An Improved MPPT Converter Using Current Compensation Method for PV-Applications

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Abstract-The use of renewable energy is experiencing a significant growth in the world.
With the increasing demand for electric power mainly for the needs of remote and deserted and mountainous regions, the photovoltaic systems, particularly telecommunications and water pumping systems, begin founding great applications.
The proposed study involves a comparison between the delivered power optimization techniques. Among all, there is the technique of truly maximum power point tracking method, and the optimization techniques with and without sunlight compensation. The last two techniques are less efficient than the first one, but easier in their implementation.
In order to increase their performance, an improvement has been proposed. The obtained results are promising and very satisfactorily.
Indeed, the true MPPT command gives high powers, compared to other MPPT commands, but its implementation is difficult in design. To get around this problem, it seemed useful to look for other alternative commands that respond to the challenges of the desired reliability and the expected complexity.
In fact, the improved "with and without sunlight compensation" command responds perfectly to the compromise of the desired implementation simplicity and the high productivity. Actually, both studied MPPT commands have been perfectly and carefully improved, the analyzes proved that the MPPT with sunlight compensation improved command reaches very high powers, equal to that delivered by the true MPPT. In this case, the suggested correction takes into consideration the variations of temperature.
Another case defines a third technique which is the command without variation of sunlight, this latter takes into consideration the variations of the voltage at the bounds of the GPV generator. These MPPT commands less complex and highly interesting can certainly find a use and an involvement in photovoltaic PV systems.

Keywords: True MPPT, Power, Technique Without Sunlight Compensation, Techniques With Sunlight Compensation, Improving of Techniques With and Without Sunlight Compensation.

1. Introduction

Solar energy is widely used to power remote or deserted regions (lighting, batteries charging, pumping, etc...). The great advantage is that this source is inexhaustible, very safe to use and so clean. In order to improve the efficiency of the photovoltaic (PV) generator, in other words, to maximize the power delivered to the load connected to the generator bounds, several criteria of the photovoltaic system efficiency optimization were applied [1-3] and techniques were surveyed for obtaining good adaptation and high productivity. Among these techniques, there are the Maximum Power Point "MPPT" Tracking P&O [4] and the techniques of optimal power points research with and without sunlight compensation.

The comparison between these techniques is fixed as a goal in the first step, then a contribution to the improvement is proposed. Throughout this study, we use the "Matlab/Simulink" software to model the different parts of the system and simulate the proposed and even the improved commands.

Through this work we found that improving the method with sunshine compensation is very succeeded and this improvement provides very high power and maximum performance system that are equal to that given by the true MPPT. By using the enhanced version of this method, the replacement of the true MPPT method in some applications requiring precise powers can be envisaged.

1.1. Physical structure of a photovoltaic cell

A solar cell is a semiconductor device which absorbs light and converts it into electric energy [5,6]. Nowadays, the most common cell is a simple silicon cell with PN junction [7], including a yield reaching about 17%. The Fig.1 represents a solar cell with standard PN junction.

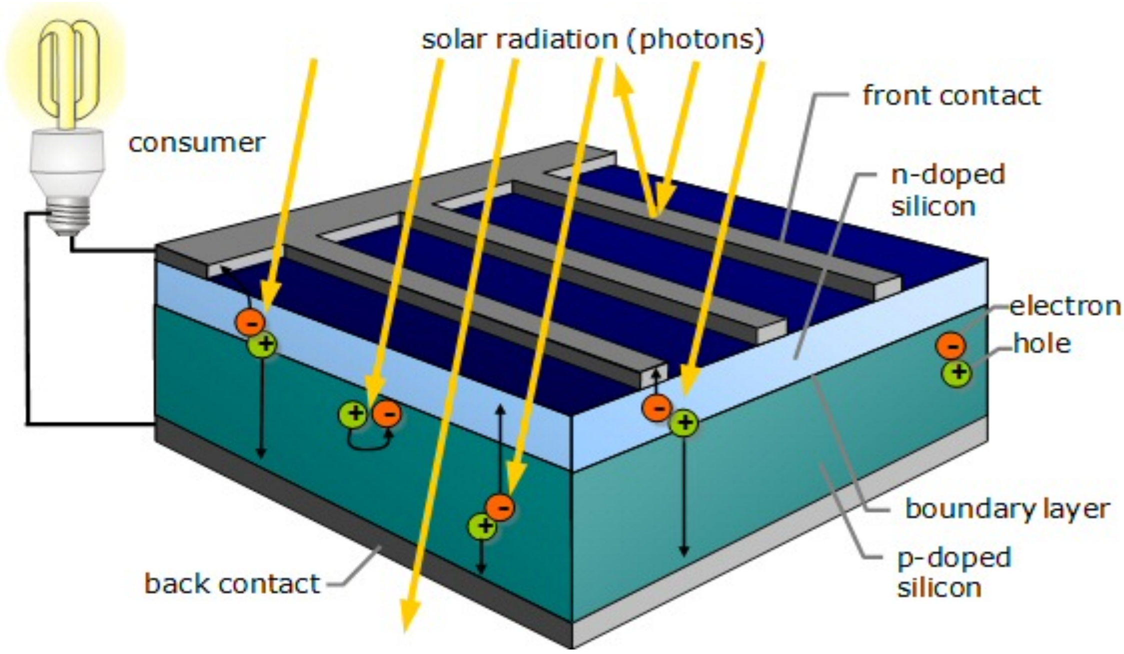


Fig. 1. Schematic representation of a solar cell with standard PN junction [5,8,9].

2. Modeling of the electrical behavior of a photovoltaic cell

2.1. Model of two exponentials

The resulting expression corresponding to a current-voltage characteristic, for known temperature and lighting [5,10], in generator mode is:

$$I = I_{ph} - I_{S1}\left[e^{\frac{q\,(V+I\,R_S)}{\eta_1 KT}} - 1\right] - I_{S2}\left[e^{\frac{q\,(V+I\,R_S)}{\eta_2 KT}} - 1\right] - \frac{V + I.R_S}{R_P} \tag{1}$$

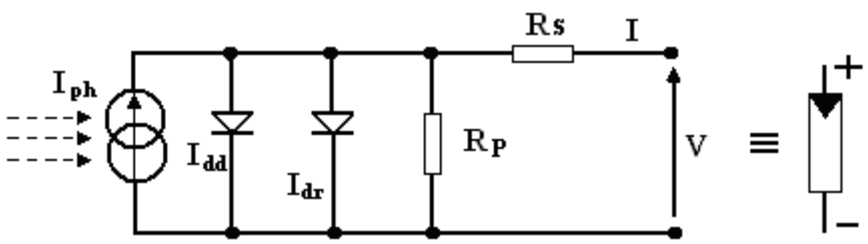


Fig. 2. Equivalent circuit deduced from the equation (1) of two exponentials of real solar cell, taking into account the resistive losses in modern technology [5,8,11].

These parameters vary with the level of illumination and with the temperature according to the involved mechanisms [5,12]. It is evident that the current-voltage characteristic, according to the equation (1), strongly depends on the insolation and the temperature. The temperature dependence is more amplified by the photocurrent I_{ph} properties and the reverse saturation currents of the diodes [5,11,13,14], which are given by [5,14,15]:

$$I_{ph}(T) = I_{ph}\big|_{(T=298.K)}\left[1 + (T - 298.K).(5.10^{-4})\right] \tag{2}$$

$$I_{S1} = K_1 T^3 . e^{-\frac{E_g}{KT}} \tag{3}$$

$$I_{S2} = K_2 \; T^{\frac{5}{2}} e^{-\frac{E_g}{KT}} \qquad (4)$$

Where E_g is the energy band of the semiconductor, with [5 ,16]:

$$\left(K_1 = 1.2 \quad A/cm^2.K^3\right) \qquad (5)$$

$$\left(K_2 = 2.9\,.10^5 \quad A/cm^2.K^{\frac{5}{2}}\right) \qquad (6)$$

3. From the cell to a photovoltaic generator (PV)

The consideration of the equivalent circuit model (Fig.2), leads to the equation for a photovoltaic cells array (generally called a solar module or solar array), where ***Z*** is the number of photovoltaic cells connected in series [5,17,18].

$$I = I_{ph} - I_{S1}\left[e^{\frac{q\,(V+I\,Z\,R_S)}{Z\eta_1 KT}} - 1\right] - I_{S2}\left[e^{\frac{q\,(V+I\,Z\,R_S)}{Z\,\eta_2 KT}} - 1\right] - \frac{V+I\;Z\,R_S}{Z\;R_p} \qquad (7)$$

The characteristics of cell used in the simulations are presented in table.1:

Table 1. Characteristics of cell used in the simulations:

n_s	n_p	P_{max}(W)	V_{oc}(V)	I_{cc}(V)	V_{opt}(V)	I_{opt}(V)	R_s(Ω)	R_{sh} (Ω)
36	1	60W	24.8 V	3.25A	20 V	3.1A	0.005Ω	30Ω

The Figure 3. Illustrates the behavior of a PV generator constituted by 36 cells in series identic to that of Fig.2 [5].

