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Maximum-Power-Point Approximation for Photovoltaic Arrays

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Abstract – **This paper describes various techniques to approximate the maximum power point (MPP) for photovoltaic arrays. The maximum power point tracking (MPPT) approaches have an importance role in PV systems by maximizing the PV output power, and therefore increasing the system electrical efficiency. Each technique has advantages and limitations. None of them is suitable for all applications. The decision is usually made by considering such factors as the complexity of the algorithm and circuitry, tracking accuracy, tracking speed, controller cost, available data and expertise of the user. In spite of MPP is approximated, such MPPT schemes are simple in their implementation, and provide satisfactory performance without complex circuitry.**

Keywords – Photovoltaic (PV) system, Maximum power point (MPP), Maximum power point tracking (MPPT).

1. INTRODUCTION

A substantial rise in global energy demand and growing concern about shortage on conventional energy reserves as well as environmental issues have drawn more attention to renewable energy sources. Combustion of the fossil fuels produces carbon dioxide (CO_2), which has the largest effect on global warming [1]. Accordingly, to mitigate the environmental problems and avoid an excessive dependence on fossil fuels, renewable energy sources have become more attractive. Solar energy has shown its potential for being an alternative energy source because it is available everywhere and more than enough for the global energy demand [2]. In addition to being essentially inexhaustible, sunlight is free and can be directly converted into electricity by means of solar cells.

Power generation systems based on the direct solar-to-electrical energy conversion are widely known as photovoltaic (PV) systems. In operation, solar cells produce neither pollution nor noise, have no moving parts and require no fuel. Therefore, they are environmentally friendly, almost maintenance-free and have low operating costs. Moreover, most solar cells are made of silicon, which is one of the cheap and most abundant materials on earth. Solar cells are usually interconnected to form PV modules, which may be connected to form PV arrays to increase power ratings. This modular feature of the PV modules means an extremely wide power range of the systems: from a few milliwatts for wristwatches or scientific calculators to megawatts for large central PV power stations [3].

Many research areas have been conducted on photovoltaics. Some have made improvements to conversion efficiencies of the solar cells by dealing with either their physical structure [4] or their materials [5]. In some cases, architecture along with savings of system installation costs is taken into account by integrating the modules into the building structure [6]. Some research has made efforts to increase the efficiencies of each system component and of the overall system. This type of study depends on the applications of the PV system.

PV systems can be widely classified into grid-connected and stand-alone types. In a grid-connected PV system, the array can be connected to the grid via a suitable inverter, the utility serves as a huge energy storage unit and thus no battery is required. On sunny days, the PV generator supplies power to the load in the domestic circuit, and surplus power is fed into the grid. During overcast days or at night the house draws power from the grid.

As the grid extension is more difficult owing to high costs of connection in remote households with their relatively low energy demand for lighting and communication, nearly 1.6 billion people have no access to electricity [7]. As the world population, especially in the rural areas of developing countries, grows rapidly, stand-alone PV systems have gained great acceptance for rural electrification. Since such systems are isolated from the public utility, batteries are required for energy storage. On a sunny day, the PV array supplies the load as well as charges the battery. When the power generated by the array is lower than that required by the load, the battery discharges to eliminate the power mismatch.

The PV system performance depends on the operating conditions. The PV array output characteristics depend mainly on the load and weather conditions. Since the PV electricity is expensive compared to that from conventional energy sources, the PV systems should be designed to provide their maximum output power in any environmental conditions. Therefore, a DC/DC converter is usually included into the PV system to maximize the array output power by using one of the so-called 'Maximum Power Point Tracking' (MPPT) approaches.

Many MPPT techniques have been developed and can be classified into 2 groups, i.e. direct and indirect methods. By means of the direct MPPT method the duty cycle of power switches in the DC/DC converter is continuously adjusted step by step in such way that the array output power increases until the maximum power is reached. On the other hand, the indirect MPPT method refers to a technique with which a voltage or current value related to the maximum power of the

PV array under a certain operating condition is estimated. Such estimation can be based on assumptions, sample measurements or mathematical models. This estimated voltage or current may then be used as a reference that the array voltage or current is forced by the DC/DC converter to meet. Though the maximum power is approximated, such MPPT scheme is simple in its implementation, and provides satisfactory performance without complex circuitry. Hereby, this paper will describe the details of various techniques that are classified as the indirect methods.

