Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions

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Abstract: As the maximum power operating point (MPOP) of photovoltaic (PV) power generation systems changes with changing atmospheric conditions (e.g. solar radiation and temperature), an important consideration in the design of efficient PV systems is to track the MPOP correctly. Many maximum power tracking (MPT) techniques have been considered in the past but techniques using microprocessors with appropriate MPT algorithms are favoured because of their flexibility and compatibility with different PV arrays. Although the efficiency of these MPT algorithms is usually high, it drops noticeably in cases of rapidly changing atmospheric conditions. The authors have developed a new MPT algorithm based on the fact that the MPOP of a PV generator can be tracked accurately by comparing the incremental and instantaneous conductances of the PV array. The work was carried out by both simulation and experiment, with results showing that the developed incremental conductance (IncCond) algorithm has successfully tracked the MPOP, even in cases of rapidly changing atmospheric conditions, and has higher efficiency than ordinary algorithms in terms of total PV energy transferred to the load.

1 Introduction

A powerful attraction of PV systems is that they produce electric power without harming the environment, by directly transforming a free inexhaustible source of energy, solar radiation, into electricity. This fact, together with the continuing decrease in PV arrays cost (tenfold in the last two decades) and the increase in their efficiency (threefold over the same period), imply a promising role for PV generation systems in the near future [1].

The dependence of power generated by a PV array and its MPOP on atmospheric conditions can readily be seen in the current–voltage (I–V) and the power–voltage (P–V) characteristics of PV arrays as shown in Fig. 1.

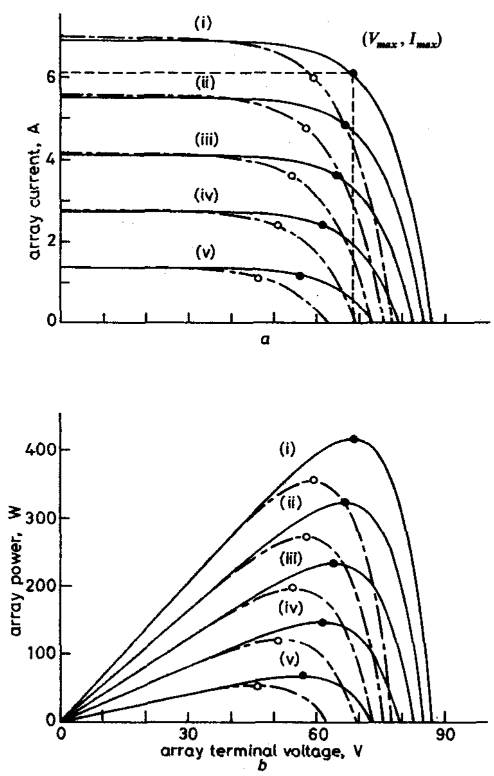

Fig. 1 *Simulated characteristics of the PV array*
a Current–voltage
b Power–voltage
——— 28°C
– – – – 56°C
(i) radiation = 100 mW/cm²
(ii) radiation = 80 mW/cm²
(iii) radiation = 60 mW/cm²
(iv) radiation = 40 mW/cm²
(v) radiation = 20 mW/cm²

The nonlinear nature of PV systems is apparent from Fig. 1, i.e. the array current and power depend on the array terminal operating voltage. Moreover, the MPOP (denoted as (V_{max}, I_{max})) changes with changing radiation and temperature, implying continuous adjustment of the array terminal voltage if maximum power is to be transferred.

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Different techniques to maximise PV power transfer to various loads have been reported in the literature: some depend on the selection of the PV module characteristics to suit particular loads [2, 3], others require changing the array configuration (switching the modules parallel–series connections) in order to match the MPOP to the load line [4]. However, these techniques only approximate the maximum transfer of PV energy because they are associated with specific atmospheric and load conditions: when these conditions are changed, a loss of energy results. Another class of maximisation, or MPT, is based on continuous adjustment of the load seen by the PV array to coincide with its MPOP, as will be explained in the following sections. MPT can be achieved using discrete circuit elements and sensors, however, the use of microprocessors or microcontrollers has the extra advantages of control flexibility and ease of application with different types of PV arrays [5]. The heart of MPT techniques is the software algorithm that hunts for the MPOP relying on measured aray parameters (voltage, current and power).

