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New Direct Nonlinear MPPT design for Photovoltaic System Using Backstepping and Synergetic Controllers

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ABSTRACT : Among the different renewable energy resources, photovoltaic (PV) energy has found increased attention and wide attraction from researchers in several applications, for its capabilities of direct electric energy conversion without any environmental damage, ease of implementation, flexibility in size and low operation cost. The output power induced in the PV modules depends on solar radiation and temperature of the solar cells. To maximize the efficiency of the system, it is necessary to track the maximum power point of the PV array. In this study, two direct maximum power point tracking (MPPT) algorithms based on backstepping and synergetic approaches for a photovoltaic power system are investigated. Both nonlinear algorithms are designed to be applied to a boost DC-DC converter in order to achieve an optimal PV array output voltage. The simulation results validate the rapid tracking and efficient performance of the two controllers. For further validation of the results, it also provides a comparison of the two proposed controllers with conventional perturb and observe (P&O) under abrupt changes in environmental conditions.

KEYWORDS: synergetic controllers backstepping controllers, P&O, direct MPPT, photovoltaic systems.

I. INTRODUCTION

Greater part of the countries in the world adopt the renewable energy sources as an alternative to conventional power generation due to numerous advantages like reduced greenhouse gas emission, unlimited nature of solar energy, eco-friendly nature, etc**.** [1]. Particularly, photovoltaic (PV) energy source is usually employed and become widespread everywhere [2], and it is one of the latest technologies used in electrical power generation; it converts sunlight directly into electricity. The major problem with a PV system is its characteristic affected by the continuous variation in the environmental condition, primarily the temperature and solar irradiance [3], for this, it is essential to run it at maximum power point (MPP) to obtain the highest power from it [4]. Currently, MPPT system is considered the central part of any photovoltaic system to obtain the maximum power at all time under the change in weather conditions. There are a large number of MPPT algorithms developed and discussed in scientific research. Each MPPT technique has its own advantages and disadvantages and the best algorithm is select according to accurate and fast-tracking performance and minimum error due to changing conditions of weather [4, 5]. From all conventional MPPT control algorithms mentioned in literature, P&O is the most used for his simplicity and ease of implementation. The P&O algorithm consists of disturbing the PV output voltage and observing the PV output power to determine the peak power direction. However, the main drawbacks of these MPPT are the power oscillation around the MPP and the confusion in the tracking direction that occur because of the rapid change in atmospheric conditions [5].

In order to overcome the above-mentioned drawbacks, a large number of intelligent and advanced control techniques have attracted a lot of interest over the past few years such as generalized method [6], fuzzy logic controllers [4, 7, 8], artificial neural networks [9], sliding mode control [10, 11, 13], backstepping control [8, 10, 12], synergetic control [5] and meta-heuristic techniques like Genetic Algorithm (GA), Particle Swarm Optimization (PSO) [14], Cuckoo Search (CS) [15, 16] and Grey Wolf Optimization (GWO) [1, 17, 4]. Despite their effectiveness, right tracking and fast response compared to the conventional techniques, these MPPT techniques are more complex and require great knowledge in the design of the control system.In this paper, two news strategies of MPPT based on backstepping and synergetic approaches are adopted to track the maximum power point for PV systems under different atmospheric conditions and therefore increase the PV system efficiency. First, we present the PV system including the used PV array model and the dynamic model boost converter. Then, The proposed design of the control to make the system operating at maximum power point is developed, where the nonlinear controllers are detailed. Finally, the simulation results and the corresponding analysis are shown to make comparison between the proposed methods with conventional P&O. A conclusion resumes the present study.

II. PV SYSTEM DESCRIPTION

The PV system used in this study is shown in Figure 1. A photovoltaic module constitutes the energy source of the PV system. In order to control the operating point, an adaptation stage is added between the photovoltaic generator and the load. This stage which aims to minimize the difference between the maximum available power and the power actually recovered, is only a DC/DC boost converter controlled by a maximum power point tracking technique (MPPT) [5]. It is generally based on the adjustment of the duty cycle d of the converter until it is placed on the MPP in all climatic conditions.

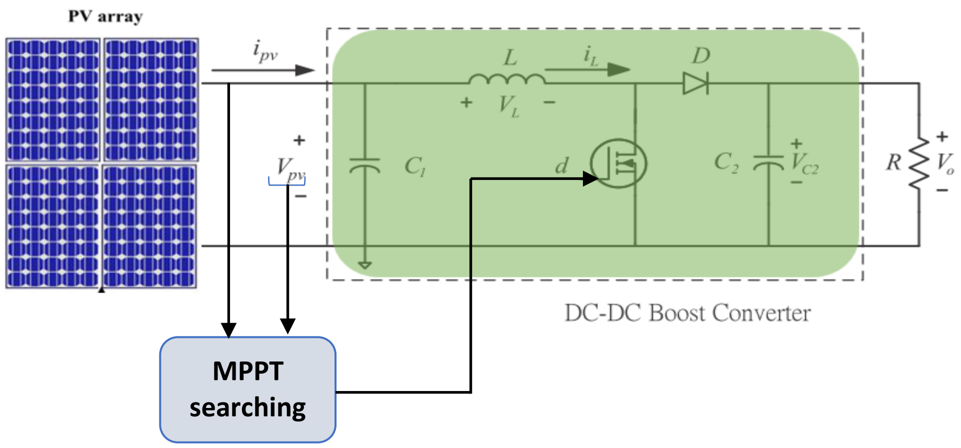


Figure 1. Photovoltaic system with MPPT controllers

A. PV module models: The PV single diode model, shown in Figure 2, is studied and used in this work. This model offers a good compromise between simplicity and accuracy. The equivalent circuit consists of a photocurrent source in parallel with one diode. The solar cell losses are represented by two resistance, the series resistance Rs to represent the ohmic resistance losses and the shunt resistance Rp, to describe the leakage currents through the edges of the solar cell as well as the P-N junction [13, 14, 12, 16].

