Experimental validation of synergetic approach based MPPT controller for an autonomous PV system

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Abstract
A novel nonlinear maximum power point tracking (MPPT) controller for autonomous photovoltaic systems based on synergetic control theory is presented in this paper as a solution to eliminate the chattering drawback provided by sliding mode controller, where the proposed strategy allows to generate continuous control law instead of a switching term. A DC/DC boost converter is introduced in the content of this work as an interface between a photovoltaic array and a resistive load. The developed MPPT controller was tested both in simulations using Matlab/Simulink tool and experimentally using dSPACE RTI 1104 real-time platform and compared with the sliding mode-based MPPT controller. Furthermore, the EN 50530 standard test with different ramp gradients values is used to calculate the MPPT efficiency under irradiance changes from the slow to the very fast. Illustrative results that prove the effectiveness and the robustness of the proposed MPPT controller even the non-uniform conditions (temperatures and solar irradiances) are presented here. The fast response and the accurate tracking to the maximum power point (MPP) with considerable reduction in the oscillations are successfully reached with the developed controller which is much better than sliding mode controller.

1 INTRODUCTION

The huge restriction of fossil fuels on human development and the ever-increasing energy demand in every sphere have resulted to its depletion without forgetting the serious problems on the environment. To break these drawbacks, research and development of new energy has sparked wide interest worldwide.

Over the past few decades, renewable energy sources are considered to be a perfect choice to generating sustainable, abundant, inexhaustible energy and even more environmentally friendly. Among the various types of renewable energy sources is solar energy, or more popularly known as photovoltaic (PV) energy which has attracted a lot of interest with many important applications expanding continuously from lighting systems [1] to pumping systems [2].

Many people probably wonder: if solar energy is so beneficial, why do not we consume it more? The answer to this question is the unbalance between the high installation cost and the low energy conversion of PV array which varies according to irradiation and temperature during its operation. Thus, because of these limitations, we should extract the maximum power and enhance the PV system’s efficiency despite all these climatic variations. This challenge can be achieved by the wise choice of maximum power point tracker (MPPT) which determines the optimal functioning of the PV systems.

A large number of MPPT control algorithms have been developed for several years which drive the PV array to the peak of the power against environment changes. Each MPPT technique has its own advantages and disadvantages. These control techniques could be classified into two categories namely the conventional methods and intelligent methods.

Among conventional MPPT mentioned in the literature, perturbation and observation (P&O), incremental conductance (IC) and the hill climbing (HC), are the most widely used since they are simple and easy to implement. The P&O algorithm consists of disturbing the PV output voltage and observing the PV output power to determine the peak power direction [3–5]. The IC method compares between the instantaneous conductance ($I/V$) of PV array and the incremental conductance ($dI/dV$) to track MPP [4,6,7]. The HC technique locates
the MPP by relating changes in the power output to changes in duty ratio of the converter. Mathematically, the MPP is achieved when $dP/dD$ is forced to be zero, where $D$ represent the duty ratio $[6,8]$. However, these techniques have some disadvantages. The major of them is the power oscillation around MPP and the confusion in the direction of tracking caused by rapidly changing in atmospheric conditions $[3,9]$. Moreover, these commands vary in speed of convergence, cost and efficiency.

In order to overcome the above-mentioned drawbacks, a large number of intelligent control techniques have attracted a lot of interest over the past years such as fuzzy logic controller $[10]$, artificial neural-network $[11]$ and meta-heuristic techniques which are used for the global search under partial shading conditions like genetic algorithm (GA) $[12]$, particle swarm optimization (PSO) $[13]$, artificial bee colony (ABC) $[14]$ and ant colony optimization (ACO) $[15]$. Despite of their effectiveness, these techniques are more complex and require huge knowledge in the design of the control system.

