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Energy Comparison of MPPT techniques for PV Systems

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Abstract: - *Many maximum power point tracking techniques for photovoltaic systems have been developed to maximize the produced energy and a lot of these are well established in the literature. These techniques vary in many aspects as: simplicity, convergence speed, digital or analogical implementation, sensors required, cost, range of effectiveness, and in other aspects. This paper presents a comparative study of ten widely-adopted MPPT algorithms; their performance is evaluated on the energy point of view, by using the simulation tool Simulink®, considering different solar irradiance variations.*

Key-Words: - *Maximum power point (MPP), maximum power point tracking (MPPT), photovoltaic (PV), comparative study, PV Converter.*

I. 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 main applications of photovoltaic (PV) systems are in either stand-alone (water pumping, domestic and street lighting, electric vehicles, military and space applications) [1-2] or grid-connected configurations (hybrid systems, power plants) [3].

Unfortunately, PV generation systems have two major problems: the conversion efficiency of electric power generation is very low (9÷17%), especially under low irradiation conditions, and the amount of electric power generated by solar arrays changes continuously with weather conditions.

Moreover, the solar cell V-I characteristic is nonlinear and varies 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, converter, 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. Therefore Maximum Power Point Tracking (MPPT) techniques are needed to maintain the PV array's operating point at its MPP.

Many MPPT techniques have been proposed in the literature; examples are the Perturb and Observe (P&O) methods [4-7], the Incremental Conductance (IC) methods [4-8], the Artificial Neural Network method [9], the Fuzzy Logic method [10], etc...

These techniques vary between them in many aspects, including simplicity, convergence speed, hardware implementation, sensors required, cost, range of effectiveness and need for parameterization.

The P&O and IC techniques, as well as variants thereof, are the most widely used.

In this paper, ten MPPT algorithms are compared under the energy production point of view: P&O, modified P&O, Three Point Weight Comparison [12], Constant Voltage (CV) [13], IC, IC and CV combined [13], Short Current Pulse [14], Open Circuit Voltage [15], the Temperature Method [16] and methods derived from it [16]. These techniques are easily implemented and have been widely adopted for low-cost applications. Algorithms such as Fuzzy Logic, Sliding Mode [11], etc…, are beyond the scope of this paper, because they are more complex and less often used.

The MPPT techniques will be compared, by using Matlab tool Simulink®, created by MathWorks, considering different types of insulation and solar irradiance variations. The partially shaded condition will not be considered: the irradiation is assumed to be uniformly spread over the PV array.

The PV system implementation takes into account the mathematical model of each component, as well as actual component specifications. In particular, without lack of generality, we will focus our attention on a stand-alone photovoltaic system constructed by connecting the dc/dc Single Ended Primary Inductor Converter (SEPIC) [17-18] between the solar panel and the dc load as reported in Fig.1.

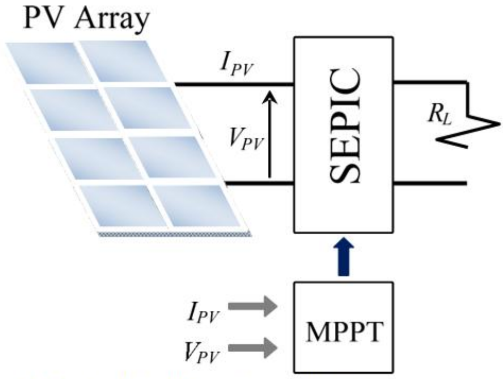

Fig. 1. Stand-alone PV system analyzed.

II. PV ARRAY

A mathematical model is developed in order to simulate the PV array. Fig. 2 gives the equivalent influenced 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.