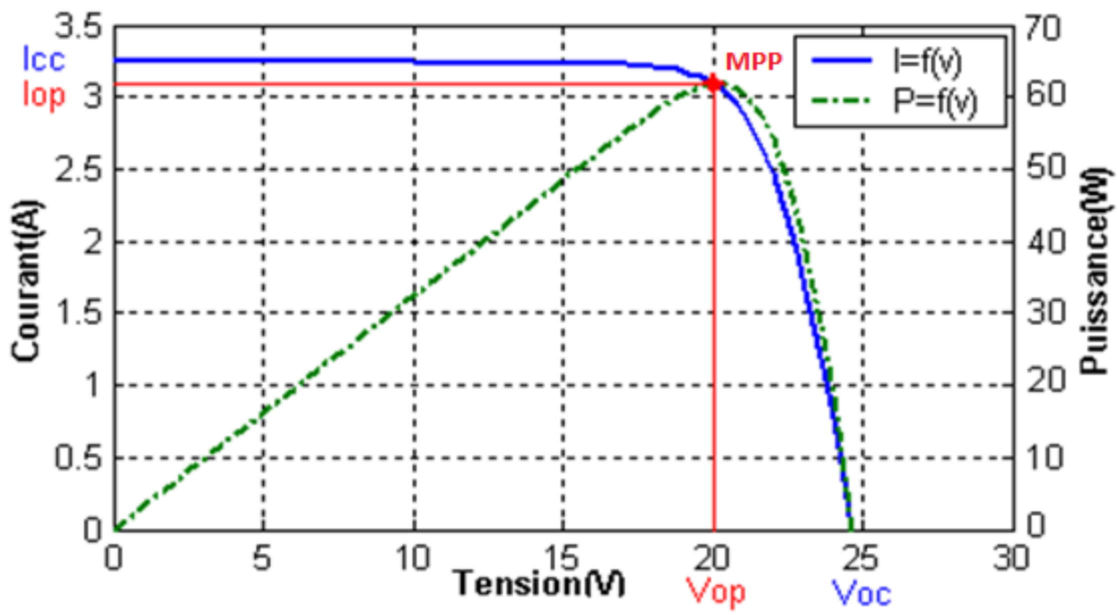


Fig. 3. Behavior of a PV generator constituted by 36 cells in series identic to that of Fig.2.

4. Photovoltaic system

Simulation is a powerful tool for assessing the theoretical performance of different systems. The test device can be functioned in easily controllable conditions and its execution can be precisely monitored [5].

We established with Simulink, physical subsets such as the solar panel, the load, the chopper and MPPT controller as independent units and to check their appropriate functionality. Finally these subsets can be combined to form a complete photovoltaic power system with a MPP (Maximum Power Point) control [5].

The values for cells temperature (T), irradiation (R), the number of photovoltaic cells in series are available as external variables and can be changed at any time during the simulation process. This allows the observation and evaluation of the system response to sudden changes in operating conditions [5].

Concerning the weather conditions (temperature and irradiation), they are modeled by a “building bloc” or we can form virtual data similar to actual conditions [5] and also allows us to perform various climatic changes.

The basic principle common to all of these commands is to perform a continuous search of maximum power point (MPP) [5,19,20,21]. Actually this is done by the cyclic measurement of voltage V and current I of the solar panel, which are the input values of controller, and the latter generates the suitable control "the cyclic rapport d" on output [5,22,23].

Figure 4 shows the block diagram of a photovoltaic system powering a resistive load.
Indeed, the system studied consists of the PV generator, the DC-DC converter and the load, power P_n (w).

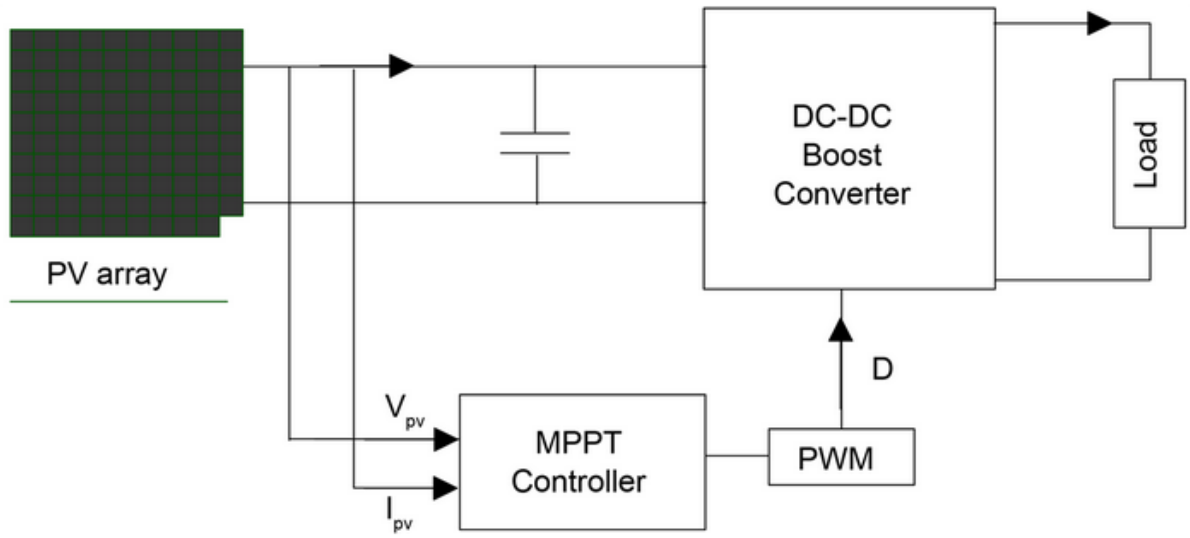


Fig. 4. Block diagram of the photovoltaic system operation controlled by an MPPT control system.

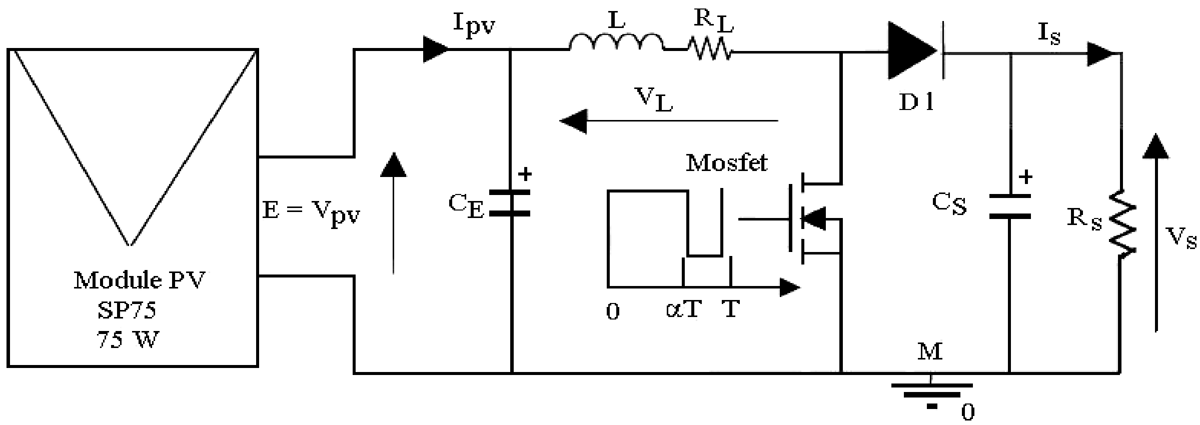


Fig. 5. PV System constituted form a module, energy converter " booster " and a load R_S, mosfet switch controls a period signal T and duty cycle.

The Figure 6, presents the functional scheme of global PV system, used for simulation:

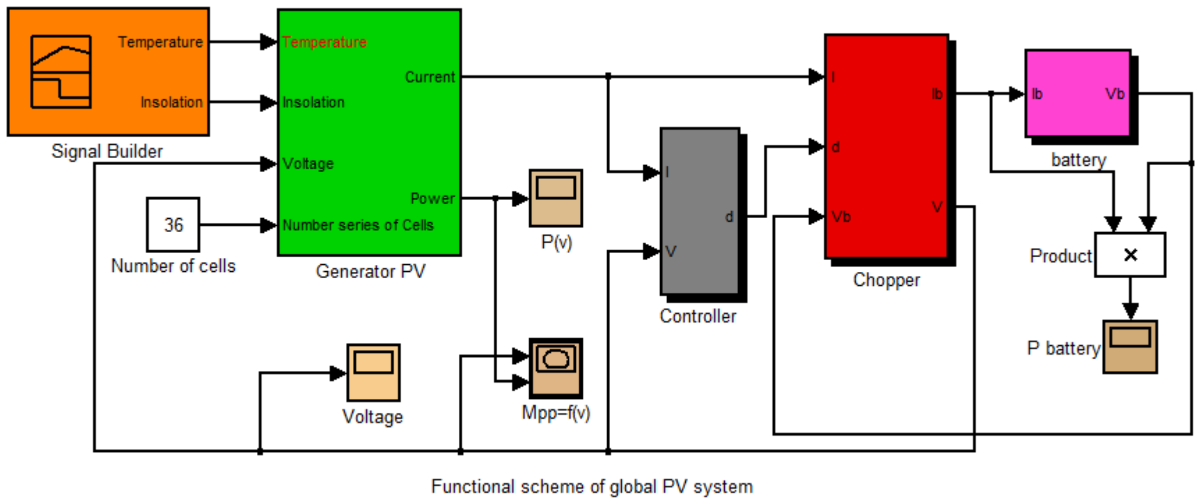


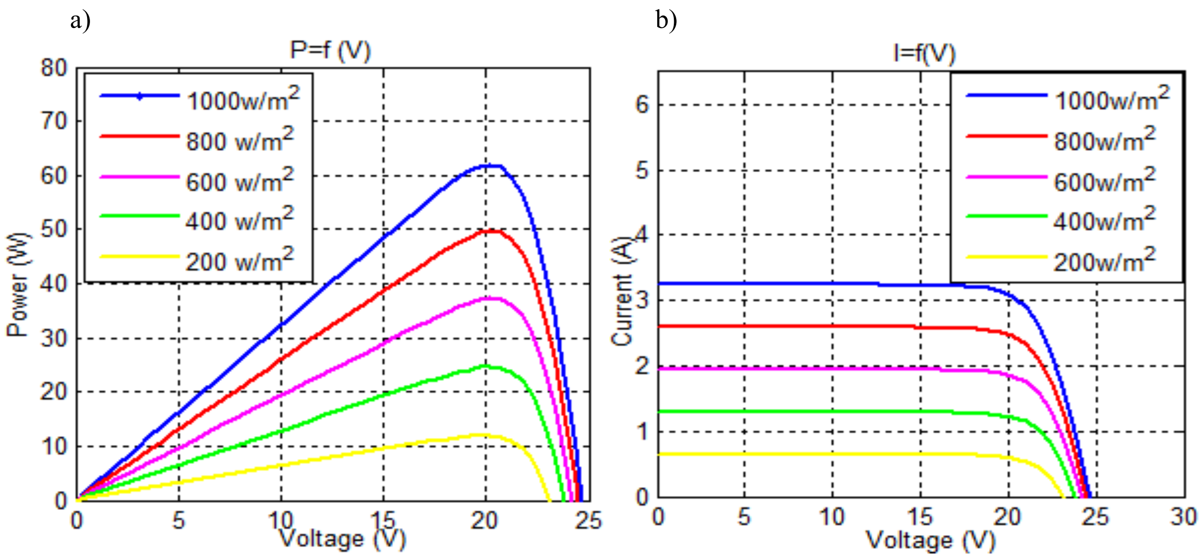
Fig. 6. Functional scheme of global PV system, used for simulation.