2. PV ARRAY OUTPUT CHARACTERISTICS AND MPP

A typical current-voltage characteristic curve of a PV array is shown in Fig. 1. Under a certain weather condition, as the terminals of the array is short-circuited, the output current generated by the array is called 'short-circuit current' (I_{sc}). For small output voltage values, the array current nearly equals to the I_{sc}. As the array voltage is increased, the array current reduces and becomes zero when the array terminals are open-circuited, where the array voltage becomes maximum and is named 'open-circuit voltage' (V_{oc}). The array output power can be derived from the product of the array current and voltage. The output power equals zero under short-circuit and open-circuit conditions. However, the output power is maximum at the so-called 'Maximum Power Point (MPP)', which is located at the knee of the curve. The array voltage and current that correspond to the MPP are referred to as the MPP voltage (V_{mpp}) and MPP current (I_{mpp}) respectively.

It is desirable to keep the array operate at or near the MPP all the time. However, the operating point of the array is affected by the load connected to the array itself. Intersection of the current-voltage curve and the load line dictates an operating point of the array. For instance, a DC load is connected across the array output, and so the operating point of the array is shown in Fig. 1. Therefore under a certain condition, the array may operate far from the MPP, and the power loss arises.

Apart from the load, the array output depends strongly on the weather conditions, i.e. light intensity that is incident on the array as well as the array temperature. When the solar cell is illuminated, electron-hole pairs are generated by means of the photoelectric absorption. The higher light intensity corresponds to a greater number of photons, and therefore more charge carriers are produced. The sum of the charge carriers generated in the solar cell material determines the output current of the solar cell [8]. Hence, the so-called 'photocurrent' (I_{ph}) is proportional to the light intensity, aka irradiance. In addition, the array current equals photocurrent under the short-circuit condition.

According to [2] the irradiance outside the Earth's atmosphere is between 130 and 140 mW/cm^2, which is called the 'extra-terrestrial radiation'. After being reflected, scattered and absorbed by the atmosphere, about 100 mW/cm^{2}is

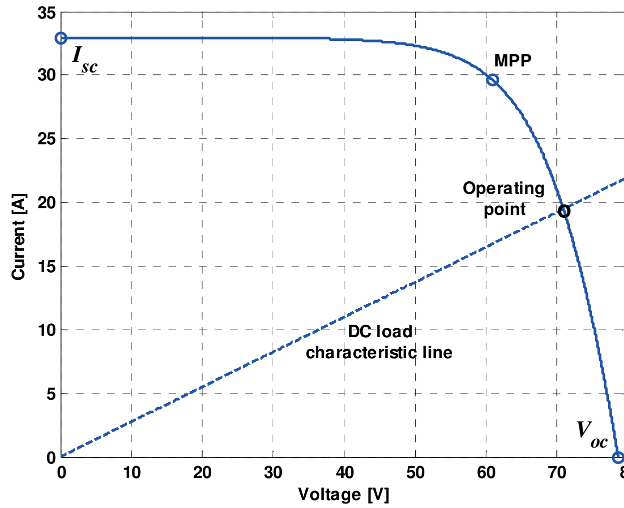

Figure 1 PV current-voltage characteristic curve versus DC load line

incident on the Earth's surface at midday when the sky is cloudless. The value of irradiance in an area may vary between 60 and 100 mW/cm^2 under a clear blue sky, between 20 and 40 mW/cm^2 under hazy weather conditions or when the sun is visible as a whitish yellow disc and between 5 and 15 mW/cm^2 under overcast sky. The current-voltage curves for various irradiance levels are presented in Fig. 2. Since the photocurrent varies linearly with the light intensity when the cell temperature is held constant. Therefore, the short-circuit current is directly proportional to the irradiance.