Recently, sliding mode control (SMC) is considered to be a powerful technique because of its fast convergence and high robustness $[16,17]$. On the other hand, its major flaw is a chattering phenomenon which induces many undesirable oscillations in control signal which may lead the system into instability $[18–20]$. All these difficulties inspired from the above study in particular, oscillation behaviour, robustness and speed of the MPPT in tracking the optimal power, have guided to move to improve the performance of the PV system. To achieve this objective, one of the most promising robust control strategy named synergetic control (SC) is suggested $[21,22]$. The synergetic control depends on the same invariance property of systems found in SMC, but without its chattering drawback because it provides a continuous control law unlike the conventional SMC which combines two terms, one ensures the attractiveness of the system states to the sliding surface while the other one maintains the operating point on sliding surface and displace it to the origin, this sudden change leads to the chattering phenomena. This theory has initially been successfully applied in power electronics control $[23,24]$, in battery charging system $[25]$, then recently in control of the epidemic system $[26,27]$ and in the control of wind turbine system $[28]$.

This paper proposes a new strategy based on synergetic control theory to track the MPP for stand-alone photovoltaic system under different atmospheric conditions. The main goal of the proposed MPPT controller is to ensure the system stability at the maximum power, good robustness and fast dynamic response simultaneously. The design of the synergetic MPPT controller is explained and mathematically described in the paper. The developed MPPT controller was tested both in simulations using Matlab/Simulink tool and experimentally using a dSPACE based experimental test bench, the MPPT efficiency is calculated using the EN 50530 standard test and illustrative results are presented here. It is shown via simulation and experimental results that the developed MPPT controller ensures an excellent transient and steady state performance without oscillations around the MPP, reduces greatly the tracking time in the right direction and moreover the high efficiency under atmospheric changes unlike other techniques.

2 | PHOTOVOLTAIC SYSTEM DESCRIPTION

The configuration of the proposed system consists of PV array, a DC–DC boost converter, a resistive load and a nonlinear MPPT controller as shown in Figure 1.

In order to extract the maximum power from the PV module regardless weather changes, a MPPT algorithm is used to adjust the duty cycle of the boost converter by continuously opening and closing the switch. This topology can be extended to a grid connected system through an inverter.

2.1 | Photovoltaic panel modelling

When the surface of the PV cell (the basic units in the structure of a PV module) is exposed to light it absorbs light energy and converts it into electrical energy $[29]$. Since the power generated by a solar cell is very small, they have to be compiled in series or parallel to produce enough amount of electrical power whether for industry or domestic use $[30]$.

In this paper we use the single diode model proposed in references $[30,31]$. Its equivalent circuit consists of a current source in parallel with one diode, and two resistances, one in series and other in parallel as shown in Figure 2. According to this scheme,
the mathematical model for the I-V characteristic is given by:

\[
I_{\text{pv}} = I_{\text{ph}} - I_0 \left\lfloor \exp \left( \frac{q (V_{\text{pv}} + I_{\text{pv}} R_S)}{AKT} \right) - 1 \right\rfloor - \frac{V_{\text{pv}} + I_{\text{pv}} R_S}{R_{\text{sh}}} 
\]

where \( I_{\text{pv}} \) is the PV output current, \( V_{\text{pv}} \) is the PV output voltage, \( R_{\text{sh}} \) is the shunt resistance and \( R_s \) is the series resistance. \( I_0 \) is the saturation current of the diode which depends on temperature \( T \) (in Kelvin) given as follows:

\[
I_0 = I_{0r} \left( \frac{T}{T_r} \right)^3 \exp \left( \frac{qE_g}{X_{bA} k T} \left( \frac{1}{T} \right) - \frac{1}{T} \right) 
\]

where \( A \) is the diode ideality factor, \( k_b \) is Boltzmann’s constant, \( E_g \) is the band gap energy, \( I_{0r} \) is the saturation current at the reference temperature \( (T_r) \), \( I_{\text{sc}} \) is the short-circuit current of PV cell under standard conditions and \( I_{\text{ph}} \) is the photogenerated current, depends on solar irradiance \( E \) (W/m²), often given by:

\[
I_{\text{ph}} = \frac{E}{E_{\text{ir}}} \left[ I_{\text{sc}} + K (T - T_r) \right]
\]

This equation show clearly that the generated power of the PV module is strongly influenced by irradiance and temperature. So, it is necessary to study how these two climatic parameters will affect at the characteristics of the cell by drawing the curve of power \( (P) \) versus voltage \( (V) \) for various irradiations at constant temperature (Figure 3), and for different temperatures at constant irradiance (Figure 4). It is obvious that the maximum power increases with irradiance increasing or temperature decreasing.