4.1. Behavior of a photovoltaic (PV) generator

Two main parameters, illumination and temperature, affect the operation of the generator. Fig.7(a-f) shows the reaction of the generator according to the variations of these two parameters.

4.1.1. Influence of illumination changes

The power delivered by a PV generator depends on the received irradiation [5,24] as it is shown in the example below. Indeed, for a given module, the influence of illumination, simply represented by a current source, which is proportional to the irradiation, can be done in first approximation [5,25]. Fig.7(a-b) demonstrates the simulation obtained results [5,26,27,28,29].

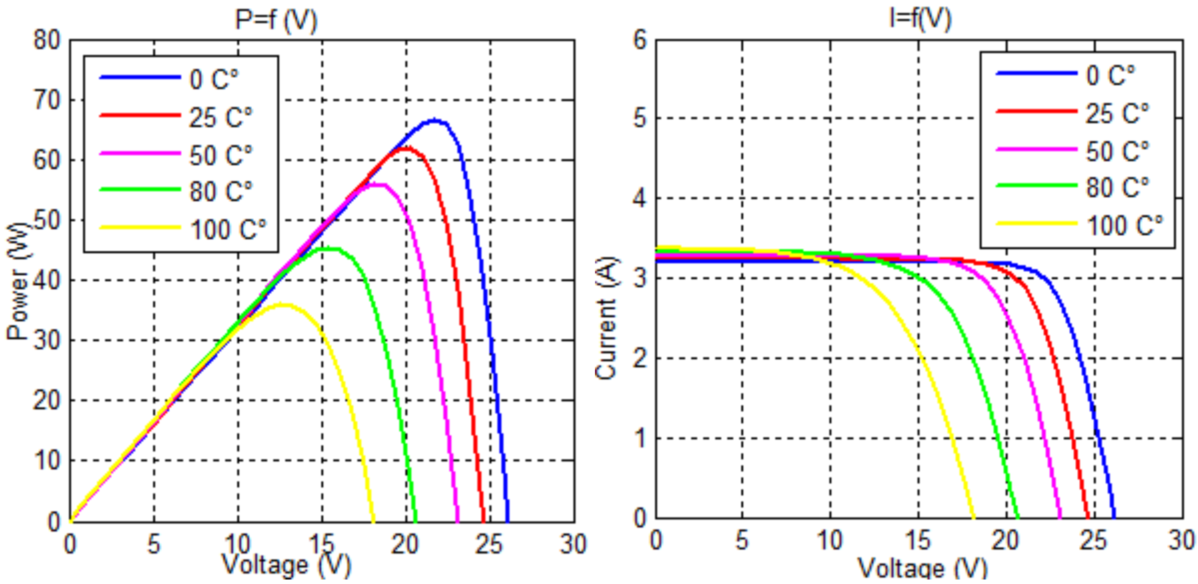


Effect of illumination at T = 25 ° C.

4.1.2. Influence of the temperature

If we take in consideration Equation (1), we perceive that the current delivered by each cell depends on the internal temperature of the PN junction that constitutes the photovoltaic PV cell [5,26,27,28,29]. If we consider the PV generator heating from 0°C to 60°C and considering in first approximation that the back face temperature of each cell is close to PN junction temperature, then it can be considered that the temperature influence is well represented by Equation (1). We conclude that the open circuit voltage decreases with a temperature rise. Consequently, we lose available power at the bounds of the PV generator. The Fig.7(c-d) demonstrates this effect.

c) d)



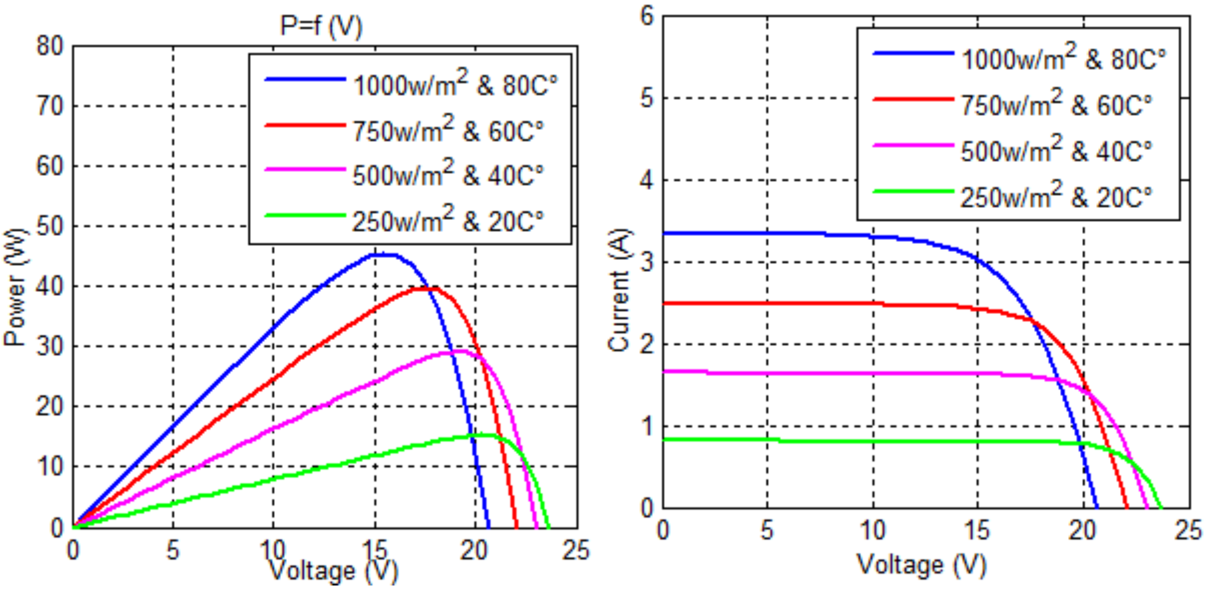
Effect of temperature, with $\phi = 1000$ W/m^2.

The voltage drops are due to an increase in the reverse saturation current in the diode (see equations (3) and (4)) [5].

4.1.3. Influence of simultaneous illumination of the illumination and temperature

The Figure 7(e-f) present the l'influence of simultaneous illumination of the illumination and temperature, Indeed, the influence of both parameters are visible on the power produced by photovoltaic panels.

e) f)



Effect of simultaneous illumination of the illumination and temperature.

Fig. 7. (a-f) . Effect of the temperature and the illumination on the I-V and P-V characteristics of the PV generator.

5. Direct coupling

This coupling is illustrated in Fig.8, the operating point of the system is obtained by the intersection of the I-V characteristics of the generator and that of the load [30]. The resolution of the equality of the previous nonlinear equations is performed by the "Newton Raphson" method under Matlab software for half a day where the illumination is variable from the minimum value up to the maximum value

(1000 W/m^2). It is shown later that some operating points do not correspond to the optimal allowable powers. In order to maximize the amount of power output from the generator, we must make the system operate at the maximum of the P-V characteristic of the generator. For this reason the optimization techniques were applied.

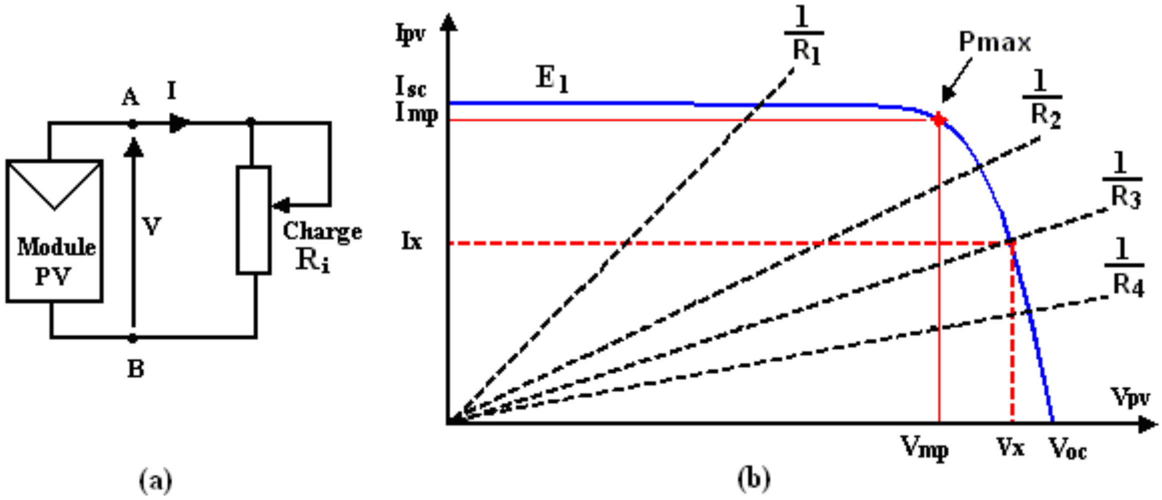


Fig. 8 .(a) Direct electrical connection between a PV generator and a load [5].
(b) Points of operation resulting from the combination of the PV generators under an illumination level E_1 with variable resistive load (R1, R2, R3, R4) [5].