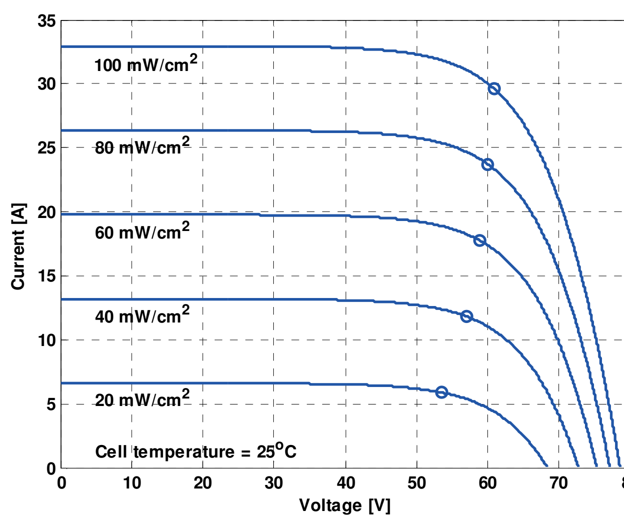

Figure 2 Effect of irradiance on current-voltage characteristics

In addition, without considering the parasitic resistance effects the open-circuit voltage of the array [9] can be expressed as

$$V_{oc} = \frac{n_s A k T_{cell}}{q} \ln\left(\frac{I_{ph}}{I_o} + 1\right), \tag{1}$$

where n_s is the number of series cells per string in the array, A is the p-n junction perfection factor of the solar cell, T_{cell} is the solar-cell temperature in Kelvin, I_o is the reverse saturation current of the solar cell in Ampere, k is the Boltzmann's constant (1.380658×10^{-23} J/K), and q is the electron charge (1.6×10^{-19} C). Equation (1) shows that while the photocurrent is linearly proportional to the light intensity, the open-circuit voltage varies logarithmically. The corresponding power-voltage curves are shown in Fig. 3. The array power clearly reduces with lower irradiance.

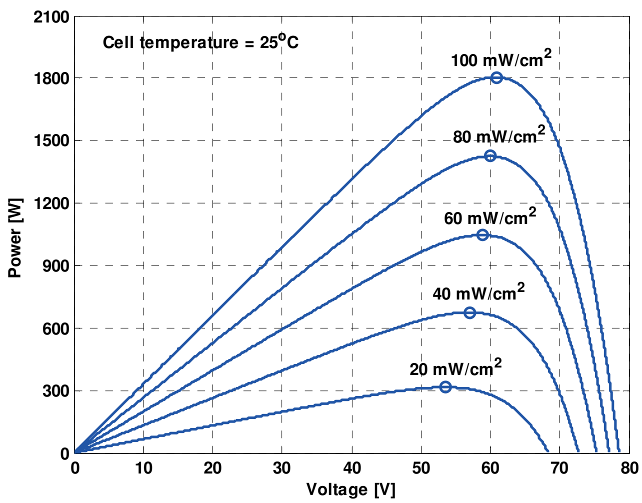

Figure 3 Effect of irradiance on power-voltage characteristics

The current-voltage curves for different cell temperatures are shown in Fig. 4. The photocurrent increases with rising cell temperature due to the narrower band gap and improvement in diffusion length of the charge carriers [8]. However, this effect on the short-circuit current is small, about 0.07%/°C for silicon cells [2]. The open-circuit voltage, on the other hand, strongly depends on the temperature. As seen in Equation (1), the open-circuit voltage would be directly proportional to the temperature. However, this is not the case because the reverse saturation current is also strongly temperature dependent. The rising temperature greatly increases the reverse saturation current. Furthermore, the open-circuit voltage is directly related to the band gap. Higher temperature reduces the band gap and therefore decreases the open-circuit voltage. As demonstrated in [8], the open-circuit voltage changes approximately linearly and inversely with the cell temperature, and the rate of change is about 0.4%/°C for silicon cells [2].