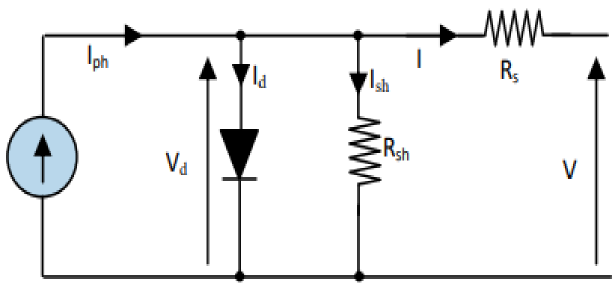


Figure 2. Equivalent circuit of PV solar cells

According to this scheme, the mathematical model of the generated current in a PV system is represented by [6]:

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (1)$$

Where, I_{ph} is a photo current, I_d is a diode current and I_p a shunt current.

The PV cell equation is given by relation (2) [6, 14, 17, 9]:

$$I_{pv} = I_{ph} - I_s[\exp(\frac{q(V_{pv} + R_s I_{pv})}{nkT}) - 1] - \frac{(V_{pv} + R_s I_{pv})}{R_{sh}} \quad (2)$$

where Vpv is the panel voltage; Ipv is the panel current; Rs is the equivalent series resistance; Rp is the equivalent shunt resistance; n is the ideality factor; k is the Boltzmann constant; q is the electron charge; T is the temperature in Kelvin; and Is is saturation current.

As for the model of a PV module, it can be described by the following equation [6, 12]:

$$I_{pv} = N_p I_{ph} - N_p I_s[\exp(\frac{q(V_{pv} + R_s I_{pv})}{N_s nkT}) - 1] - N_p \frac{(V_{pv} + R_s I_{pv})}{R_p} \quad (3)$$

Here, **Ns** and **Np** are the number of PV cells in series and parallel respectively.

B. PV module characteristics: The PV module considered in this work is Solarex MSX-60. It consists of 36 solar cells connected in series to give a maximum output power of 60 W. Figure 3 and Figure 4 show the MATLAB simulated P-V and I-V characteristics curves of PV modules under different irradiation levels at fixed temperature. The corresponding P-V and I-V characteristics curves for different temperature levels at fixed irradiation are given in Figure 5 and Figures 6, respectively. The most important points of a PV module are the short-circuit current Isc, the open-circuit voltage Voc and the maximum power point [9].