6. Techniques of optimization

The improvement of the productivity of the PV system requires the maximization of the PV generator power. The first optimization technique is the maximum power point searching technique, called true or real MPPT method, which makes the system to operate at its maximum power, i.e. at optimal current and voltage. This is achieved by interposing a chopper between the PV source and the load, acting as an impedance adapter. The rigorous control of the cyclic rapport of this latter allows the achievement of this duty, by continuously following of the power theoretically provided taken as a reference. Another technique of power optimization, less complex than the real MPPT, called technique of power optimization without sunlight compensation, is used. It is based on a suitable choice of a reference current, corresponding to the current that can be generated by the lowest sunlight value in the place where the GPV is. In the case of the studied system, this current is selected from the interval of 1.4-1.5 A. This also depends on the characteristics of the used module. This predetermined current will be used as a control parameter to fix the cyclic rapport of the DC-DC converter. Another case which defines a third technique, instead of using a fixed reference current, is that in which we use a value proportional to the short circuit current (I_{CC}) value of a measurement module. This allows the reference value to take in account the sunlight changes. Usually, a proportion of the order of 85-92% of short circuit current is adopted. This technique is called technique of optimal power searching with sunlight compensation.

6.1. Simulation results

Figure 9 represents the I-V characteristics of the PV generator and the load for the direct coupling and true MPPT. The operation of the system is improved by the use of the MPPT technique, where the load is powered by voltages closer to the nominal values.
The effect of the MPPT technology, compared to the direct coupling is very obvious for small values of illumination. The supply voltage is increased by a value as low as 1 V for direct coupling up to 19 V value as a result of optimization. This increase is accompanied with increasing in generated power. Fig.10 shows the differences between maximized powers and those of direct coupling. Fig.11 illustrates the optimized powers for the techniques that are mentioned above. All these optimization techniques seem more or less comparable at high sunlight values. Table 2. Summarizes the values of the powers debited for these cases.

A loss of 51.86% of the maximum power for an insolation of 1000 W/m^2 is achieved with the technique of optimization without sunlight compensation. These energy losses are less important for the technique with sunlight compensation and the retrieved value is about 49.82 % compared to the previous technique.

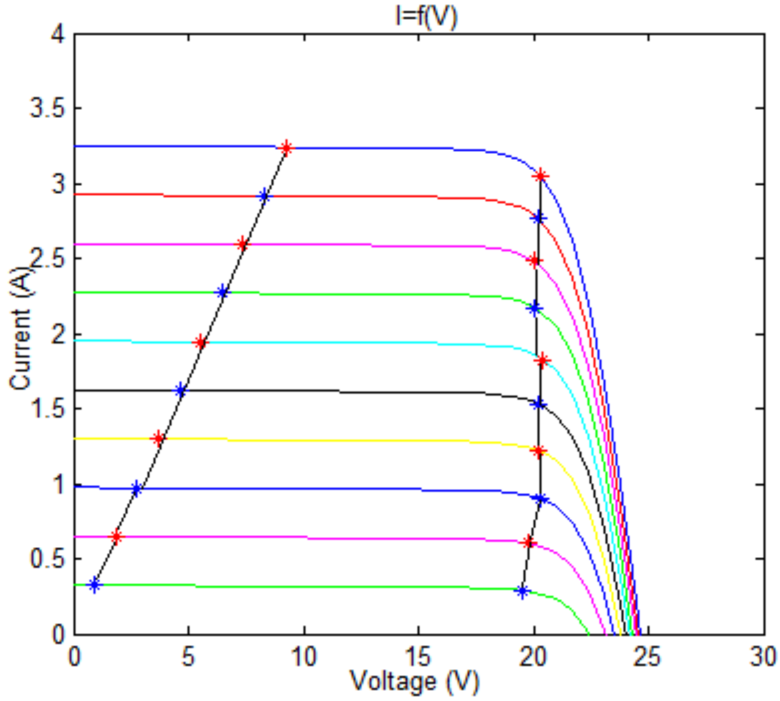


Fig. 9. Characteristic of the photovoltaic system: I-V characteristics and point resulting with coupling: real MPPT in right and direct coupling in left for ϕ = 100-1000 W/m^2.

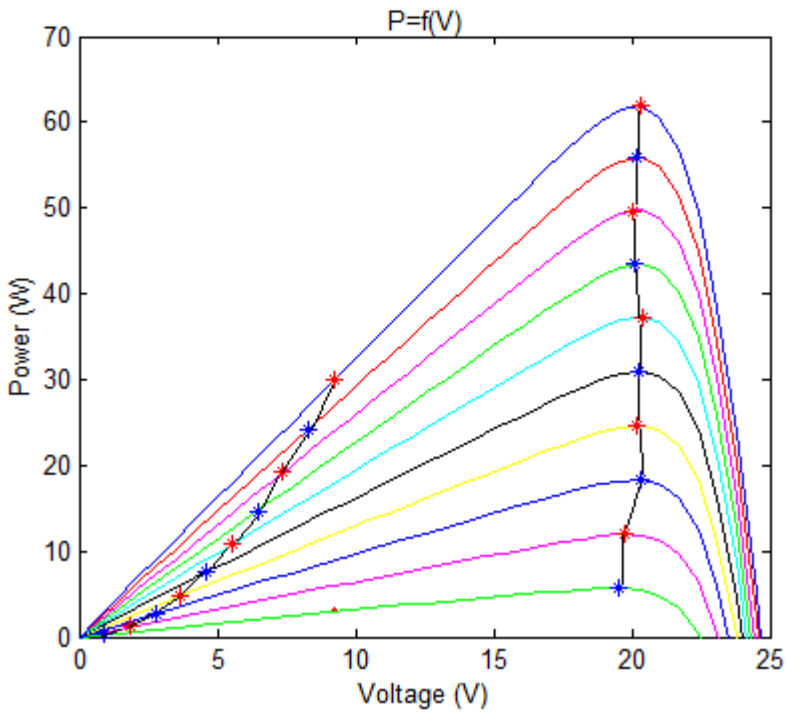


Fig. 10. Characteristic of the photovoltaic system: P-V characteristics and point resulting with coupling: real MPPT in right and direct coupling in left for ϕ = 100-1000 W/m^2.

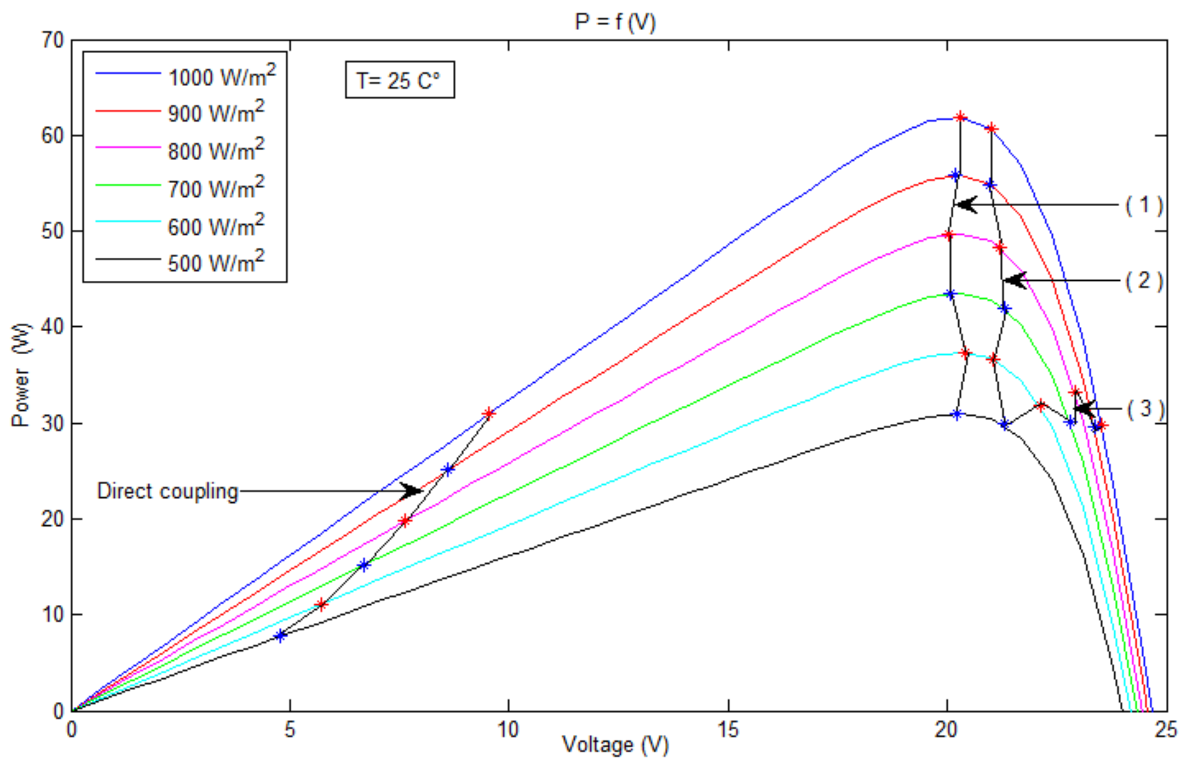


Fig. 11. System power curves for different optimization techniques
(1): MPPT P&O, (2): $I_{ref} = 0.885I_{cc}$, (3): $I_{ref} = 1.438A$.

Table 2. Powers generated for different optimization techniques

	Illumination E (W/m²)	**500**	**600**	**700**	**800**	**900**	**1000**
Power generated (W)	**Direct Coupling**	7.477	10.77	14.65	19.14	24.22	29.91
	True MPPT P&O	31	37.29	43.51	49.67	55.87	61.9
	MPPT without compensation	29.86	31.85	30.11	33.28	29.53	29.8
	MPTT with compensation	29.86	36.68	41.99	48.31	54.89	60.64

As the calculated yield is defined as the ratio between the power obtained at the output of CC-CC converter and the maximum available power, the yield is 100% for real MPPT technique (taken as assumption of reference powers); however, the direct coupling is characterized by low productivity especially for low illumination values. For example, for E = 500 W/m², the yield was 24.12 %. But for E =900 W/m² or more, performance values will be increased. This increase demonstrates the good adaptation between the load and generator in the direct coupling for strong illumination; however, this remains insufficient for applications that require high productivity. For techniques with and without sunlight compensation, yields are improved compared to direct coupling, even during low illumination, as Fig.12 shows.