As the cell temperature rises, the increased short-circuit current is not sufficient to offset the detrimental effects of temperature upon the open-circuit voltage. Therefore, the conversion efficiency reduces at higher temperature. The rate of efficiency reduction with temperature is about 0.04-

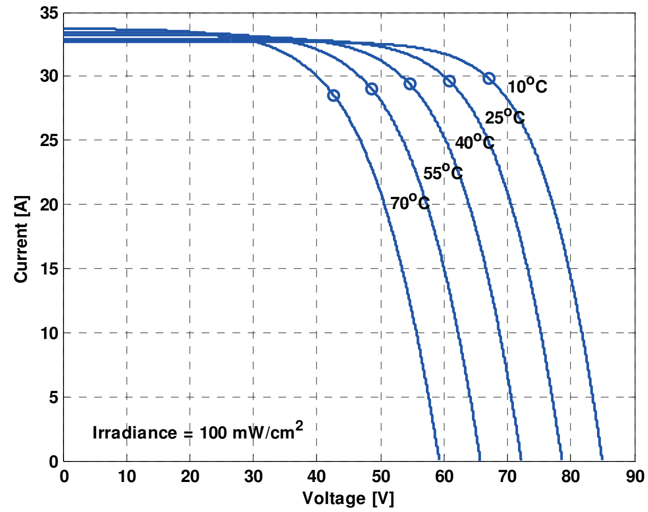

Figure 4 Effect of cell temperature on current-voltage characteristics

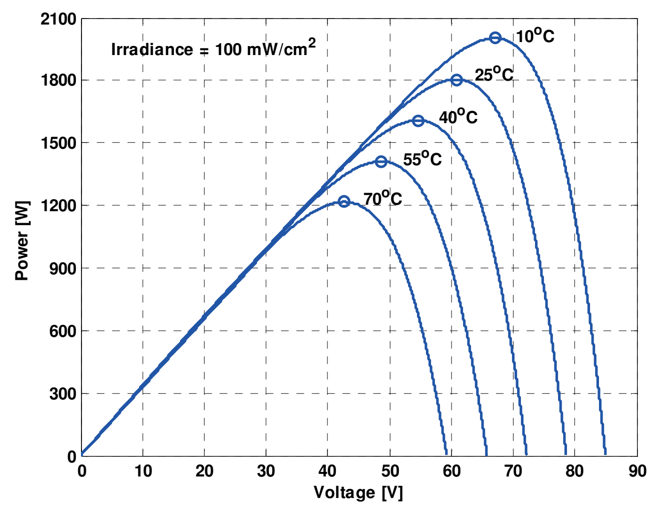

Figure 5 Effect of cell temperature on power-voltage characteristics

0.06%/°C for silicon cells [2]. Fig. 5 shows the temperature effect on the power-voltage characteristic. The output power is slightly affected at the voltage much below the MPP because the temperature effect on the short-circuit current is small.

Since the weather conditions vary according to seasons of the year, geological areas and the time of the day, the operating point of the PV array fluctuates and may not be at or even near the MPP. Therefore, a MPPT scheme should be included maximize the array output power all the time regardless of the weather fluctuations. In the next section, this paper will describe the details of various indirect MPPT techniques, which estimate the MPP voltage or current, to approximate the MPP.

3. MAXIMUM-POWER-POINT APPROXIMATION

Hereby, the features of different MPP approximation techniques are presented in an arbitrary order.

3.1 Array Reconfiguration

A simple MPPT technique is based on reconfiguration of the PV array. This strategy is implemented by rearranging the series and parallel connection of the modules in the array to match the load demand [10]. This technique is relatively straightforward, but has low tracking speed and accuracy and fails to seek the MPP in real time. Normally, both voltage and current sensors are needed and analog implementation is usually non-realistic. As a result, this method is not widely used.

3.2 Fractional Voltage

This technique is developed on the basis of simple direct relationships between the MPP voltage and open-circuit voltage. This 'fractional voltage' method is based on the assumption that the relationship between the open-circuit voltage and MPP voltage of a solar cell is approximately linear [11] and described as

$$V_{mpp} = k_v \cdot V_{oc}\,, \tag{2}$$

where V_{mpp} is the MPP voltage, V_{oc} is the open-circuit voltage, and k_v is a proportional coefficient. The value of k_v is obtained empirically and determined beforehand for a specific PV array under various irradiance and temperature conditions. For polycrystalline PV modules, the value of k_v between 0.71-0.80 is given in the literature [12, 13]. The value of V_{oc} is measured when having the array terminals open-circuited momentarily. This can be done by using the switching function of the DC/DC converter, e.g. during a turn-off interval of a switch in a buck converter. Following the measurement of V_{oc} the value of V_{mpp} can be calculated by using the predetermined k_v. By means of a closed-loop control the DC/DC converter then act in such a way that the array voltage reaches this desired V_{mpp}. The measurement of V_{oc} is carried out regularly, so the value of V_{mpp} is up-to-date and the tracking accuracy is maintained.

