COMPARATIVE STUDY OF TEN MAXIMUM POWER POINT TRACKING ALGORITHMS FOR PHOTOVOLTAIC SYSTEM

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The output characteristic of a photovoltaic array is nonlinear and changes with solar irradiation and the cell's temperature. A Maximum Power Point Tracking (MPPT) technique is needed to draw peak power from the solar array in order to maximize the produced energy. This paper presents a comparative study of ten widely-adopted MPPT algorithms; their performance is evaluated using the simulation tool Simulink®. In particular, this study compares the behaviors of each technique in the presence of solar irradiance variations.

Keywords: Maximum power point (MPP), maximum power point tracking (MPPT), photovoltaic (PV).

1. Introduction

Solar energy is one of the most important renewable energy sources. As opposed to conventional unrenewable resources such as gasoline, coal, etc..., solar energy is clean, inexhaustible and free.

The solar cell V-I characteristic is nonlinear and changes with irradiation and temperature. In general, there is a unique point on the V-I or V-P curve, called the Maximum Power Point (MPP), at which the entire PV system (array, inverter, etc…) operates with maximum efficiency and produces its maximum output power. The location of the MPP is not known, but can be located, either through calculation models or by search algorithms. Maximum Power Point Tracking (MPPT) techniques are used to maintain the PV array's operating point at the MPP.

In this paper, ten MPPT algorithms are considered: P&O [2-5], modified P&O [2-5], Three Point Weight Comparison [10], Constant Voltage (CV) [11], IC [2-6], IC and CV combined [11], Short Current Pulse [12], Open Circuit Voltage [13], the Temperature Method [14] and methods derived from it [14]. These techniques are easily implemented and have been widely adopted for low-cost applications. Algorithms such as Fuzzy Logic, Sliding Mode [7-9], etc…, are beyond the scope of this paper, because they are more complex and less often used.

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We will focus our attention on a grid-connected photovoltaic system constructed by connecting a dc/dc SEPIC converter between the solar panel and the grid. The MPPT techniques will be tested on solar panels with different types of insulation. The partially shaded condition will not be considered; thus radiation is assumed to be uniformly spread over the PV array.

2. PV Array

A mathematical model was developed in order to simulate a PV array. Fig. 1 gives the equivalent circuit of a single solar cell, where I_{PV} and V_{PV} are the PV array's current and voltage, respectively, I_{ph} is the cell's photocurrent, R_j represents the nonlinear resistance of the p-n junction, and R_{sh} and R_s are the intrinsic shunt and series resistances of the cell.

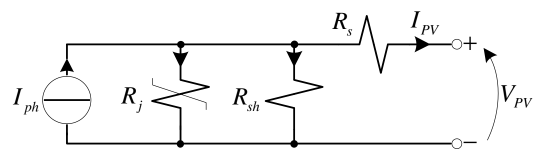


Fig. 1. Equivalent circuit of PV cell

Since R_{sh} is very large and R_s is very small, these terms can be neglected in order to simplify the electrical model. The following equation then describes the PV panel [6]:

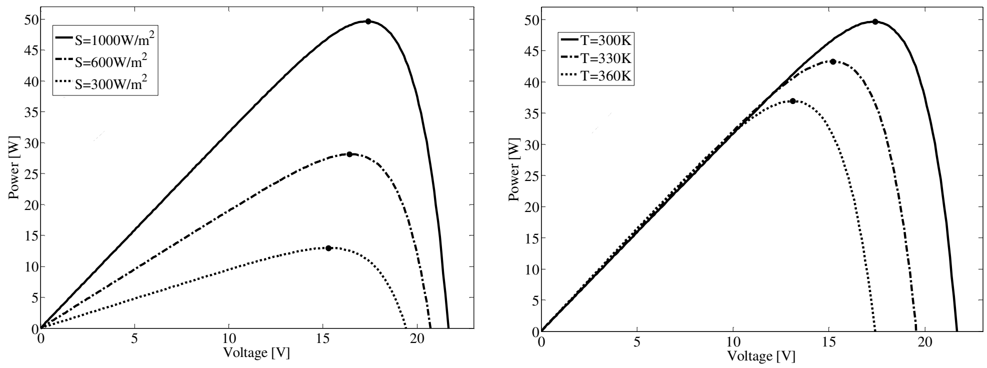
$$I_{PV} = n_p \cdot I_{ph} - n_p \cdot I_{rs} \cdot \left[\exp\left(\frac{q}{k \cdot T \cdot A} \cdot \frac{V_{PV}}{n_s} \right) - 1 \right] \tag{1}$$

where n_s=36 is the number of modules connected in series, n_p=1 is the number of modules connected in parallel, q=1.602·10^{-19} C is the electron charge, k=1.3806·10^{-23} $J{\cdot}K^{-1}$ is Boltzman's constant, A=2 is the p-n junction's ideality factor, T is the cell's temperature (K), I_{ph} is the cell's photocurrent (it depends on the solar radiation and temperature), and I_{rs} is the cell's reverse saturation current (it depends on temperature).