The PV panel used for simulations is Kyocera KC85T consists of 36 solar cells connected in series to give a maximum output power of 87 W. Its electrical characteristics at standard test conditions (1000 W/m² and \( T = 25^\circ \text{C} \)) are given in Table 1.

| Description | Kyocera KC85T |
|-------------|---------------|
| Maximum power \( (P_{\text{max}}) \) | 87 W |
| Open-circuit voltage \( (V_{\text{oc}}) \) | 21.7 V |
| Short-circuit current \( (I_{\text{sc}}) \) | 5.34 A |
| Optimum operating voltage \( (V_{\text{mpp}}) \) | 17.4 V |
| Optimum operating current \( (I_{\text{mpp}}) \) | 5.02 A |
2.2 | DC–DC boost converter modelling

The most usual technique to extract the maximum power at any time is to use an adaptation stage between the PV array and the load. The use of DC–DC boost converter as an interface between the two elements enables the step up of the input voltage $V_{pv}$ to the desired output voltage $V_o$ [32]. The circuit of the DC–DC boost converter is shown in Figure 5.

The dynamic model of the DC–DC boost converter used in this paper can be described by the Equations (4). Where $D$ is the duty ratio, which is also the control law.

$$\frac{di}{dt} = -\left(1 - D\right) \frac{V_o}{L} + \frac{V_{pv}}{L}$$  \hspace{1cm} (4a)

$$\frac{dV_o}{dt} = (1 - D)  \frac{i}{C} - \frac{V_o}{RC}$$  \hspace{1cm} (4b)

3 | SLIDING MODE BASED MPPT CONTROLLER

SMC is considered as one of the most well-known nonlinear control techniques where its design involves two basic steps. Firstly, determine the sliding surface that ensures the convergence property towards the desired values. Secondly, establish the control law that forces the system trajectory to reach and stay within the chosen sliding surface [33].

The MPP of the PV system is achieved when the following equality is satisfied:

$$\frac{dP_{pv}}{dI_{pv}} = \frac{dP_{pv}V_{pv}}{dI_{pv}} = V_{pv} + I_{pv} \frac{dV_{pv}}{dI_{pv}} = 0$$  \hspace{1cm} (5)

Accordingly, the sliding surface can be chosen as:

$$S = V_{pv} + I_{pv} \frac{dV_{pv}}{dI_{pv}}$$  \hspace{1cm} (6)

Let be the positive definite quadratic Lyapunov function $V_L = \frac{1}{2} S^2$. In order to ensure the attractiveness of the surface $S = 0$ over the entire operating range; it is enough that the time derivative of $V_L$ must be negative.

$$\dot{V}_L = S \dot{S} < 0$$  \hspace{1cm} (7)

Where the surface derivative is given by:

$$\dot{S} = \frac{dS}{dt} = \left[\frac{dS}{dx}\right]^T \dot{x}$$  \hspace{1cm} (8)

The general control law $D$ consists of two parts, the discrete control $D_d$ and the equivalent control $D_{eq}$.

$$D = D_d + D_{eq}$$  \hspace{1cm} (9)

The discrete control $D_d$, is determined to ensure the attractiveness to the sliding surface and is defined as follows:

$$D_d = K \times \text{sgn}(S)$$  \hspace{1cm} (10)

where $K$ is a positive constant.

The equivalent control $D_{eq}$, serves to maintain the operation point on the sliding surface and displace it towards the origin, it is defined as follows:

$$D_{eq} = 1 - \frac{V_{pv}}{V_o}$$  \hspace{1cm} (11)

So, the overall control law $D$ has the expression mentioned in the following Equation (12), where the corresponding block diagram is shown in Figure 6.

$$D = K \times \text{sgn}(S) + 1 - \frac{V_{pv}}{V_o}$$  \hspace{1cm} (12)

As the control law generated by the SMC combines two terms, it is not continuous. This sudden change or switching in the control law leads to the chattering phenomena [34–37].