3.3 Fractional Current

Likewise, the assumption that the relationship between the short-circuit current and MPP current of a solar cell is approximately linear gives rise to the 'fractional current' technique [14], which is expressed as

$$I_{mpp} = k_i \cdot I_{sc}\,, \tag{3}$$

where I_{mpp} is the MPP current, I_{sc} is the short-circuit current, and k_i is a proportional coefficient. The value of k_i is derived empirically for a particular PV array at different values of irradiance and temperature and decided prior to implementation. For polycrystalline PV modules, the value of k_i between 0.78-0.92 is documented in the literature [12, 13]. Before the calculation of I_{mpp}, the array terminals are short-circuited briefly, so that I_{sc} is measured. This may require an extra switch as well as a current sensor. However by means of a boost converter, the array can be short-circuited and therefore the I_{sc} is measured during a turn-on interval of the converter's switch. Though the measurement of I_{sc} is carried out frequently to update the value of I_{mpp} in order to maintain the tracking accuracy.

Although the 'fractional voltage' and 'fractional current' techniques are inexpensive and simple to implement with analog circuits, they are applicable merely to a specific PV module. Optimum values of k_v and k_i are also difficult to obtain because they are really not constant but affected by weather conditions. Thus, the PV generator rarely operates at the MPP. In addition, these coefficients are influenced by module ageing, so they must be occasionally updated. Moreover, measurement of the open-circuit voltage or short-circuit current interrupts the normal system operation momentarily and therefore causes power loss.

3.4 Pilot Cell

To avoid frequent interruption of the system operation as required for the aforementioned techniques, the open-circuit voltage or short-circuit current can be measured from a single solar cell that is electrically isolated from the PV array [15]. The operating voltage or current of the PV array is subsequently set to a fixed multiple of the value measured from the single cell. This technique is based on the assumption that all solar cells of the PV array are identical. Any mismatch between the pilot cell and the array leads to power loss. Therefore, the cell must be carefully selected to represent the array characteristics.

3.5 Look-Up Table

Since the techniques described above neglect the effect of weather fluctuations, they can not accurately seek the MPP under varying environmental conditions. An attempt to include the effect of light intensity in MPPT is found in [16] by storing the information about the MPP for different irradiance levels in a look-up table in a computer. Here, the MPP voltage is looked up in the table against the measured open-circuit voltage of a PV module. However, this algorithm requires a large capacity of memory for data storage. Moreover, the method can be applied only to a specific PV module, and prior knowledge about the module is needed to generate the data stored in the look-up table.

3.6 Model-Based Prediction

For the case where MPP information for various weather conditions is available, a mathematical equation for the MPP voltage affected by the irradiance and the cell temperature can be established, and the coefficients of the equation are obtained using a curve-fitting technique [17]. For instance, the MPP voltages corresponding to different irradiance and cell temperature values are extracted from the available data, e.g. those given in Figs. 2 and 4. By including the temperature effect, the MPP voltages at different values of irradiance and cell temperature are plotted as shown in Fig. 6. Based on observation, the relationship between the MPP voltage and irradiance can be well described by a logarithmic function. Therefore, by means of curve-fitting technique applied to the data plotted in Fig. 6, the MPP voltage, V_{mpp}, may be expressed as in Equation (4).

$$V_{mpp} = 5 \cdot \ln(G) + 33 - 0.285 \cdot (T_{cell} - 40), \qquad (4)$$

where G is the irradiance in mW/cm^2, T_{cell} is the solar-cell temperature in Celsius. Although both irradiance and temperature effects are included, each equation is derived for a specific array. In addition, both irradiance and temperature sensors are required, therefore the system costs are increased.