A frequently used class of MPT algorithms operates by continuously changing the operating point of the PV array and detecting the corresponding change in the array output power; therefore they are known as 'perturb and observe (P&O)' algorithms. The new IncCond algorithm presented in this paper is a software development of a previous MPT technique constructed using discrete circuit elements to overcome the drawbacks of the P&O algorithms [6]. In the paper, models and simulations of our PV array and MPT algorithms are presented together with analysis of the achieved simulation and experimental results. An evaluation of the performance of the developed MPT algorithm is also given.

2 Simulation of the PV array

The building block of PV arrays is the solar cell, which is basically a *p–n* semiconductor junction that directly converts light energy into electricity: it has the equivalent circuit shown in Fig. 2 [7]. The current source I_{Ph} represents the cell photocurrent; R_j is used to represent the nonlinear impedance of the p–n junction; R_{sh} and R_s are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of R_{sh} is very large and that of R_s is very small, hence they may be neglected to simplify the analysis. PV cells are grouped in larger units called PV modules which are further interconnected in a parallel–series configuration to form PV arrays or PV generators.

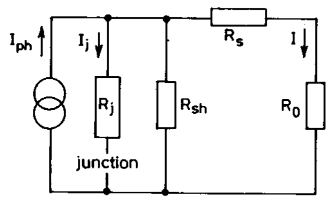

Fig. 2 *Equivalent circuit of a PV cell*

To simulate our PV array, a PV mathematical model was used according to the following set of equations:

$$I = n_p I_{Ph} - n_p I_{rs}\left[\exp\left(\frac{q}{kTA}\frac{V}{n_s}\right) - 1\right] \tag{1}$$

where I is the PV array output current (A); V is the PV array output voltage (V); n_s is the number of cells connected in series; n_p is the number of modules connected in parallel; q is the charge of an electron; k is Boltzmann's constant; A is the p–n junction ideality factor; T is the cell temperature (K); and I_{rs} is the cell reverse saturation current. The factor A in eqn. 1 determines the cell deviation from the ideal p–n junction characteristics; it ranges between 1 and 5, 1 being the ideal value [9]. In our case, $A = 2.46$.

The cell reverse saturation current I_{rs} varies with temperature according to the following equation from Reference 8:

$$I_{rs} = I_{rr}\left[\frac{T}{T_r}\right]^3 \exp\left(\frac{qE_G}{kA}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right) \tag{2}$$

where T_r is the cell reference temperature, I_{rr} is the reverse saturation current at T_r, and E_G is the band-gap energy of the semiconductor used in the cell. The photocurrent I_{Ph} depends on the solar radiation and the cell temperature as follows [8]:

$$I_{Ph} = [I_{scr} + k_i(T - T_r)]\,\frac{S}{100} \tag{3}$$

where I_{scr} is the cell short-circuit current at reference temperature and radiation, k_i is the short circuit current temperature coefficient, and S is the solar radiation in mW/cm^2. The PV array power P can be calculated using eqn. 1 as follows:

$$P = IV = n_p I_{Ph} V - n_p I_{rs} V\left[\exp\left(\frac{q}{kTA}\frac{V}{n_s}\right) - 1\right] \tag{4}$$

from which the MPOP voltage V_{max} can be calculated by setting $dP/dV = 0$; thus at the MPOP

$$\exp\left(\frac{q}{kTA}\frac{V_{max}}{n_s}\right)\left[\left(\frac{q}{kTA}\frac{V_{max}}{n_s}\right) + 1\right] = \frac{I_{Ph} + I_{rs}}{I_{rs}} \tag{5}$$

Solving eqn. 5 using numerical methods, V_{max} can be calculated as a function of I_{Ph} and I_{rs}, which are in turn functions of the atmospheric conditions (S and T).

By making step variations in the solar radiation S and the cell temperature T in eqns. 1–4, the I–V and the P–V characteristics of the PV array were simulated as shown earlier in Fig. 1. Simulation of the PV array provides a flexible means of analysing and comparing the performance of different MPT algorithms when operated under randomly varying solar radiation and cell temperature, as will be demonstrated shortly.

3 Perturb and observe MPT algorithms

P&O algorithms are widely used in MPT because of their simple structure and the few measured parameters which are required. They operate by periodically perturbing (i.e. incrementing or decrementing) the array terminal voltage and comparing the PV output power with that of the previous pertubation cycle. If the power is increasing, the perturbation will continue in the same direction in the next cycle, otherwise the perturbation direction will be reversed. This means the array terminal voltage is perturbed every MPT cycle; therefore when the MPOP is reached, the P&O algorithm will oscillate around it resulting in a loss of PV power, especially in cases of constant or slowly varying atmospheric conditions. This problem can be solved by improving the logic of the P&O algorithm to compare the parameters of two preceding cycles in order to check when the MPOP is reached, and bypass the perturbation stage [10]. Another way to reduce the power loss around the MPOP is to decrease the perturbation step, however, the algorithm will be slow in following the MPOP when the atmospheric conditions start to vary and more power will be lost.

