\exp\left(\frac{V + IR_s}{aV_T}\right) - 1\right) + \frac{V + I_{Rs}}{R_p} \qquad (12)$$

Having the IPV value which ranges from 13 to 15, ISC can be calculated, and the equation can be repeated m times and in each iteration, Isc will be replaced in the previous iteration. Because of the short-circuit current convergence, ISC does not make much difference after m iterations. Besides, as m is a small integer, IPV value estimated initially would be very close to the ISC. In other words, ISC will be found with an acceptable approximation in several iterations.

$$\mathrm{I_{SC,1}} = \mathrm{I_{PV}} \tag{13}$$

$$I_{sc,2} = I_{PV} - I_o\left(\exp\left(\frac{I_{sc,1}R_s}{aV_T}\right) - 1\right) - \frac{I_{sc,1}R_s}{R_P} \tag{14}$$

$$I_{sc,m+1} = I_{PV} - I_o\left(\exp\left(\frac{I_{sc,m}R_s}{aV_T}\right) - 1\right) - \frac{I_{sc,m}R_s}{R_P} \qquad m = 1,2,\dots,m, ISC = ISC, m + \cdots \tag{15}$$

In the proposed method, the fine-tuning loop is used to calculate ISC accurately and to compensate for the effects of measurement errors and the possibility of incompatibility with solar panels. Besides, in the case small variations in temperature and IPV, the fine-tuning loop will adjust the output power. Since I_{PV} varies due to the light intensity variations, it can be concluded that the repeated fine-tuning will run as long as weather conditions are relatively stable [10, 11].

Table (1): Photovoltaic system parameters

Symbol	Description	Value
P_{nom}	Nominal power	4Kw
V_{nom}	Nominal voltage	220v
q	Electrons	$1.602 \times 10^{-19} C$
K	Boltzmann's constant	$1.38 \times 10^{-23}\ J/K$
Isc	Short circuit current	5.09261A
Voc	Short circuit voltage	59.2619V
T	Temperature	25°
S	The sun irradiation	0~1000

The battery energy storage system

The battery bank includes a number of 12-voltage batteries which are usually connected in series and provide the required voltage for the system. In systems which are disconnected from the network, the energy stored in batteries is used at night or under urgency conditions [11]. Batteries are also used in support systems when there is a power cut. However, network-connected systems do not require batteries. In the battery energy storage system, lithium-ion which is used as the base to store energy has been employed as the most popular energy storage system with high efficiency, discharge efficiency, and high energy density. To maximize the efficiency, the lithium-ion battery is based on the energy storage system with high efficiency.

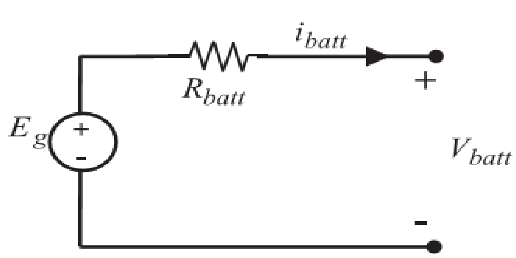

Figure 2: Equivalent battery circuit

Types of batteries used in solar systems

Due to advancements made in various fields, humans are in increasing need for energy and this prompted them to acquire the energy in various ways. One of these methods used by humans over the last 20 years is the use of solar batteries. The sun transfers about 1000 joules per second for square meter of the earth's surface and if this energy can be absorbed properly it can be used for different functions. .

Batteries used in solar systems must have a long lifetime as they are used continuously in various conditions. Generally, the lifetime of a battery is expressed based on the number of charge and discharge cycles and the battery discharge level. Batteries used in solar systems are charged during the day and discharged during the night by a consumer and thus each 24 hours is regarded as a charge and discharge cycle for a battery [7]. Another important feature of these batteries is the ability to be discharged to their nominal capacity. In solar systems, batteries may be discharged to 80% of its capacity during a cloudy day and they must be able to provide the required load under these conditions. Early solar batteries were made of single silicon crystals (Si) that are placed next to each other on a flat plane. This method was very costly for general consumptions and energy production for big areas. Although the raw material for producing Si SiO2 is plentiful, sand refining and sufficient Si purification as a part of the process of producing solar batteries is costly.

Features of different batteries

Available batteries with the largest share of the market include car batteries and, especial batteries used in UPS devices known as UPS batteries. AS UPS batteries are used only in times of emergency and power cut they have smaller number of charging and discharging cycles compared to batteries used in solar systems [8]. Batteries in used in solar systems must have the ability to be charged and discharged more frequently. One important point about rechargeable batteries is that they must be fully discharged and then fully recharged so that they can have the longest lifetime possible. In addition, the size and shape of the battery need to be designed based on the voltage system operation, overnight use, and in-site weather conditions. In some of these systems, a charge controller has been designed to prevent unusual discharges and overcharges by disconnecting modules from the battery supply and that is effective in maintaining the battery quality and lifetime. Unfortunately, batteries used in solar systems in most cases are as UPS batteries with a lifespan of only one to two years. Since the battery costs contributed significantly to a solar system's costs (about 30 to 40%of the total system cost) it is very important to choose the right battery [12].

CONCLUSION

One of the main features of the proposed method is that the maximum power tracking is performed with a relatively high speed and there is no vacillation around the maximum power point. Besides, the proposed system does not require a solar panel. The results of our experiments show that the high-efficiency lithium-ion batteries can be used as a rational choice in different systems. These batteries can store solar or wind power or wind power so that the stored power can be used when there is a need for it. When batteries are correctly they can balance network load so they are justifiable from an economic point of view. Despite the high price of lithium-ion batteries, this technology is considered as a valuable option especially in areas with unstable energy resources. In this article, a different schematic simulated PV array model is presented and radiation and temperature parameters of each PV module can also be defined separately. The simulated PV model allows us to examine the characteristics of PV array under various conditions in terms of temperature and radiation, especially when radiation is non-uniform. The proposed model not only studies the behavior of PV and battery storage systems, but also gives credit to the MPPT control strategy.

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