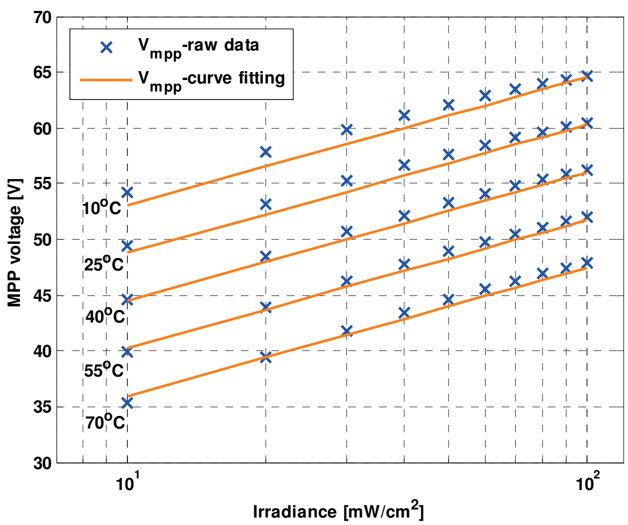

Figure 6 Effects of irradiance and cell temperature on MPP voltages

4. Discussion

Decision of which MPPT technique suits a given PV system generally depends on such factors as the ease of implementation, costs, tracking speed, and accuracy [12, 13]. Normally, it is more convenient and reliable to measure voltage. The fractional voltage technique is therefore preferable to the fractional current method because it may often be impractical to short-circuit the array terminals. In addition, current sensors are generally bigger and more expensive. Therefore, in case of large PV systems where individual arrays have their own MPP tracking device, the methods related to current sensing is inappropriate. Using only one voltage sensor and then estimating the current from the measured voltage value can be an interesting strategy. Although the fractional voltage, fractional current and pilot-cell methods are inferior to the others in terms of tracking speed due to frequent interruption in the normal system but for those who prefer analog systems they are good alternatives. In fact, ease of implementation relies also on expertise of the user. All techniques mentioned above can be applied using digital circuitry. Regarding the tracking accuracy the look-up table and model-based prediction techniques give better performance because the irradiance and temperature effects are included. However, their implementation complexity makes them impractical in analog circuitry. Moreover, irradiance value, which is necessary for the model-based prediction technique, is usually measured by a costly pyranometer. Apart from the type and number of sensors, cost comparison can be made by taking into account MPPT circuit topology, software or programming requirement. Analog circuitry is basically cheaper than digital implementation, which normally requires a microcontroller to be programmed.

It should be noted that an MPP corresponding to a specific weather condition relocates due to ageing effect. Thus, some parameters and constants used in the MPPT techniques should be retuned periodically in order to maintain the tracking accuracy. In addition, most of these techniques can seek the MPP under uniform irradiance on the PV module whereby only one MPP is present. However, multi-local MPPs are present when the array is partially shaded, and such techniques may not locate the real one. Though one possible solution in case of using the fractional voltage and fractional current methods is that the values of k_v and k_i are updated regularly, e.g. every few minutes, while sweeping the array voltage from open-circuit to short-circuit condition [18]. Nonetheless, the problem of partial shading is not investigated in this study.

5. Conclusions

MPPT algorithms have an importance role in PV systems by maximizing the PV output power, and in turn increasing the system electrical efficiency. In the literature, several methods for tracking the MPP have been developed. Each has advantages and limitations. None of them is suitable for all applications. The decision is usually made by considering such factors as the complexity of the algorithm and circuitry, tracking accuracy, tracking speed, controller cost, available data and expertise of the user. Most of these methods have been developed for grid-connected PV systems. For a stand-alone configuration with using limited computing power, we require the MPPT scheme to not only operate in high performance, but also be simple in its implementation, hence low in computation cost. Therefore, the indirect MPPT techniques are more of interest for small stand-alone systems. In spite of MPP is approximated, such MPPT schemes are simple in their implementation, and provide satisfactory performance without complex circuitry.

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7. BIOGRAPHY

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