In cases of rapidly changing atmospheric conditions, as a result of moving clouds, it was noted that the P&O MPT algorithm deviates from the MPOP: this can be explained by considering the change in solar radiation as shown in Fig. 3. Assume that initially the array operating

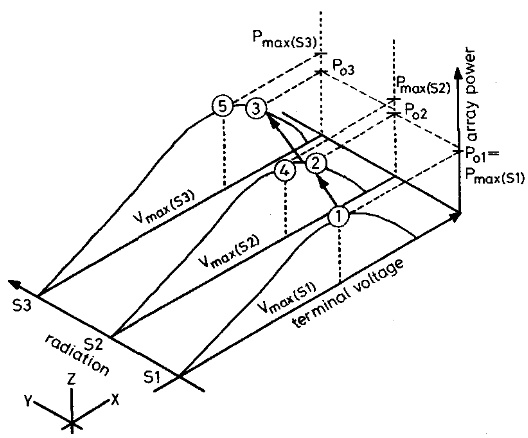

Fig. 3 *Deviation of the P&O algorithm from the MPOP*
$P_{o3} > P_{o2} > P_{o1}$
but
$P_{o3} < P_{max}(S3)$
$P_{o2} < P_{max}(S2)$

voltage, *Point(1)*, coincides with the MPOP when a perturbation is made towards *Point(2)*. Now, an increase in the array power will be measured because the solar radiation has increased from S_1 to S_2. However, for the P&O algorithm, the power has increased because the new MPOP is towards the right whereas it has already been passed, i.e. *Point(4)*. In the following perturbation the P&O algorithm will increment the array operating voltage further right, *point(3)*, and again an increase in the array power will be measured because the solar radiation has increased from S_2 to S_3 with a new MPOP, *Point(5)*. In this way, the P&O algorithm will continue to deviate from the actual MPOP, with a corresponding power loss, until the solar radiation change slows or settles down.

To solve this problem, the authors developed the IncCond algorithm which tracks the MPOP of the PV array using a different technique.

4 Incremental conductance MPT algorithm

From the previous section we can conclude that the failure of the P&O algorithm to follow rapidly varying atmospheric conditions is due to its inability to relate the change in the PV array power to the change in the atmospheric conditions. The change in power is only considered to be a result of the array terminal voltage perturbation. In other words, the P&O algorithm cannot compare the array terminal voltage with the actual MPOP voltage.

Avoiding the P&O algorithm drawbacks formed the basis of the IncCond algorithm in which the array terminal voltage is always adjusted according to its value relative to the MPOP voltage. The basic idea is that at the MPOP the derivative of the power with respect to the voltage vanishes because the MPOP is the maximum of the power curve, as shown in Fig. 1*b*. Also from Fig. 1*b* we note that to the left of the MPOP the power is increasing with the voltage, i.e. $dP/dV > 0$, and it is decreasing to the right of the MPOP, i.e. $dP/dV < 0$. This can be rewritten in the following simple equations:

$$dP/dV = 0 \quad \text{at the MPOP} \tag{6}$$

$$dP/dV > 0 \quad \text{to the left of the MPOP} \tag{7}$$

$$dP/dV < 0 \quad \text{to the right of the MPOP} \tag{8}$$

These relations can further be written in terms of the array current and voltage using

$$dP/dV = d(IV)/dV = I + V\, dI/dV \tag{9}$$

Hence, the PV array terminal voltage can be adjusted relative to the MPOP voltage by measuring the incremental and instantaneous array conductances (dI/dV and I/V, respectively) and making use of eqns. 6–9. The detailed operation of the IncCond algorithm can be followed with reference to the flow chart of Fig. 4.