With regard to the power generated by the method without sunlight compensation for different insolation levels, we perceive that it is fixed, it is around of 30 W, but the calculated yield decreases in the same time, therefore we deduce that the method is applicable only if the reference current imposed by the command is equal or close to that generated by the place sunlight.

The method with sunlight compensation gives very close powers to that of the true MPPT, consequently a very high productivity.

Table 3. Yield calculated for different optimization techniques.

	Illumination E (W/m²)	500	600	700	800	900	1000
Generator efficiency (%)	Direct Coupling	24.12	28.88	33.67	38.54	43.35	48.32
	True MPPT (P&O)	100	100	100	100	100	100
	MPPT without compensation	96.32	85.42	69.20	67	52.85	48.15
	MPTT with compensation	96.32	98.36	96.51	97.26	98.25	97.96

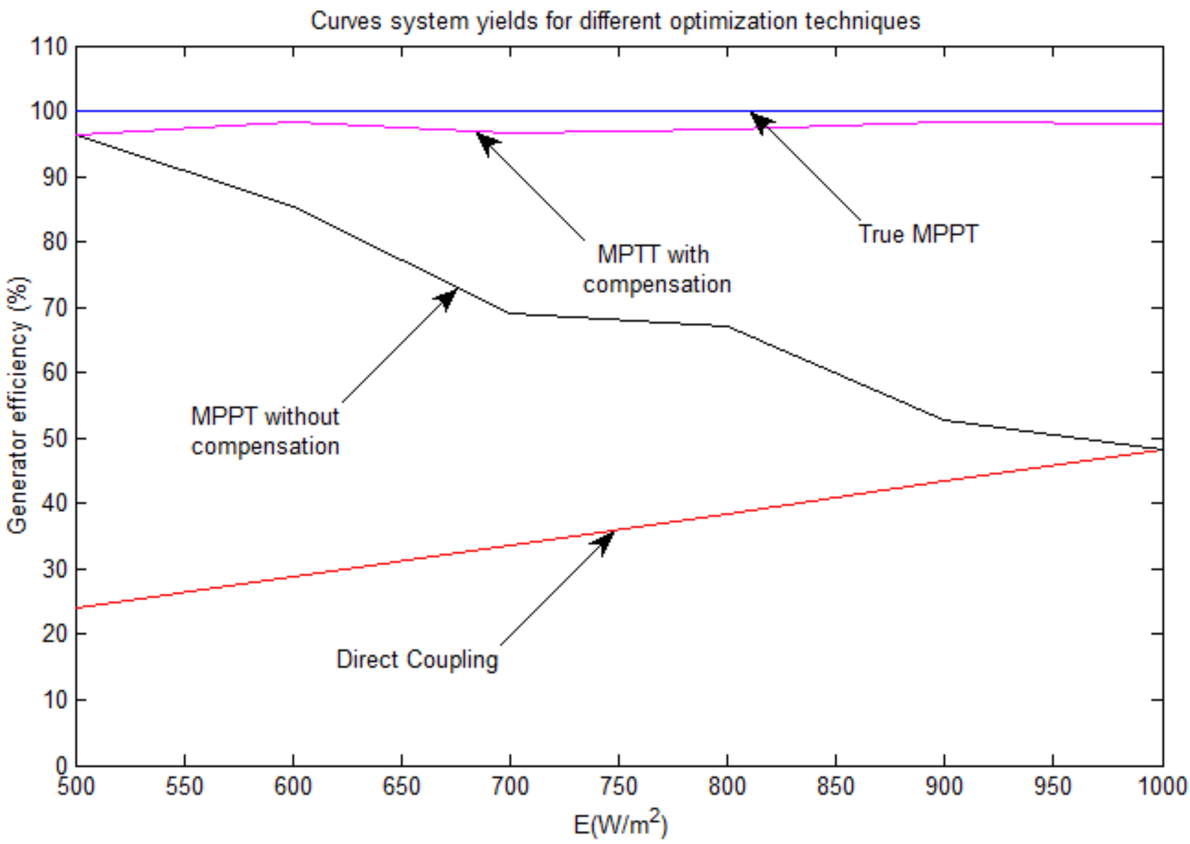


Fig. 12. Curves of system yields for different optimization techniques.

Figure 13 show an example of generated power and the GPV voltages for different proposed optimization techniques at ϕ = 1000 W/m² and ϕ = 500 W/m² for T = 25°C.

The use of true MPPT technique gives the highest power value, followed by the technique with sunlight compensation. The technique without sunlight compensation comes third in terms of the generated power, though direct coupling gives poor powers. This occurs for both proposed insolation values.

Figure 14 shows the response time of different MPPT optimization techniques and their corresponding cyclic rapports.

The true MPPT technique has a shorter response time than other MPPT command techniques, thus faster to detect the MPPT, however techniques with and without sunlight compensation have the same response time.

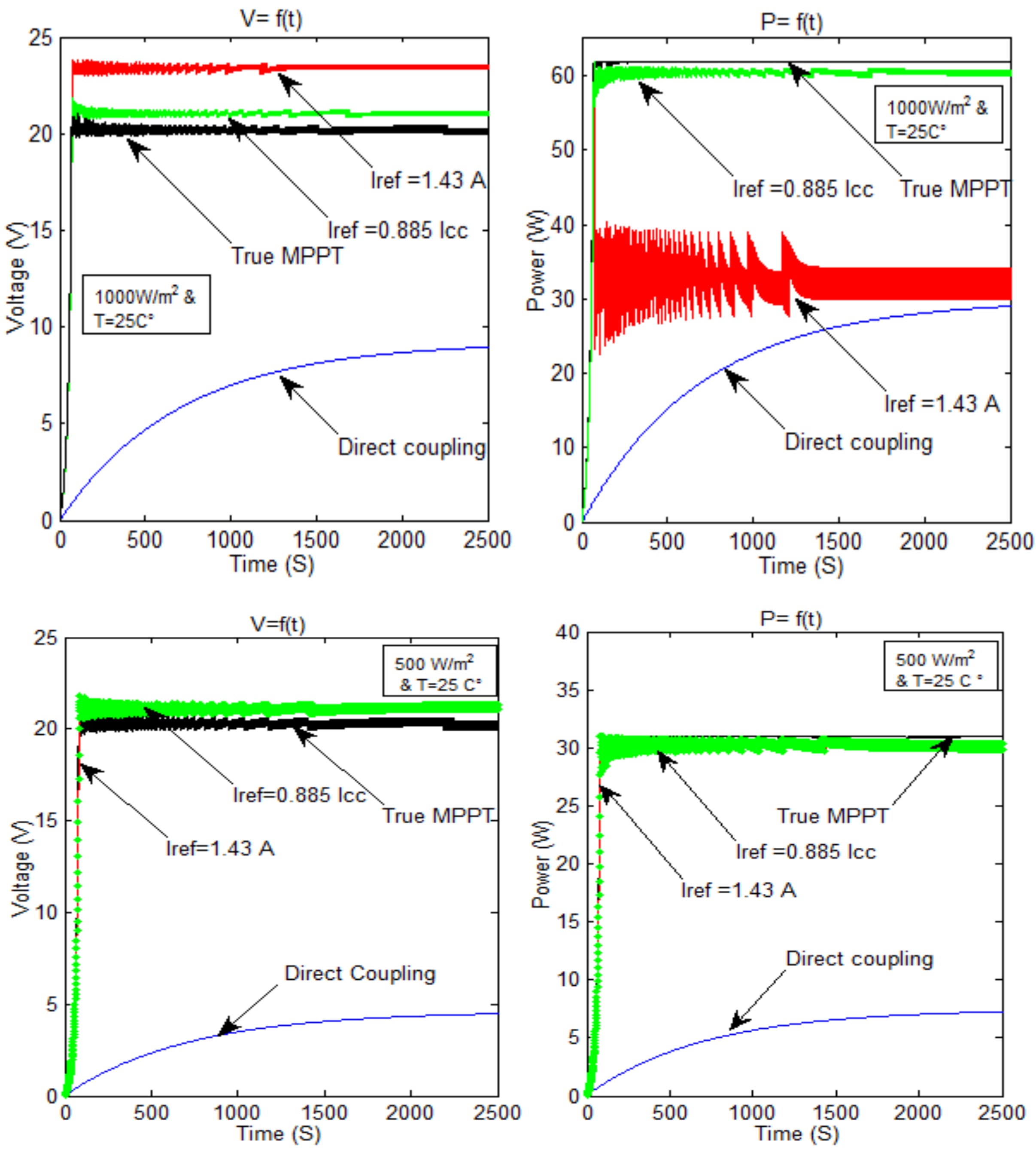


Fig. 13. Voltage V = f (t) and power P = f (t) for different proposed optimization techniques ϕ = 1000 W/m² and ϕ = 500 W/m² at T = 25°C.