The PV panel we will consider is a typical 50W PV module. The module has 36 series-connected polycrystalline cells.

Fig. 2 shows the power output characteristics of the PV system as functions of irradiance and temperature, respectively. These curves are nonlinear and are crucially influenced by solar radiation and temperature.

The PV system is composed of three strings in parallel, each string consisting of 31 PV arrays in series. The total power installed is 4650W.



(a) (b)

Fig. 2. V-P characteristics for three different irradiance levels.

2. MPPT Control Algorithm

The MPP of the PV array changes continuously; consequently the PV system's operation point must change to maximize the energy produced. An MPPT technique is therefore used to maintain the PV array's operating point at its MPP. There are many MPPT methods available in the literature; the most widely-used techniques are described in the following sections, starting with the simplest method.

2.1 Constant Voltage Method

The Constant Voltage (CV) algorithm is the simplest MPPT control method. The operating point of the PV array is kept near the MPP by regulating the array voltage and matching it to a fixed reference voltage V_{ref}. This method assumes that individual insulation and temperature variations on the array are insignificant, and that the constant reference voltage is an adequate approximation of the true maximum power point.

It is important to observe that when the PV panel is in low insulation conditions, the CV technique is more effective than either the P&O method or the IC method (analyzed below), as shown in [11].

2.2 Short-Current Pulse Method

The Short-Current Pulse (SC) method achieves the MPP by giving a current command $I^{*}=I_{op}$ to a current-controlled power converter. In fact, the optimum operating current I_{op} for maximum output power is proportional to the short-circuit current I_{sc} under various conditions of irradiance level S as follows [12]: $I_{op}\left(S\right)=k\cdot I_{SC}\left(S\right)$ where k is a proportional constant. From this equation, it is clear that I_{op} can be determined instantaneously by detecting I_{sc}.

This control algorithm requires measurements of the current I_{sc}. To obtain this measurement, it is necessary to introduce a static switch in parallel with the PV array, in order to create the short-circuit condition. It is important to note that when V_{PV}=0 no power is supplied by the PV system; consequently the total energy generated by the PV system is reduced.

2.3 Open Voltage Method

The Open Voltage (OV) method is based on the observation that the voltage of the maximum power point is always close to a fixed percentage of the open-circuit voltage. Production spread, temperature, and solar insulation levels change the position of the maximum power point within a 2% tolerance band.

The OV technique uses 76% of the open-circuit voltage as the optimum operating voltage V_{op}, at which the maximum output power can be obtained.

This control algorithm requires measurements of the voltage V_{ov}. Here again it is necessary to introduce a static switch into the PV array; for the OV method, the switch must be connected in series to open the circuit. When I_{PV}=0 no power is supplied by the PV system; consequently the total energy generated by the PV system is reduced.

2.4 Perturb and Observe Methods

The P&O algorithms operate by periodically perturbing (i.e. incrementing or decrementing) the array terminal voltage and comparing the PV output power with that of the previous perturbation cycle. If the PV array operating voltage changes and power increases ($dP/dV_{PV}>0$), the control system moves the PV array operating point in that direction; otherwise the operating point is moved in the opposite direction. In the next perturbation cycle the algorithm continues in the same way.

There are three different P&O methods available in the literature. In the classic P&O technique (P&Oa), the perturbations of the PV operating point have a fixed magnitude. In our analysis, the magnitude of perturbation is *2 V*. In the optimized P&O technique (P&Ob), an average of several samples of the array power is used to dynamically adjust the magnitude of the perturbation of the PV operating point. In the three-point weight comparison method (P&Oc), the perturbation direction is decided by comparing the PV output power on three points of the *P-V* curve. These three points are the current operation point (A), a point B perturbed from point A, and a point C doubly perturbed in the opposite direction from point B.