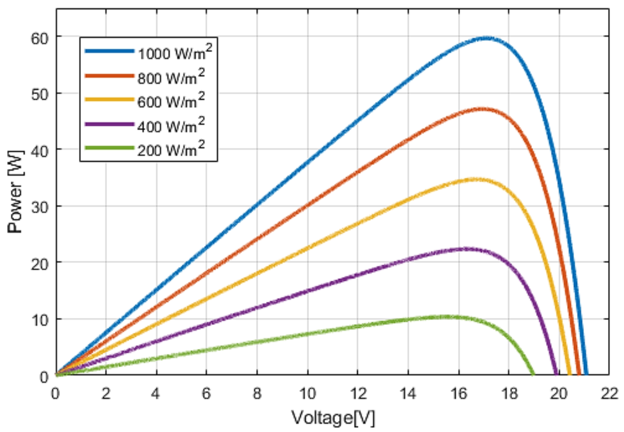


Figure 3. P-V curves under different solar irradiance levels at 25°C

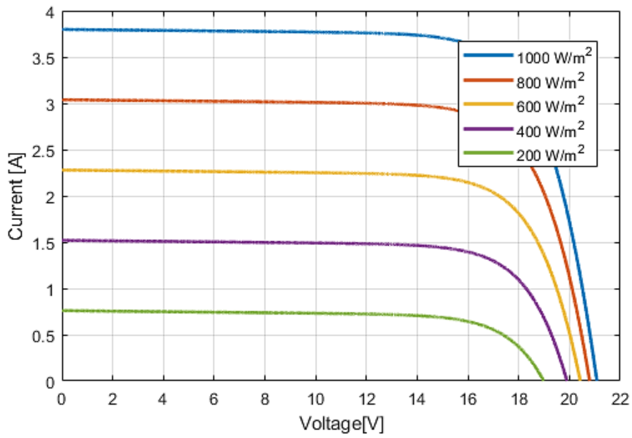


Figure 4. I-V curves under different solar irradiance levels at 25°C

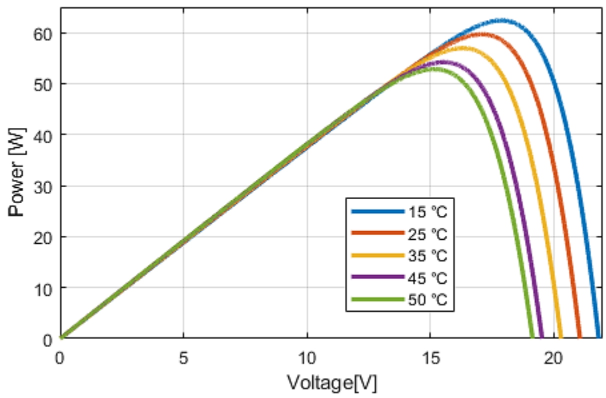


Figure 5. P-V curves under different temperatures at 1000 W/m²

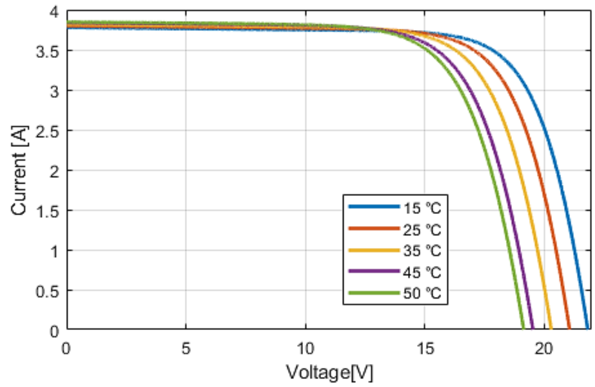


Figure 6. I-V curves under different temperatures at 1000 W/m²

From these figures, we can observe the important effect of atmospheric conditions on the maximum power. For a constant solar irradiation, the output power of the PV module decreases with increasing temperature. The open-circuit voltage decreases linearly with cell temperature increase, while short-circuit current slightly increases with cell temperature. On the other hand, for a constant cell temperature, the output power of the PV module decreases with decreasing in solar irradiation. The open-circuit voltage decreases slowly when decreasing in solar irradiation, while short-circuit current increases with solar irradiation [5, 9, 10].

C. DC-DC Boost Converter*:* The DC-DC converter is a necessary stage in the PV systems, which is adopted as a power interface between the PV panel and the load, to operate at maximum power when the MPPT algorithm changes and adjusts the duty cycle [12, 5]. A DC-DC boost converter is simply a power converter that regulates the average output voltage at a level higher than the input or source voltage [13]. For this reason, the boost converter is often referred to as a step-up converter or regulator. The general circuit of Boost Converter is shown in Figure 7.

The voltage output V_o is given by:

$$V_o = \frac{V_{PV}}{1-d} \tag{4}$$

Where d denotes the duty cycle and varies between 0 and 1.

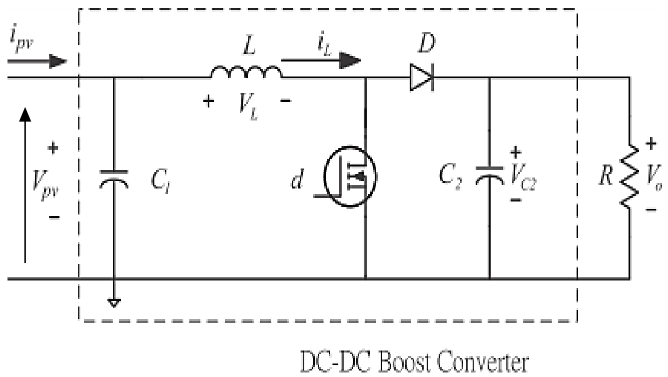


Figure 7. DC-DC boost converter

The dynamic model of the boost converter circuit is [18, 19]:

$$\begin{cases} \dfrac{dx_1}{dt} = \dfrac{V_{pv} - x_2}{L} + \dfrac{x_2}{L} d \\ \dfrac{dx_2}{dt} = -\dfrac{x_2}{RC_2} + \dfrac{x_1}{C_2}(1-d) \end{cases} \tag{5}$$

Where $x = [x_1 \quad x_2]^T = [I_L \quad V_0]^T$

III. DIRECT MPPT CONTROLLER DESIGN

Numerous MPPT Algorithms with different levels of complexity, accuracy, efficiency, time response, cost, and implementation difficulty have been proposed for maximizing the energy utilization efficiency of the PV arrays in the literature [5]. In this paper a backstepping and a synergetic MPPT controllers are developed. To compare the performance of proposed MPPT, a conventional P&O MPPT technique will be studied and used, the flow chart of this method is described in Figure 8.

D. Classical P&O Algorithm *:* The P&O algorithm is considered to be the most commonly used MPPT algorithm among the other techniques because of its simplicity, low cost and ease of implementation [5, 9]. From its name, the P&O algorithm operates by continuously perturbing PV systems either by increasing or decreasing the operating PV output voltage and observing its effect on the output power of the PV array. This perturbation directly affects the duty cycle of the signal which controls the DC-DC converter. This perturbation is followed by the observation of its impact on the output power of the PV panel with the aim of eventually correcting this duty cycle.

Referring to figure 8, the P&O algorithm can be detailed as follows:

- When dP/dV>0, the voltage is increased, this yields to D (K)= D (K)+ΔD,
- When dP/ dV< 0, the voltage is decreased through D (k) = D (k −1) −ΔD.

The ΔD crisp value is chosen by trial and tests in the simulation. Despite its performance, this technique presents some problems related to oscillations around the MPP. These oscillations can be minimized by reducing the variable value of the perturbation. A low increase value slows down the searching of the MPP. As such, it is necessary to find a compromise between precision and fastness.