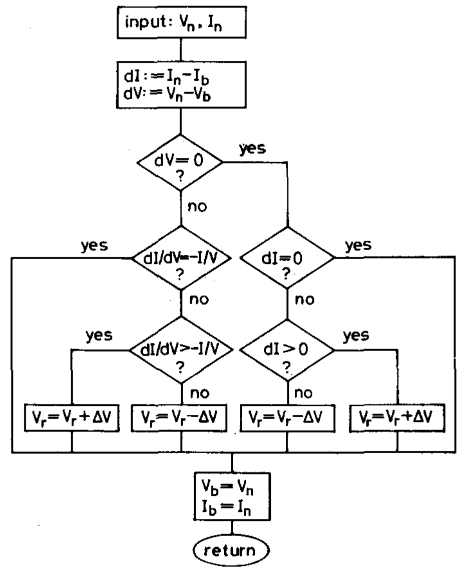

Fig. 4 *Flow chart of the IncCond MPT algorithm*

The algorithm starts its cycle by obtaining the present values of I and V, then using the corresponding values stored at the end of the preceding cycle, I_b and V_b, the incremental changes are approximated as: $dI \approx I - I_b$, and $dV \approx V - V_b$. The main check is carried out by comparing dI/dV against $-I/V$, and according to the result of this check, the control reference signal V_{ref} will be adjusted in order to move the array terminal voltage towards the MPOP voltage. At the MPOP, $dI/dV = -I/V$, no control action is needed, therefore the adjustment stage will be bypassed and the algorithm will update the stored parameters at the end of the cycle as usual. Two other checks are included in the algorithm to detect whether a control action is required when the array was operating at the MPOP in the preceding cycle ($dv = 0$); in this case the change in the atmospheric conditions is detected using ($dI \neq 0$). Now the control signal V_{ref} adjustment will depend on whether dI is positive or negative, as shown in the flow chart.

When the above IncCond MPT algorithm was tested we noted that the condition $dP/dV = 0$ (or $dI/dV = -I/V$) seldom occurred because of the approximation made in the calculation of dI and dV. However, this condition can be detected by allowing a small marginal error (E) in the above comparisons, i.e. $dP/dV = \pm E$ and the value of E depends on the required sensitivity of MPT.

Next, simulation programs were used to evaluate the overall performance of the IncCond MPT algorithm in comparison with the P&O algorithms described earlier. The PV array was simulated using the model presented by eqns. 1–4 and the solar radiation was simulated to be varying randomly with a normal distribution [11]. Two P&O algorithms were developed for the comparison: one following the typical P&O algorithm described earlier and the other modified to avoid the oscillation around the MPOP [10]. The results of the simulation are shown in Fig. 5.

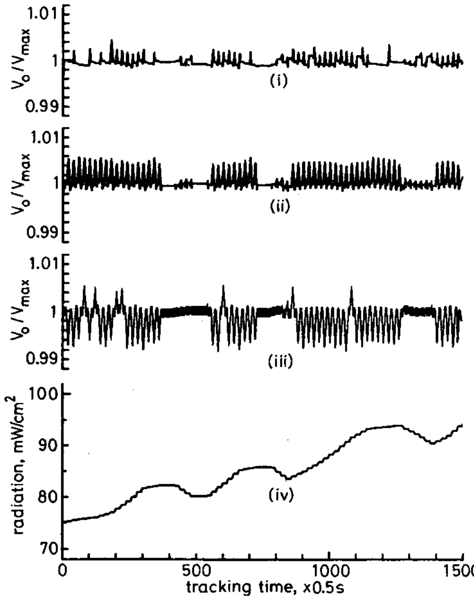

Fig. 5 *Simulation results comparing the IncCond algorithm with the P&O algorithms*

(i) Incremental conductance algorithm
(ii) Modified P&O algorithm
(iii) P&O algorithm
(iv) Solar radiation

In Fig. 5, the PV array terminal voltage controlled by the different algorithms is shown relative to the theoretical MPOP voltage (V_{max}) calculated using eqn. 5 as a means of measuring the deviation of each algorithm in following the MPOP. From these simulation results it is clear that the IncCond MPT algorithm has a better performance than the P&O algorithms (i.e. less deviation from V_{max}) and hence it is more efficient in following the MPOP.

5 Experimental evaluation of the IncCond algorithm

The optimum load of the PV array is defined by the coordinates of the MPOP, i.e. $R_{opt} = V_{max}/I_{max}$ and since the MPOP varies with the atmospheric conditions, it is clear that the value of R_{opt} will be affected by this variation. Hence, for maximum power transfer from the PV array to a fixed load, an impedance matching transformer design with a controlled time-variable transfer ratio is indispensible [12]. In our design we adopted a step-down DC/DC converter (or chopper) as a DC transformer which can match the array optimum load by changing its switching duty ratio (D). The operation of the DC transformer is described by the following equations [13]:

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = D \tag{10}$$

where V_1 and I_1 are the voltage and current at the primary side of the chopper (i.e. the PV array side), and V_2 and I_2 are voltage and current at the secondary side of the chopper (i.e. the load side).