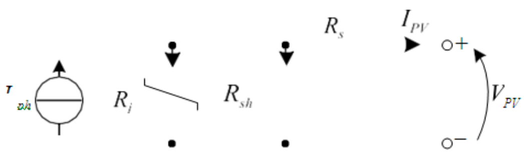

Fig. 2. Equivalent circuit of PV cell

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 [8]:

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

where n_s and n_p are the number of cells connected in series and the in parallel, q=1.602·10^{-19} C is the electron charge, k=1.3806·10^{-23} J·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 irradiation and temperature), and I_{rs} is the cell's reverse saturation current (it depends on temperature).

The PV panel here considered is a typical 50W PV module composed by n_s=36 series-connected polycrystalline cells (n_p=1). Its main specifications are shown in Table 1 while Fig. 2 and Fig. 3 show the power output characteristics of the PV panel as functions of irradiance and temperature, respectively. These curves are nonlinear and are crucially influenced by solar radiation and temperature.

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

Table 1. Electrical characteristics of PV panel with an irradiance level of 1000 W/m^2

Symbol	Quantity	Value
PMPP	Maximum Power	50 W
VMPP	Voltage at P_{MPP}	17.3 V
IMPP	Voltage at I_{MPP}	2.89 A
ISC	Short-Circuit Current	3.17 A
VOV	Open-Circuit Voltage	21.8 V
TSC	Temperature coefficient of I_{SC}	(0.065±0.015)%/°C
TOC	Temperature coefficient of V_{OC}	-(80±10) mV/°C

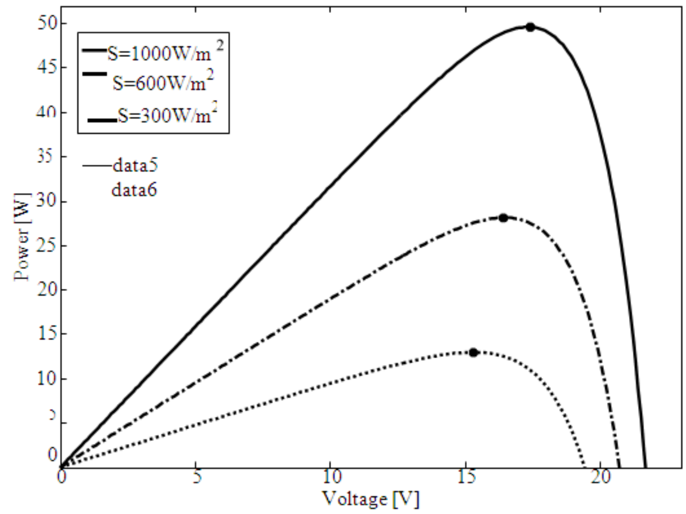

Fig. 3. V-P panel characteristics for three different irradiance levels. Each point represents the MPP of related curve.

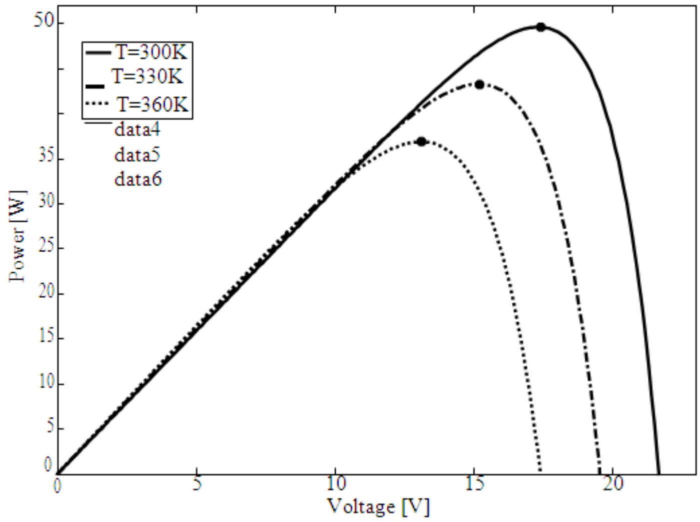

Fig. 4. V-P panel characteristics for three different temperature levels. Each point represents the MPP of related curve.