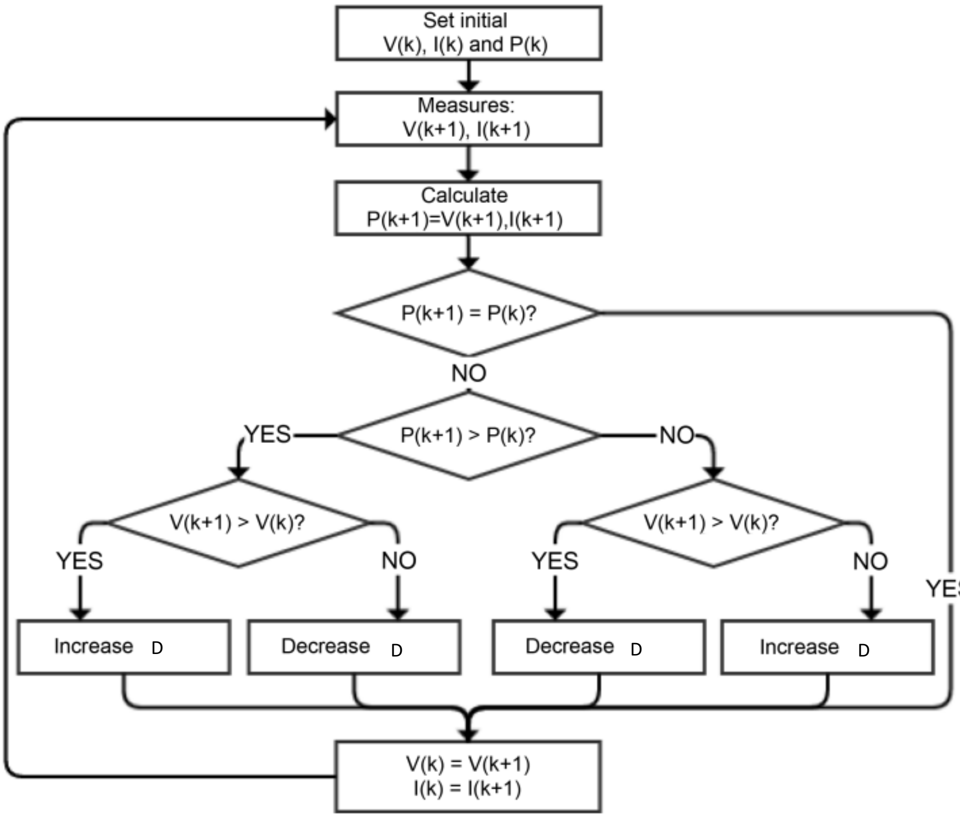


Figure 8. Flow chart of P&O method

- **Synergetic MPPT Controller Design:**

- **Synergetic control theory:** The nonlinear system dynamics are expressed by the differential equation as follows [19, 20]:

$$\frac{dx(t)}{dt} = f(x, u, t) \tag{6}$$

Where x is the n-dimensional state vector, u is the m - dimensional control input and t is time.
The Synergetic approach is based on a particular choice of the macro variable. Therefore, we started by defining a nonlinear macro-variable as follows [18, 19]:

$$\Psi = \psi(x, t) \tag{7}$$

The synergetic control will drive the system to converge to the manifold ($\Psi = 0$). The selection of macro-variable is based on the specifications for example the settling time, the steady state error and constraints on control output [20]. The desired dynamic evolution of the macro-variable is:

$$T\dot{\psi} + \psi = 0, \quad \text{avec} \qquad T > 0 \tag{8}$$

Where T is a specific designer chosen that determines the rate of convergence speed to the manifold specified by the macro-variable.
The solution of the equation (8) gives the following function:

$$\psi(t) = \psi_0 \exp(-\frac{t}{T}) \tag{9}$$

Figure 9 shows that the macro-variable $\psi(t)$ converges to $\psi = 0$ different initial conditions ψ_0, where t represents time, and T is a parameter of control which indicates the system convergence speed.
Considering the chain rule of differentiation that is given by:

$$\frac{d\psi(x,t)}{dt} = \frac{d\psi(x,t)}{dx}\frac{dx}{dt} \tag{10}$$

Combining equations 6, 8 and 10:

$$T\frac{d\psi(x,t)}{dx}f(x,u,t)+\psi(x,t)=0 \quad (11)$$

Finally, upon solving equation 11, the control law can be described as follows:

$$u=g(x,\psi(x,t),t,T) \quad (12)$$

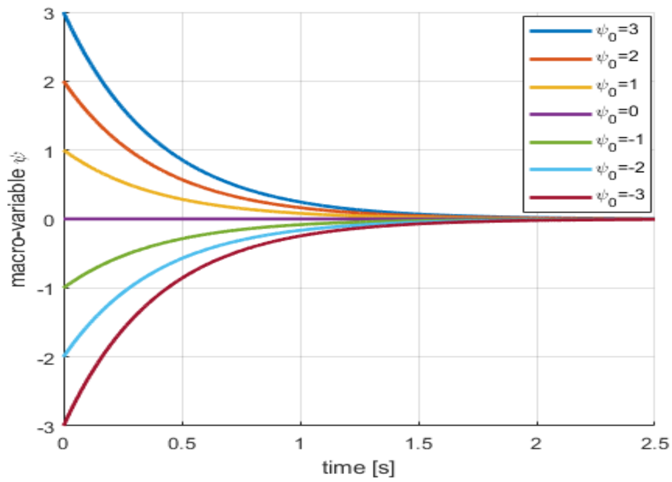


Figure 9. Convergence of ψ various initial conditions ψ_0

- **The synergetic MPPT controller:** Like all other MPPT controller, the modeling of the synergetic MPPT controller is based on the output power of the photovoltaic cell. The optimization of the output power is achieved by solving the following function:

$$\frac{dP_{pv}}{dV_{pv}}=0 \quad (13)$$

Hence, the manifold is defined as:

$$\psi=\frac{dP_{pv}}{dV_{pv}}=I_{pv}+\frac{dI_{pv}}{dV_{pv}}V_{pv}=0 \quad (14)$$