Now, by controlling the duty ratio D, the impedance seen by the PV array ($R_1 = V_1/I_1$) can be changed as follows

$$R_1 = \frac{V_1}{I_1} = \frac{V_2/D}{I_2 D} = R_2\left[\frac{1}{D}\right]^2 \tag{11}$$

Since we require the value of R_1 to be always equal to the varying R_{opt}, we can achieve our goal even if we have a fixed load R_2 by changing the duty ratio D in eqn. 11. Thus, for a particular load R_2, using eqns. 1–5 together with eqn. 11, we can calculate the value of D that matches the load to the PV array as a function of the atmospheric conditions, as shown in the graph of Fig. 6.

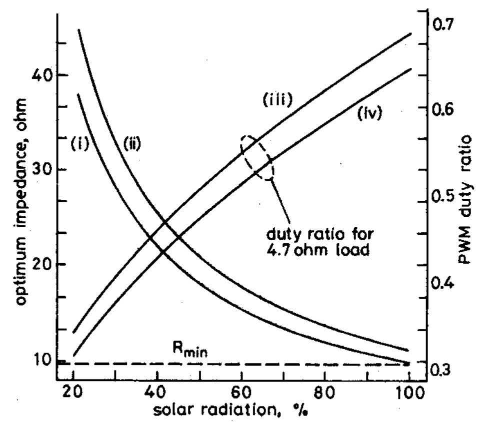

Fig. 6 *Duty ratio of the step-down chopper to match a fixed load to the PV array*

(i) Opt. imped. 56°C
(ii) Opt. imped. 28°C
(iii) 56°C
(iv) 28°C

From Fig. 6 we note that the optimum load decreases with increasing solar radiation and temperature and has a minimum value ($R_{min} \approx 10\,\Omega$ for our array) at 100% solar radiation and 56°C (considered as the maximum array temperature). Also from eqn. 11 we note that since $D \leqslant 1$, then $R_2 \leqslant R_1$. Therefore, using a step-down converter, the value of the load to be connected to the PV array must not exceed R_{min} otherwise a step-up converter design has to be used [13]. The task of varying the duty ratio to match R_2 is carried out by the IncCond algorithm.

5.1 Experimental setup

Our experimental setup to evaluate the performance of the MPT algorithms consists of two identical fixed-axis PV arrays connected to two identical loads; one array is connected directly to the load and the other is connected through a DC transformer circuit. Each array is made of six 70 W PV modules arranged in a 3 (series) × 2 (parallel) configuration. The loads are ohmic loads, 4.7 Ω each. The DC transformer is a step-down chopper built using an isolated gate bipolar transistor (IGBT) as shown in Fig. 7. The IGBT is switched at 20 kHz and is driven

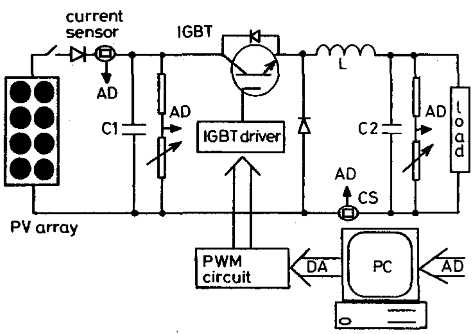

Fig. 7 *Experimental circuit setup*

by pulse-width-modulation (PWM) circuitry which controls the duty ratio D. The personal computer (PC) monitors the different system parameters through A/D converters, and controls the PWM duty ratio through a D/A converter after executing the MPT algorithm. In practical systems, the role of the PC can be performed by a programmed microcontroller. A pyranometer and a surface thermocouple are used to measure the solar radiation and the array temperature, respectively; both sensors are used only to help in the evaluation of the performance of the algorithms.

5.2 Experimental results

Experimental data of the two PV arrays was recorded for different atmospheric conditions over several days and results were analysed for two cases: (i) when the IncCond MPT algorithm was used to control the array power transfer; and (ii) when the P&O MPT algorithm was used. Fig. 8 shows the performance of the IncCond MPT algorithm under rapidly changing atmospheric conditions in comparison with the theoretical maximum array power obtained by substituting the measured solar radiation and array temperature in eqns. 1–5.