2.5 Incremental Conductance Methods

The Incremental Conductance (IC) algorithm is based on the observation that the following equation holds at the MPP [2]: $(dI_{PV}/dV_{PV})+(I_{PV}/V_{PV})=0$ where I_{PV} and V_{PV} are the PV array current and voltage, respectively. When the operating point in the *P-V* plane is to the right of the MPP, $(dI_{PV}/dV_{PV})+(I_{PV}/V_{PV})<0$, whereas when the operating point is to the left of the MPP, $(dI_{PV}/dV_{PV})+(I_{PV}/V_{PV})>0$. Therefore the sign of the quantity $(dI_{PV}/dV_{PV})+(I_{PV}/V_{PV})$ indicates the correct direction of perturbation leading to the MPP. Through the IC algorithm it is therefore theoretically possible to know when the MPP has been reached, and thus when the perturbation can be stopped.The IC method offers good performance under rapidly changing atmospheric conditions.

There are two different IC methods available in the literature. The classic IC algorithm (ICa) requires, in order to determine the perturbation direction, a measurement of the voltage V_{PV} and a measurement of the current I_{PV}. The Two-Model MPPT Control (ICb) algorithm combines the CV control and the ICa methods, when the irradiation differs from the normalized insulation by more than 70% (under this irradiance level the CV method is used and upper the ICa method is adopted). This method requires an additional measurement, the solar irradiation *S*.

2.6 Temperature Methods

The open-circuit voltage of the solar cell varies with the cell temperature , whereas the short-circuit current is directly proportional to the irradiance level, and is relatively steady over cell temperature changes.

The open-circuit voltage V_{ov} can be described through the following equation [14]:

$$V_{ov} \cong V_{ovSTC} + \left(T - T_{STC}\right) \cdot {dV_{ov}}/{dT} \tag{2}$$

where V_{ovSTC}=21.8*V* is the open-circuit voltage under Standard Test Conditions (STC), (dV_{ov}/dT)=-0.08*V/K* is the temperature gradient, *T* is the cell temperature (*K*), and T_{STC} is the cell temperature under STC. On the other hand, the optimal voltage is described through following equation:

$$V_{op} \cong \left(u + s \cdot v\right) - T \cdot \left(w + s \cdot y\right) \tag{3}$$

There are two different temperature methods available in the literature. The Temperature Gradient (TG) algorithm uses the temperature *T* to determine the open-circuit voltage V_{ov} from equation (2). The optimum operating voltage V_{op} is then determined as in the OV technique, avoiding power losses. The Temperature Parametric equation method (TP) adopts equation (3) and determines the optimal voltage V_{op} instantaneously by measuring *T*.

6. Simulation and Numerical Results

The analysis presented in this paper assumes that solar irradiation changes according to the diagrams show in Fig. 3.

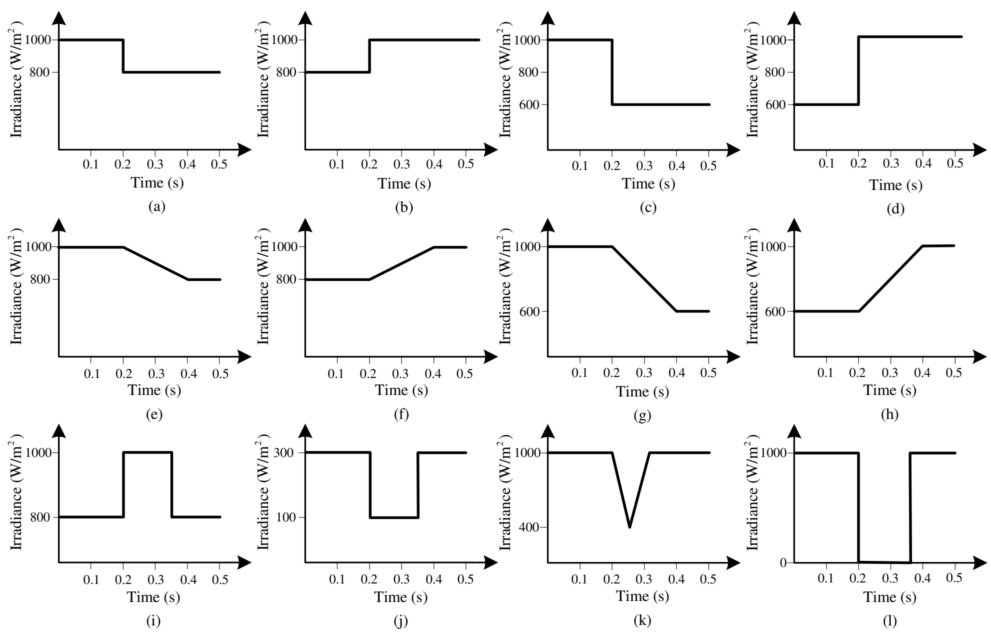


Fig. 3. Solar irradiance variations.