By applying equation (10) we find:

$$\dot{\psi}(x)=\frac{d\psi}{dt}=\frac{\partial\psi}{\partial x}\frac{\partial x}{\partial t}=\frac{\partial\psi}{\partial x}\dot{x}=\frac{\partial\psi}{\partial x_1}\dot{x}_1+\frac{\partial\psi}{\partial x_2}\dot{x}_2 \quad (15)$$

For the considered boost converter, the manifold ψ is a function of I_L only, which is the state variable x_1, the inductor current. Hence the chain rule of differentiation becomes:

$$\dot{\psi}(x)=\frac{\partial\psi}{\partial x_1}\dot{x}_1 \quad (16)$$

So, $$\dot{\psi}=\frac{\partial\psi}{\partial x_1}\dot{x}_1=\frac{\partial\left(I_{pv}+\frac{dI_{pv}}{dV_{pv}}V_{pv}\right)}{\partial x_1}\dot{x}_1 \quad (17)$$

With: $$\begin{cases} I_{pv} = \dfrac{I_s}{1-d} \\ I_s = \dfrac{V_s}{R} \\ V_s = \dfrac{V_{pv}}{1-d} \end{cases} \tag{18}$$

where: $$\begin{cases} \dfrac{dI_{pv}}{dV_{pv}} = \dfrac{1}{R(1-d)^2} \\ \dfrac{dP_{pv}}{dV_{pv}} = I_{pv} + \dfrac{dI_{pv}}{dV_{pv}} V_{pv} = I_{pv} + \dfrac{1}{R(1-d)^2} V_{pv} = 2I_{pv} \end{cases} \tag{19}$$

we find: $$\dot{\psi} = \frac{\partial \psi}{\partial x_1}\dot{x}_1 = \frac{\partial (2I_{pv})}{\partial x_1}\dot{x}_1 = \frac{\partial (2(I_L + I_{c1}))}{\partial x_1}\dot{x}_1 = 2\dot{x}_1 \tag{20}$$

Introducing equation (20) in equation (8) gives us:

$$\begin{cases} T\dfrac{\partial \psi}{\partial x_1}\dot{x}_1 + \psi = 0 \\ 2T\dot{x}_1 + \psi = 0 \\ \dot{x}_1 = -\dfrac{\psi}{2T} \end{cases} \tag{21}$$

Where: $$\dot{x}_1 = \frac{V_{pv} - x_2}{L} + \frac{x_2}{L} d = -\frac{\psi}{2T} \tag{22}$$

Finally, the control law can be described as follows:

$$d = \frac{-L}{2Tx_2}\psi - \frac{V_{pv}}{x_2} + 1 = \frac{-L}{2TV_0}\psi - \frac{V_{pv}}{V_0} + 1 \tag{23}$$

E. Backstepping MPPT Controller Design *:* In order to operate PV modules with its maximum power, a nonlinear controller based on backstepping approach is designed. For that purpose, we will find an intermediate Lyapunov function which will allow the PV system to obtain the maximum power. We definite the error as follows:

$$e = \frac{dP_{pv}}{dV_{pv}} = I_{pv} + \frac{dI_{pv}}{dV_{pv}} V_{pv} \tag{24}$$

The derivative with regard to the time of e is given by:

$$\dot{e}(x) = \frac{de}{dt} = \frac{\partial e}{\partial x}\frac{\partial x}{\partial t} = \frac{\partial e}{\partial x}\dot{x} = \frac{\partial e}{\partial x_1}\dot{x}_1 + \frac{\partial e}{\partial x_2}\dot{x}_2 \tag{25}$$

By applying the same procedure as in the preceding control to calculate $\dot{e}(x)$, we find:

$$\dot{e}(x) = \frac{\partial e}{\partial x_1}\dot{x}_1 = \frac{\partial (2I_{pv})}{\partial x_1}\dot{x}_1 = \frac{\partial (2(I_L + I_{c1}))}{\partial x_1}\dot{x}_1 = 2\dot{x}_1 \tag{26}$$

The Lyapunov function and its derivative are defined as follows:

$$V_0 = \frac{1}{2}e^2$$
$$\dot{V}_0 = e\dot{e} = e\frac{\partial e}{\partial x_1}\dot{x}_1 \quad (27)$$

So that the derivative of V_0 is always negative, it is necessary that:

$$\dot{V}_0 = e\dot{e} = e\frac{\partial e}{\partial x_1}\dot{x}_1 = -k_1 e^2 \quad (28)$$

By replacing $\dot{e}$ and $\dot{x}_1$, we obtain:

$$2\left(\frac{V_{pv} - x_2}{L} + \frac{x_2}{L}d\right) = -k_1 e \quad (29)$$

the final control law can be described as follows:

$$d = \frac{-k_1 L}{2x_2}e - \frac{V_{pv}}{x_2} + 1 = \frac{-k_1 L}{2V_0}e - \frac{V_{pv}}{V_0} + 1 \quad (30)$$

IV. SIMULATION RESULTS AND DISCUSSIONS

The PV model system, shown in Figure 1, has been implemented in MATLAB/Simulink environment for simulation. It includes the PV array, the DC–DC boost converter controlled by the proposed MPPT controllers and a resistive load. The PV modules, the system specifications and MPPT controller's parameters used in the simulation are shown in Table 1, Table 2 and Table 3 respectively.