From Fig. 8, by noticing the small difference between the theoretical maximum array power and the power extracted from the array, we can easily conclude that the developed IncCond algorithm has successfully followed the rapid solar radiation and array temperature changes. This conclusion is further supported by the fact that the theoretical array power is usually higher than the actual array output. Also, from Fig. 8, we note the significant power loss when the load was directly connected to the PV array without MPT.

In order to compare the performance of the IncCond algorithm with that of the P&O algorithm, a numerical evaluation based on the efficiency of each algorithm in

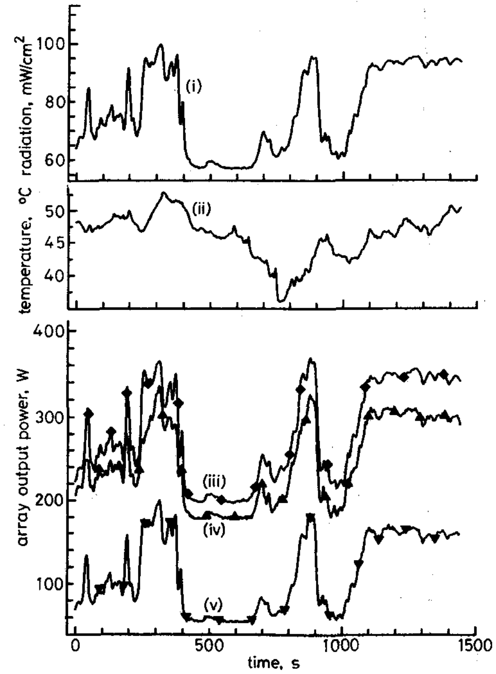

Fig. 8 *Experimental performance of the IncCond MPT algorithm*

(i) Solar radiation
(ii) Array temperature
(iii) Theoretical max. power
(iv) With IncCond MPT
(v) Without MPT
● theoretical maximum power
▲ with IncCond MPT
▼ without MPT

capturing PV energy was adopted. The efficiency η of the algorithms was calculated using the following equation:

$$\eta = \frac{\int_{t_1}^{t_2} P\,dt}{\int_{t_1}^{t_2} P_{max}\,dt} \tag{12}$$

where t_1 and t_2 are the start-up (sunrise) and shut-down (sunset) times of the system, respectively, P is the array output power, and P_{max} is the theoretical maximum array power. The integral in eqn. 12 was evaluated numerically and in order to minimise the integration errors, a small step (3 s) was considered [14]. Average daily-efficiency results for the IncCond and the P&O MPT algorithms are summarised in Table 1 together with the case of directly connecting the load to the array.

Table 1: Efficiency comparison between the MPT algorithms

MPT algorithm	Efficiency
Without MPT	31.3%
P&O	81.5%
IncCond	89.9%

The poor PV utilisation in the case of direct load connection is due to the mismatch between the load and R_{opt}, which can be greatly improved by using MPT. The noticeable increase in the efficiency achieved by the IncCond MPT algorithm is because of its ability to overcome the P&O algorithm drawbacks, namely following rapid atmospheric changes and avoiding oscillations around the MPOP, as was discussed in Sections 3 and 4.

Usually in PV system design, the inclusion of MPT depends on the size of the system and the load characteristics. This is because the gain in energy output achieved by MPT has to be counterbalanced with the increased system cost. Here we note that since the hardware requirements for both algorithms are the same (i.e. a microcontroller and a chopper) and they only differ in their logic, the higher efficiency of the IncCond algorithm makes it more cost-effective than the P&O algorithm.

6 Conclusion

In this paper, different techniques followed in tracking the maximum power operating point of PV arrays were presented with particular reference to the frequently used perturb-and-observe (P&O) technique. The drawbacks of the P&O algorithm, especially in cases of rapidly varying atmospheric conditions, were discussed and analysed. A new maximum power tracking algorithm, the incremental conductance algorithm, was developed based on the fact that the array terminal voltage can always be adjusted towards the V_{max} value by comparing the incremental and the instantaneous conductances of the PV array. Mathematical models were used to simulate the PV array in the evaluation of the algorithms performances under randomly varying atmospheric conditions. An experimental circuit utilising a step-down chopper as a DC transformer was controlled using the IncCond algorithm to maximise PV power flow to a resistive load. Both simulation and experimental results show the successful operation of the developed IncCond MPT algorithm with an experimental average daily-efficiency of about 90% in tracking the maximum available PV power. Evaluation of the IncCond algorithm performance in controlling PV power flow to other types of load (e.g. DC motors, AC loads) is scheduled in the near term.

7 References

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