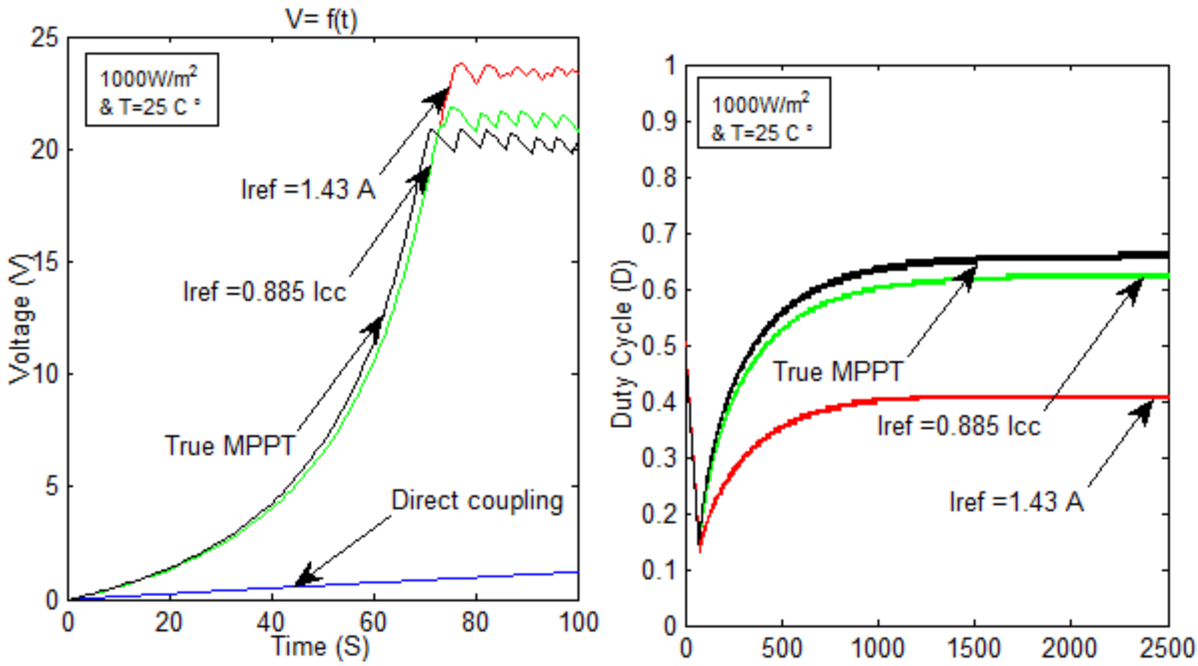


Fig. 14. Response times of different proposed MPPT techniques and their corresponding cyclic rapports for ϕ = 1000 W/m^2, at T = 25 °C.

7. Improvement of optimization techniques

In face to the poor values of the photovoltaic system productivity, especially for the optimal power point research without sunlight compensation technique, which is characterized by a yield value that decreases to 48.15% and for the complexity of implementation of the real MPPT technique, improvements in optimization techniques with and without sunlight compensation are proposed.

7.1. Improvement of MPPT without compensation technique

In this case, instead of using a constant reference, an adjustment of this value is carried out by adding a value proportional to the voltage at the generator bound; the proportionality factor may be a shunt conductance in bounds that the measurement is carried out.

$$I_{ref}^* = I_{ref} + \Delta I \quad (8)$$

$$I_{ref}^* = I_{ref} + \frac{\Delta V}{R} \quad (9)$$

$$I_{ref}^* = I_{ref} + k^*\Delta V \quad (10)$$

$$\Delta V = R^*\Delta I \quad (11)$$

with: $k = \frac{1}{R}$

7.2. Improvement of MPPT with compensation technique

Similarly, in order to optimize the maximum power point of this technique, a correction is suggested. Instead of working with a fixed proportion of short circuit (m) current, this latter will be adjusted according to a function depending on the temperature. In this case, the correction of the short circuit current percentage takes the following form:

$$I_{ref} = m_1 * I_{CC} \quad (12)$$

with:

$$m_1 = a_0 + a_1 * T \quad (13)$$

Table 4. Shows power generated for different improved optimization techniques.

Table 4. Power generated for different improved optimization techniques.

	Illumination E (W/m^2)	500	600	700	800	900	1000
Improved power generated (W)	Direct Coupling	7.477	10.77	14.65	19.14	24.22	29.91
	True MPPT P&O	31	37.29	43.51	49.67	55.87	61.90
	MPPT without compensation improved	30.65	32.39	33.14	33.63	34	34.74
	MPTT with compensation Improved	31	37.29	43.51	49.73	55.87	61.90

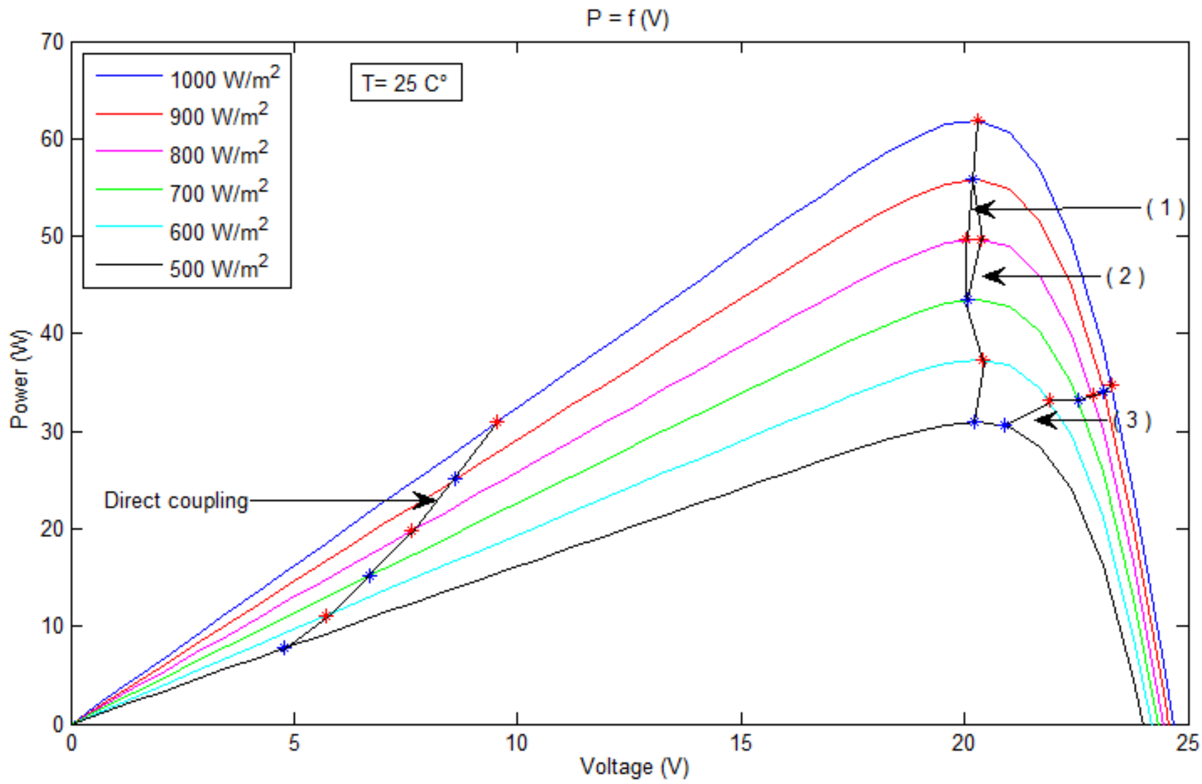


Fig. 15. System power curves for different improved optimization techniques.
(1): MPPT P&O, (2): $I_{ref} = m_1 I_{cc}$*, (3):* $I_{ref} = I^*_{ref\ impro}$

Figure 16 shows a comparison between the optimization techniques: between the original version and the improved version for the two proposed commands. In fact, the improvement of the MPPT with sunlight compensation technique gives results very close and in most cases identical to that of the true MPPT, also the improvement of the MPPT without sunlight compensation technique gives higher powers compared with the MPPT without sunlight compensation.

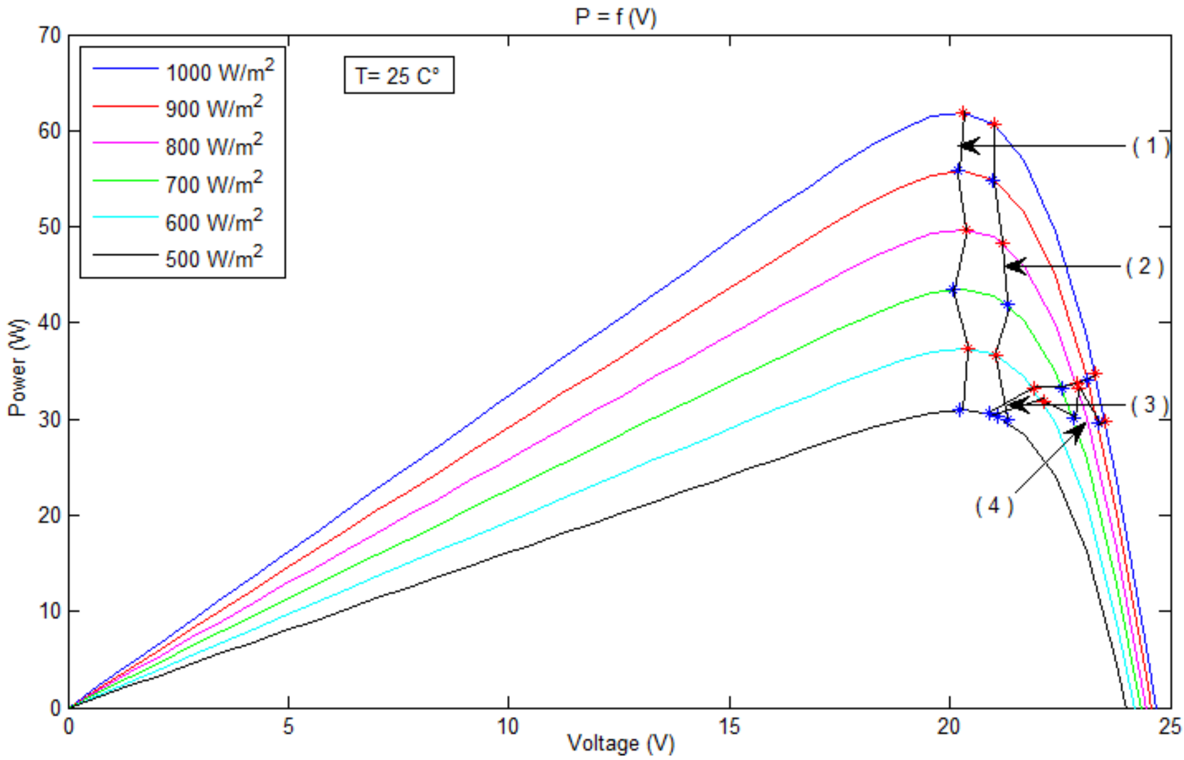


Fig. 16. System power curves for different optimization techniques with and without sunlight compensation. *(1):* $I_{ref} = m_1 I_{cc}$, *(2):* $I_{ref} = 0.885 I_{cc}$, *(3):* $I_{ref} = I^*_{ref\,improv}$, *(4):* $I_{ref} = 1.438A$.