TABLE 1: Specifications of the Solarex MSX-60 PV Module

Maximum PV Power	Pmax = 60 Wc
Optimum operating voltage	Vmpp=17.1 V
Optimum operating current	Impp = 3.5 A
Open-Circuit Voltage	Voc = 21.1 V
Short-Circuit Current	Isc = 3.8 A

TABLE 2: Boost Converter Parameters

PV Input Capacitance	C1 = 1000µF
Inductance	L = 0.22mH
Boost Converter Output Capacitance	C2 =470µF
Resistive Load	R = 25Ω
Switching Frequency	fp =5 kHz

TABLE 3: MPPT controller's Parameters

Backstepping parameter	K_1 = 1/T
Synergetic parameter	T = 4e-6
P&O perturbation value	Deltad =8e-3

To verify the success of the quality and efficiency of the proposed MPPT controllers in the PV system, we chose to test the controller's performances under variable climatic conditions solar irradiation. These performances of the three controllers are analyzed in the following conditions:

▪ **Simulation Results with Standard Operating Conditions (SOC) :** In this case, it has been supposed that the solar irradiation E and the cell temperature T are constant. The value of E is set to 1000 W/m2 and the value of T is taken 25°C. The results shown in figures 10–12 demonstrate the obtained performances of P&O, backstepping and synergetic MPPT approach. These results have confirmed the good performance and the high effectiveness of the proposed controllers in transient and steady state.