III. MPPT CONTROL ALGORITHM

As known the output power characteristics of the PV system as functions of irradiance and temperature curves are nonlinear and are crucially influenced by solar irradiation and temperature. Furthermore, the daily solar irradiation diagram has abrupt variations during the day, as shown in Fig. 5. Under these conditions, the MPP of the PV array changes continuously; consequently the PV system's operating 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.

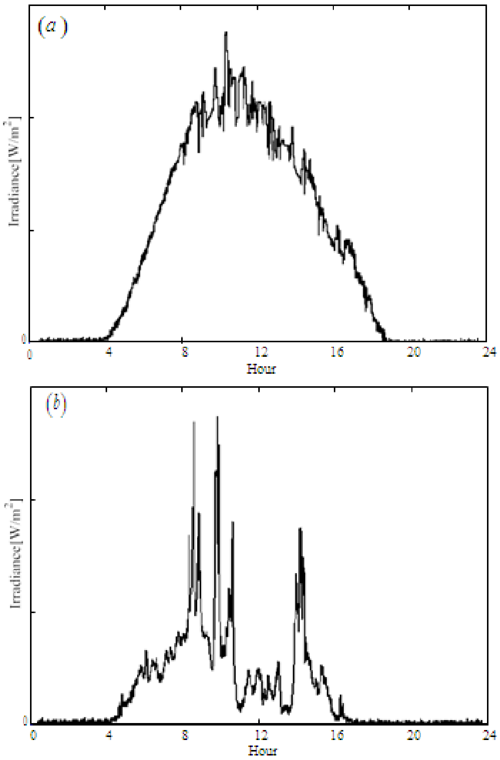

Fig. 5. Daily solar irradiation diagram: (a) sunny day (b) cloudy day.

3.1 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}. The V_{ref} value is set equal to the V_{MPP} of the characteristic PV module (see Table 1) or to another calculated best fixed voltage. 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 MPP. Operation is therefore never exactly at the MPP and different data has to be collected for different geographical regions.

The CV method does not require any input. However, measurement of the voltage V_{PV} is necessary in order to set up the duty-cycle of the dc/dc SEPIC by PI regulator, as shown in the block diagram of Fig. 6.

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) [13]. Thanks to this characteristic, CV is sometime combined together with other MPPT techniques.

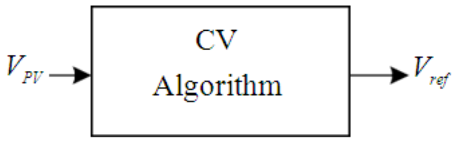

Fig. 6. CV block diagram.

3.2 Short-Current Pulse Method

The Short-Current Pulse (SC) method achieves the MPP by giving the operating current 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:

$$I_{op}(S) = k \cdot I_{SC}(S) \qquad (2)$$

where k is a proportional constant. Eq. (2) shows that I_{op} can be determined instantaneously by detecting I_{SC}. The relationship between I_{op} and I_{SC} is still proportional, even though the temperature varies from 0°C to 60°C. The proportional parameter is estimated to be approximately 92% [14].

Therefore, 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 during the short-circuit V_{PV}=0 consequently no power is supplied by the PV system and no energy is generated. As in the previous technique, measurement of the PV array voltage V_{PV} is required for the PI regulator (see Fig. 7) in order to obtain the V_{ref} value able to generate the current I_{op}.

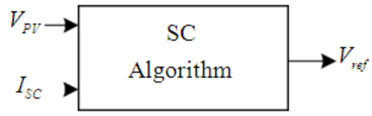

Fig. 7. SC block diagram.

3.3 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. Temperature and solar insulation levels change the position of the maximum power point within a 2% tolerance band.

In general, the OV technique uses 76% of the open-circuit voltage V_{OV} 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} (see Fig. 8). 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 and consequently the total energy generated by the PV system is reduced. Also in this method measurement of the voltage V_{PV} is required for the PI regulator.