The performance of two improved techniques compared to unimproved techniques is given in table 5.

Table 5. Yield calculated for different improved optimization techniques

	Illumination E (w/m^2)	**500**	**600**	**700**	**800**	**900**	**1000**
Generator efficiency (%)	**Direct Coupling**	24.12	28.88	33.67	38.54	43.35	48.32
	True MPPT (P&O)	100	100	100	100	100	100
	Improving the MPPT technique without compensation	98,87	86,86	76,17	67,71	60,86	56,13
	Improving the MPPT technology with compensation	100	100	100	100	100	100

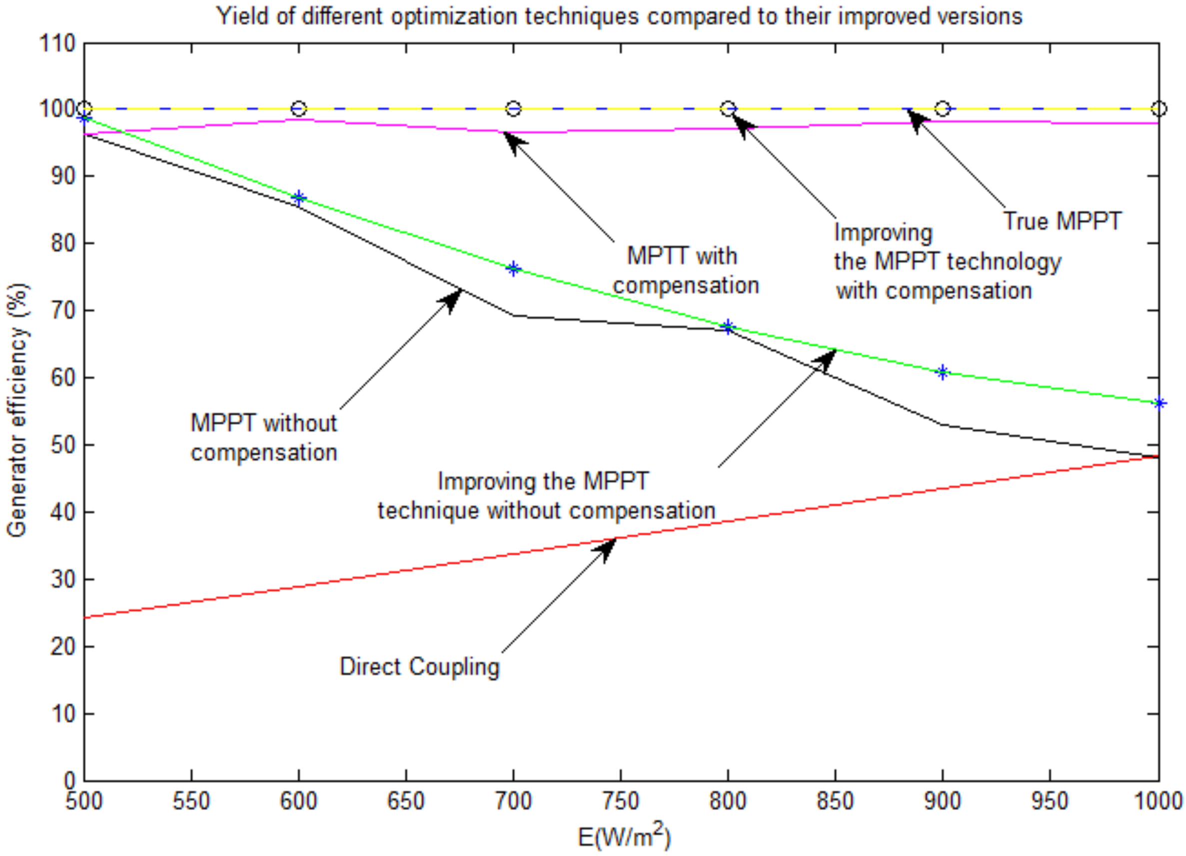


Fig. 17. Curves of system yields for different optimization techniques compared to yields obtained in the improved versions.

A better improvement could be obtained by a correction following a larger order function, but it is shown that the productivity is lower, compared to the additive complexity in practical implementation.

To better compare the results obtained by deferent techniques, an index of energy loss was calculated for each power value. This index is defined by the equation:

$$\gamma = \frac{Pmax - Pimproved}{Pmax} \ \% \qquad (14)$$

According to the power curves (Fig.18, 19 and 20) as well as Tables 6 and 7, we note first the overall improvement of the system and decreasing of the index of energy losses. In addition, it is obvious that the improvement is greater for the technique of sunlight compensation than that without compensation. These improvements require information of the temperature for the first techniques which is more difficult to measure.

Practically, appealing of the measurement of the open circuit voltage of a measuring module that appears approximately proportional to temperature. In that case, a compromise is needed between the desired reliability and the expected complexity.

Conversely, the second technique requires information of voltage therefore the generator current, which can be obtained directly through a resistance series.

Improving the MPPT technique without sunshine compensation allows for significantly improved power and Fig.18 shows this result.

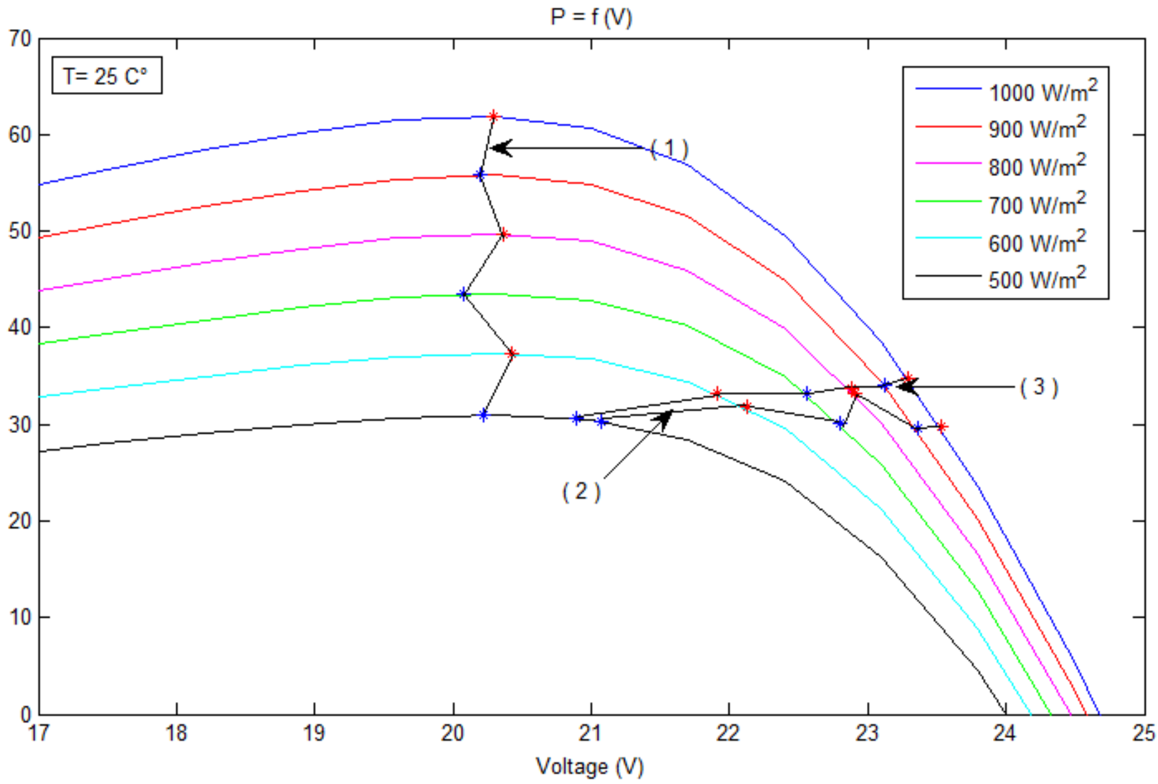


Fig. 18. Curves of optimal power without sunshine compensation improved
(1): MPPT P&O (2): I_{ref} *=1.438A, (3)* $I_{ref}=I^{*}_{ref\,impro}$.

Figure 19 shows that the improvement of the technique with sunshine compensation gives powers similar to that of true MPPT.