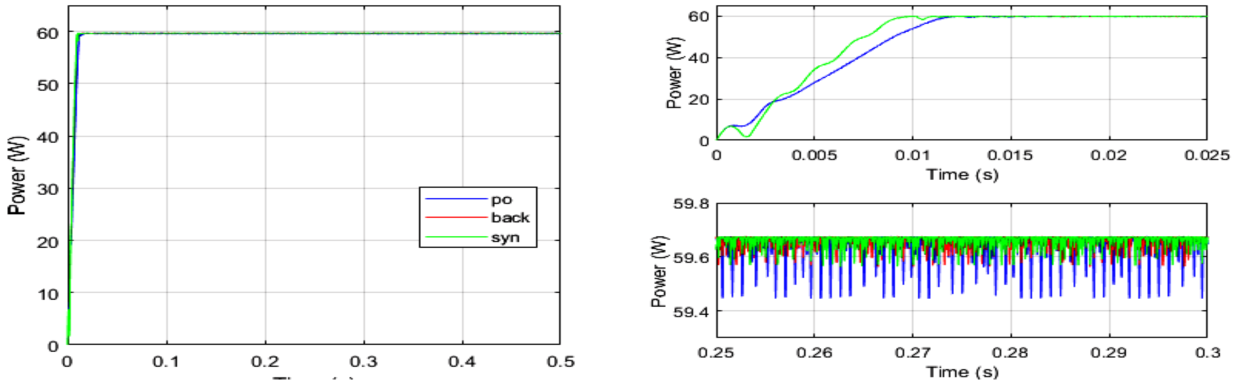


Figure 10. PV power comparison under SOC with zoom

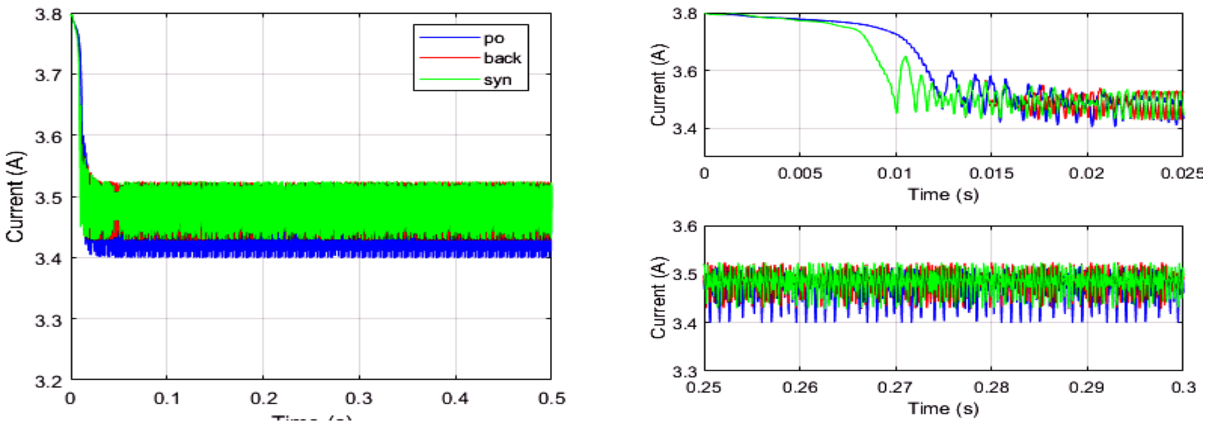


Figure 11. PV current comparison under SOC with zoom

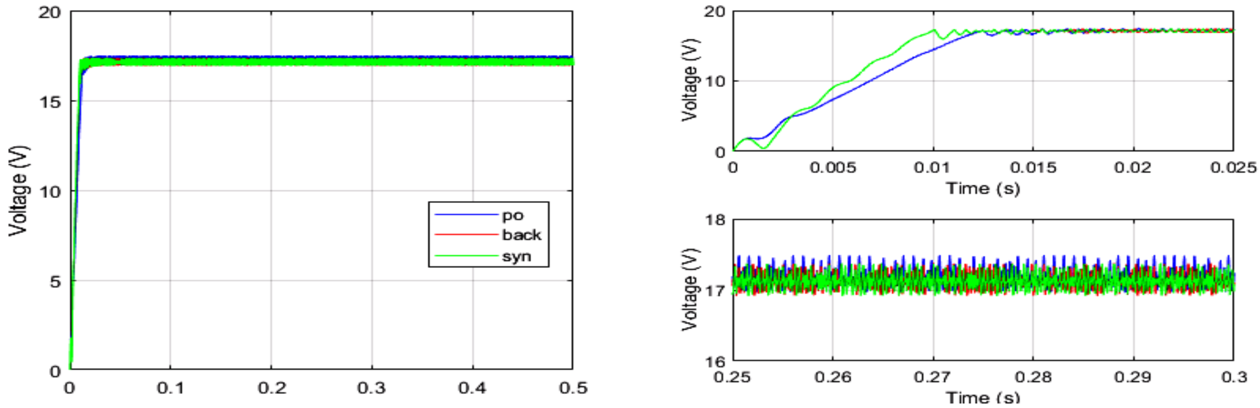
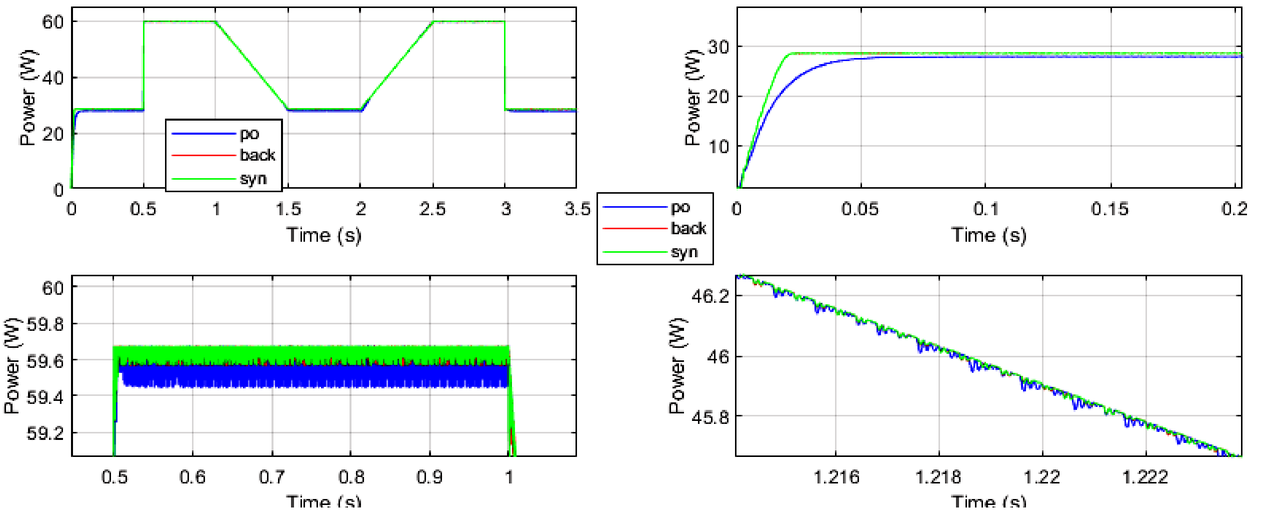


Figure 12. PV voltage comparison under SOC with zoom

Figure 10 shows the PV output power for three controllers. In each operating condition, the proposed methods attained the MPP in a relatively short time and have very small oscillations in steady state compared to the P&O classical method. The proposed methods MPPT have about the same performances. The PV outputs current and voltage waveforms of three controllers are shown in figures 11 and 12 respectively, it can be seen clearly, the classical P&O has significant oscillations and tracks the MPP within large response time compared to the two proposed methods.

- **Simulation Results under Solar Irradiation Variation (SIV) : Step and ramp test:** in this case, the temperature is constant and irradiation is changing with time under different conditions (step and ramp). Figures 13 and 14 show the different simulation results.



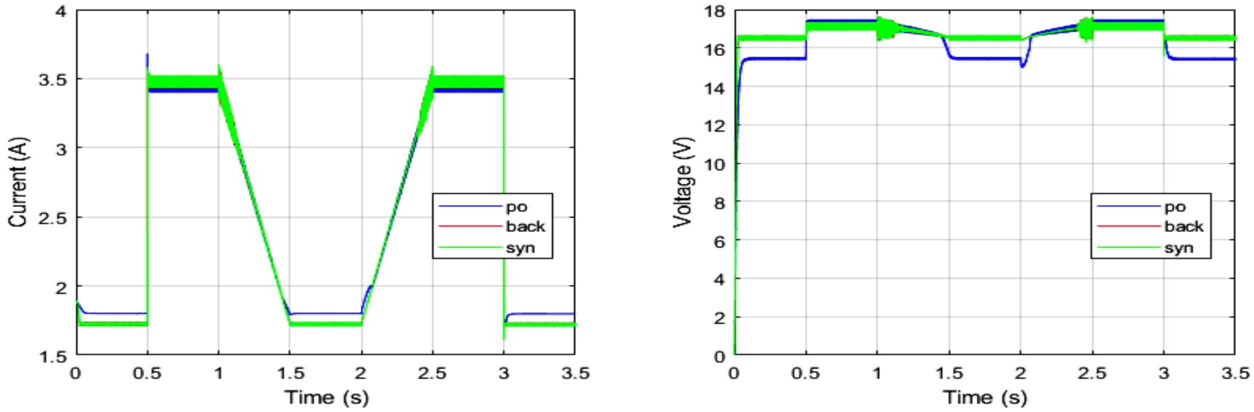


Figure 14. PV current and voltage comparison under SIV

- **The whole day test:** In this case, we observe the daily generated power, current and voltage for these three controllers.