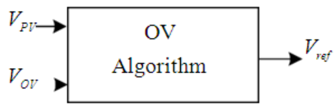

Fig. 8. OV block diagram.

3.3 Perturb and Observe Methods

The P&O algorithms operate by periodically perturbing (i.e. incrementing or decrementing) the array terminal voltage or current 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.

A common problem in P&O algorithms is that the array terminal voltage is perturbed every MPPT cycle; therefore when the MPP is reached, the output power oscillates around the maximum, resulting in power loss in the PV system. This is especially true in constant or slowly-varying atmospheric conditions.

Furthermore, P&O methods can fail under rapidly changing atmospheric conditions (see Fig. 9). Starting from an operating point A, if atmospheric conditions stay approximately constant, a perturbation ⊗V the voltage V will bring the operating point to B and the perturbation will be reversed due to a decrease in power. However, if the irradiance increases and shifts the power curve from P_1 to P_2 within one sampling period, the operating point will move from A to C. This represents an increase in power and the perturbation is kept the same. Consequently, the operating point diverges from the MPP and will keep diverging if the irradiance steadily increases.

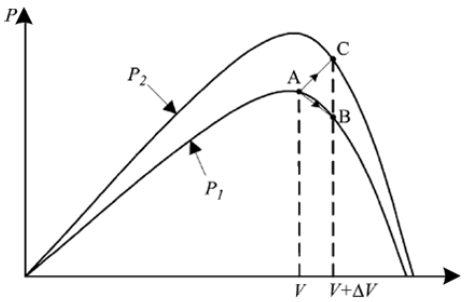

Fig. 9. Divergence of P&O from MPP [19].

There are many different P&O methods available in the literature. In this paper we consider the classic, the optimized and the three-points weight comparison algorithms.

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 0.37% of the PV array V_{OV} (around 2V)

In the optimized P&O technique (P&Ob), an average of several samples of the array power is used to dynamically adjust the perturbation magnitude 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.
All three algorithms require two measurements: a measurement of the voltage V_{PV} and a measurement of the current I_{PV} (see Fig. 10).

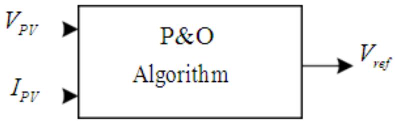

Fig. 10. P&O block diagram.

IV. COSTS COMPARISON

To complete our analysis a simple discussion about the cost of the MPPT technique is presented [20]. A satisfactory MPPT costs comparison can be carried out by knowing the technique (analogical or digital) adopted in the control device, the number of sensors, and the use of additional power component, considering the other costs (power components, electronic components, boards, etc…) equal for all the devices.

The MPPT implementation typology greatly depends on the end-users' knowledge, with analogical circuit, SC, OV, or CV are good options, otherwise with digital circuit that require the use of microcontroller, P&O, IC, and temperature methods are enough easily to implement. Moreover it is important to underline that analogical implementations are generally cheaper than digital (the microcontroller and relative program are expensive). To make all the cost comparable between them, the computation cost comparison is formulated taking into account the present spread of MPPT methods.

The number of sensors required to implement the MPPT technique also affects the final costs. Most of the time, it is easier and more reliable to measure voltage than current and the current sensors are usually more expensive and bulky. The irradiance or temperature sensors are very expensive and uncommon.

V. CONCLUSION

This paper has presented a comparison among ten different Maximum Power Point Tracking techniques in relation to their performance and implementation costs. In particular, fourteen different types of solar insulation are considered, and the energy supplied by a complete PV array is calculated; furthermore, regarding the MPPT implementation costs, a cost comparison is proposed taking into consideration the costs of sensors, microcontroller and additional power components.

A ranking of the ten methods has been proposed. Taking into account the analysis results along with hardware and computational costs, the P&Ob and ICa methods receive the best rankings.

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