For each MPPT technique and for each input, the energy supplied by the PV system was calculated over a time interval of 0.5s. The results are shown in Table 1. For each input, the minimum (underlined) and maximum (bolded) obtained energy values are also indicated. From the data in Table 1, we note that the Perturb and Observe and Incremental Conductance algorithms have very similar performance and energetic production, and that they are superior to the other methods. This is confirmed by their widespread use in commercial implementations. The ICb technique provides the greatest energy supply for ten of the twelve inputs considered.

Comparing the two different IC techniques for very low irradiance values, it can be observed that the ICb method is more advantageous than the ICa method when the solar insulation has a value less than $300W/m^2$ (for the input in Fig.3j, $E_{ICb(j)}$ is 446.3J while $E_{ICa(j)}$ is 411.6J).

The behaviour of the P&Oc technique is very different from that of the other two P&O techniques. This result is explained by the fact that an additional MPPT cycle is needed to choose the perturbation direction.

The Open Voltage and Short-Current Pulse techniques have the largest hardware cost (they require an additional static switch), yet they provide low energy supply with respect to the P&O and IC algorithms. This is mainly due to power annulment during electronic switching. Moreover, the choice of sampling period is very critical for these techniques; if the period is too short, energy production will be very low because of the increased number of electronic switching. If the period is too long, on the other hand, the MPP cannot be closely followed when rapid irradiance variation occurs.

Table 1

Electrical characteristics of PV array

In	CV [J]	SC [J]	OV [J]	P&Oa [J]	P&Ob [J]	P&Oc [J]	ICa [J]	ICb [J]	TG [J]	TP [J]
(a)	1359	1539	1627	1695	1707	1490	**1708**	**1708**	1562	1681
(b)	1410	1687	1700	1774	1781	1558	**1782**	**1782**	1643	1761
(c)	1192	1337	1403	1465	1476	1301	**1478**	**1478**	1311	1424
(d)	1290	1492	1552	1625	**1628**	1416	**1628**	**1628**	1476	1589
(e)	1403	1659	1699	1769	1780	1543	**1782**	**1782**	1643	1762
(f)	1363	1636	1630	1692	1697	1508	**1709**	**1709**	1563	1683
(g)	1298	1351	1552	1617	1627	1432	**1630**	**1630**	1477	1593
(h)	1204	1397	1409	1441	1431	1311	**1479**	**1479**	1314	1429
(i)	1339	1562	1595	1664	1671	1480	**1672**	**1672**	1522	1642
(j)	386.2	398.4	401.1	445.2	**446.3**	437.5	411.6	**446.3**	354.8	354.8
(k)	1410	1589	1730	1801	**1812**	1567	1808	1810	1681	1795
(l)	1036	1247	1245	1332	**1343**	1153	1250	1333	1259	1338

Unlike the other MPPT algorithms, which cyclically perturb the system, the temperature methods continuously calculate and update the correct voltage reference. In particular, the TP method provides only slightly less energy than the P&O and IC techniques. The TG method does not have the same efficiency, since equation (2) calculates the open-circuit voltage rather than the actual optimal voltage. Therefore the error introduced through the open-circuit voltage calculation (absent in the TP algorithm) must be summed with the error introduced in the voltage reference computation.

Finally, the CV technique is the worst of the ten MPPT methods analysed here. In fact, this technique does not follow the MPP, but instead fixes the reference voltage to the optimal voltage under Standard Test Condition values, holding it constant under any operating condition.

6. Conclusions

This paper has presented a comparison among ten different Maximum Power Point Tracking techniques. In particular, twelve different types of solar insulation were considered, and the energy supplied by a complete PV system was calculated. The results indicate that the P&O and IC algorithms are in general the most efficient of the analysed MPPT techniques. Furthermore, P&O and IC methods do not require additional static switches, as opposed to the CV and OV techniques.

The P&Oc method, unlike other P&O methods, has low efficiency because of its lack of speed in tracking the MPP.

Although the ICb method has the greatest efficiency, this does not justify the cost of using one more sensor than the ICa method. In fact, the two IC techniques have very similar efficiency.

The TP temperature technique produces good results; nevertheless it introduces two inconveniences: first of all variations in parameters of (3) create error in the optimal voltage V_{op} evaluation; secondarily the measured temperature may be affected by phenomena unrelated to the solar insulation.

Further research on this subject should focus on experimental comparisons between these techniques, especially under shadow conditions.

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