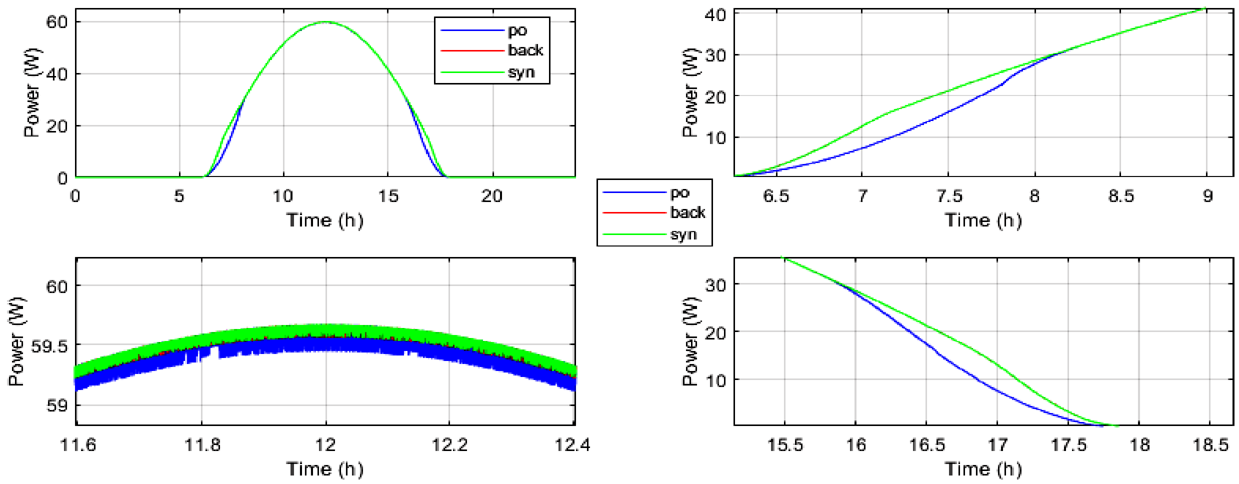


Figure 10. PV power comparison under SIV with zoom

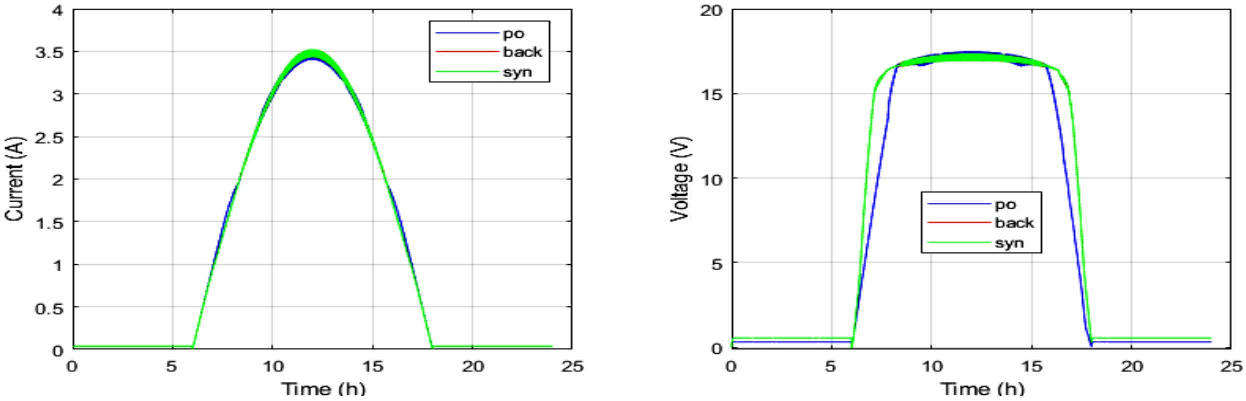


Figure 10. PV current and voltage comparison under SIV

For these three controllers, we note the impact of the increase of the power, current and voltage generated by the PV system due to the increase of irradiation E when the temperature is constant. The results reveal the effectiveness of the MPPT controllers to extract the maximum available power from the solar array at different irradiance levels. As shown, backstepping and synergetic controllers give fewer oscillations and better stable operating point than P&O. From the simulation results, it can be deduced that the nonlinear controllers give better performance than P&O, and it has more accuracy for operating at Maximum Power Point

V. CONCLUSION

This paper presents two direct nonlinear MPPT controllers based on the backstepping and synergetic theories applied to a standalone MPPT PV system using a boost converter. The whole system was modeled and simulated in the Matlab/Simulink software. The simulation results prove the good performance in transient and steady state of the proposed MPPT controllers, under different solar irradiance and constant temperature. Moreover, both proposed MPPT controllers assure better tracking performance and high robustness related to higher tracking speed, faster convergence towards the MPP, better tracking efficiency and lower power oscillations at MPP than P&O.

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