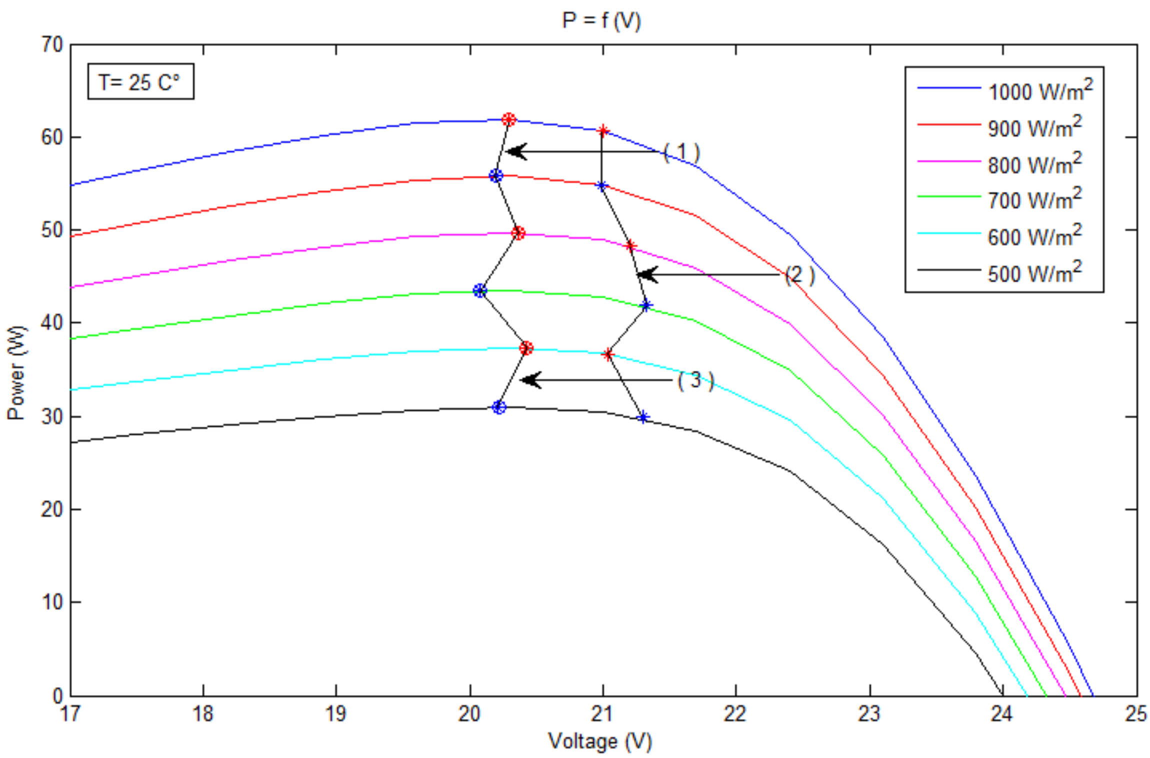


Fig. 19. Curves optimal power with sunshine compensation improved
(1): MPPT P&O, (2): $I_{ref}=0.885I_{cc}$*, (3):* $I_{ref}=m_1I_{cc}$.

The figure 20 summarizes all optimized methods used. Indeed, one could perceive that the data power values by the command without sunshine compensation improved approach increasingly to that given by the true MPPT at low sunshine values. Against by improving the MPPT control with sunshine compensation provides power equal to that given by the true MPPT.

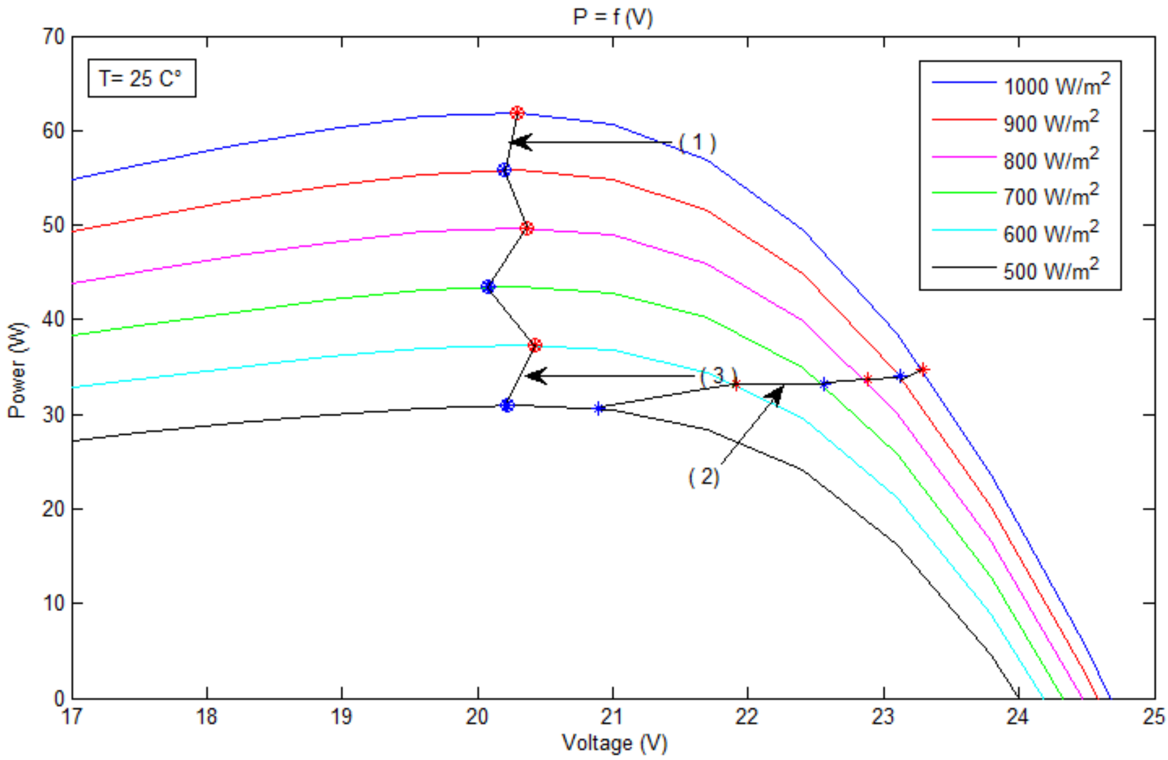


Fig. 20. Summary of the curves of the improved optimum power with and without sunlight compensation, compared to the real MPPT.

(1): MPPT P&O, (2): $Iref = I^{*}_{ref\,impro}$, *(3):* $I_{ref} = m_1 I_{cc}$.

The Table 6 summarizes all the methods used. Indeed, the Table illustrates the different expressions of the optimization technics, compared with that obtained with the improved versions.

Table 6. Summarizes all the methods used compared with that obtained with the improved versions. .

MPPT command	MPPT without compensation	MPTT with compensation
without correction	$I_{ref}^* = I_{ref}$	$I_{ref} = m * I_{CC}$
With linear correction	$I_{ref}^* = I_{ref} + \Delta I$ $I_{ref}^* = I_{ref} + k * \Delta V$	$I_{ref} = m_1 * I_{CC}$ $m_1 = a_0 + a_1 * T$

Tables 7 and 8. Present the correction index for both of techniques with and without sunshine compensation.

The results found show the decrease of the correction index for both the methods improved. However, this index is more improved for the MPPT technology with sunshine compensation improved, whose value is zero regardless of the value of the sunshine. This proves the effectiveness of the proposed improvement method.

Table 7. Correction index for technique without compensation

Illumination E (W/m²)		500	600	700	800	900	1000
Index correction	**without correction I_{ref}=1.438A**	3.68	14.59	30.80	33	47.15	51.86
	With linear correction	1.13	13.14	23.83	32	39.14	43.87

Table 8. Correction index for technique with compensation

Illumination E (W/m²)		500	600	700	800	900	1000
Index correction	**without correction I_{ref}=0.885I_{cc}**	3.68	1.64	3.50	2.74	1.75	2.04
	With linear correction	0	0	0	0	0	0

8. Conclusion

Direct coupling is the simplest connection, the cheaper in front of all the techniques studied.

The paper presents a new controls strategy for the photovoltaic PV, it is a command based on technique with and witout sunshine compensation. It's the first time that this technique is introduced for synthesizing control laws for the converters of power electronics. We conclude our study with the following points:

The new control strategy proposed by the author has been demonstrated by computer simulation using Matlab/Simulink. Indeed, the simple amelioration as desired are shown in Fig.(8-11).
The real MPPT technique represents a case of ideal operation of the PV system, given the complexity of the research system of maximum points. Other techniques such as the technique with and without sunshine compensation are exploited. The implementation of these two techniques is fairly simple compared to the real MPPT method but their performance did not reach that of the latter, and some energy will be lost. To remedy to this problem, the improvement of the latter two techniques offer a new path for optimization techniques. The proposed improvements in this work are still simple, easy for practical realization, and give powers to close ideal powers. Simulation results show that this proposal deserves deeper view and realize through practical implementation that we are working on and that constitute our future publication work and contribution.

Abbreviations:

MPPT: Maximum Power Point Tracking.

P&O: Perturbation and Observation.

MPP: Maximum Power Point.

PN: PN junction.

PV: Photovoltaic.

GPV: Generator Photovoltaic.

DC: Direct Current.

CS: Static Converter.

Symbols:

I : Current of the generator PV [A].

V : Voltage at the output of a solar module or cell [V].

I_{ph} : Photo-current generated by the PV module or cell [A].

I_{S1} *and* I_{S2} :Diodes saturation currents.

η_1 *and* η_2 : Ideality factor of the diode.

R_S *and* R_p : Series resistance and parallel resistance, respectively (Ω).

T : Temperature of the junction of the cells PV [K].

q: Elementary charge $\left(q = 1.602 * 10^{-19} C\right)$.

K :Constant of Boltzmann $\left(K = 1.380 * 10^{-23} J / K\right)$.

I_{dr} I_{dd}: Currents flowing through a diode [A].

E_g : Energy gap [eV].

V_{oc} : Open-circuit voltage [V].

I_{cell}: Current delivered by the cell [A].

V_{cell}: Terminal voltage at the cell [A].

I_{SC} and I_{CC}: Short-circuit current [A].

Z: Number of photovoltaic cells connected in series.

I_{OP} : Optimal current of generator PV in MPP point [A].

V_{OP} : Maximum voltage of generator PV in MPP point [V].

S, E, Φ (W/m^2) :Sunshine [W/m²].

P : Power from a generator PV [W].

R_i, RS: Variable load (Ω).

V_b: Battery voltage (V).

d : Duty cycle.

I_S: Output current of the converter [A].

V_S: Output voltage of the converter [V].

R_{op}: Optimal resistance of the generator (Ω).

T: Cells temperature (K).

V_{ref} : Output a voltage of PV at moment (k) [V].

P_{pv}(k) : Output power of PV at moment (k) [W].

I(V): Current-voltage characteristic.

P(V): Characteristic power-voltage.

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