To break this drawback, we propose in the next section the adoption of a new strategy to track the MPP depends on the same invariance property of systems found in SMC but provides
a continuous control law instead of a switching term in order to either reduce or eliminate the chattering phenomenon.

4 | SYNERGETIC BASED MPPT CONTROLLER

Synergetic control theory was first developed and introduced in general terms by Prof. Anatoly Klesnikov and his team [21]. The design of SC is very similar to that of the SMC; the main advantage of this command is the elimination of chattering problem.

4.1 | Synergetic control theory

Let us consider the system to be controlled is described by a non-linear differential equation of this form:

$$\frac{dx}{dt} = f(x, D, t)$$  \hspace{1cm} (13)

where $x$ represents the system state vector, $D$ the control input vector and $f$ a continuous differentiable nonlinear function.

Synergetic controller design starts by selecting a macro-variable (MV): $\Psi(x, t)$ as function of the system state variables according to performance and control specifications [19, 21]. This controller will force the system trajectory approaching exponentially to the manifold.

$$\Psi = 0$$  \hspace{1cm} (14)

Once the trajectory reaches the desired manifold, the synergetic controller will keep it there. The desired dynamic evolution of the MV is chosen such as Equation (15):

$$T_s \left( \frac{d\Psi}{dt} \right) + \Psi = 0; \quad T_s > 0$$  \hspace{1cm} (15)

where $T_s$ is a positive value which will affect smoothly at the convergence speed of the system to the desired equilibrium point. Differentiating the macro-variable along Equation (13) leads to Equation (16):

$$\frac{d\Psi}{dt} = \left( \frac{d\Psi}{dx} \right) \left( \frac{dx}{dt} \right)$$  \hspace{1cm} (16)

By combining Equations (13), (15), and (16) we get:

$$T_s \left( \frac{d\Psi}{dx} \right) f(x, D, t) + \Psi = 0$$  \hspace{1cm} (17)

Finally, when solving Equation (17), we can describe the control law as follows:

$$D = g(x, t, \Psi(x, t), T_s)$$  \hspace{1cm} (18)

It is obvious from Equation (18), that the control output depends not only on the system state variables $(x, t)$, but also on the adequate selection of the MV and time constant $T_s$ to ensure the system stability and the good transient and steady state performances.

4.2 | Synergetic MPPT controller design

In what follows, we applied the concept of the SC explained above for the MPPT controller design. To apply this strategy we start by selecting a MV. This selection is based on the output power of the cell as follows:

$$\Psi(x, t) = \frac{dP_{pv}}{dI_{pv}}$$  \hspace{1cm} (19)

Hence, the manifold is defined as:

$$\Psi = \frac{dP_{pv}}{dI_{pv}} = \frac{dI_{pv}}{dV_{pv}} = V_{pv} + I_{pv} \frac{dV_{pv}}{dI_{pv}} = 0$$  \hspace{1cm} (20)

By applying Equation (16) we find:

$$\frac{d\Psi}{dt} = \left( \frac{d\Psi}{dI_{pv}} \right) \left( \frac{dI_{pv}}{dt} \right)$$  \hspace{1cm} (21)

Compensating Equation (21) in Equation (15) give us:

$$T_s \left[ \left( \frac{d\Psi}{dI_{pv}} \right) \left( \frac{dI_{pv}}{dt} \right) \right] + \Psi = 0$$  \hspace{1cm} (22)

Where:

$$\frac{d\Psi}{dI_{pv}} = \frac{2}{dV_{pv}} + \frac{dV_{pv}}{dI_{pv}}$$  \hspace{1cm} (23)

$$\frac{dI_{pv}}{dt} = - (1 - D) \frac{V_o}{L} + \frac{V_{pv}}{L}$$  \hspace{1cm} (24)

The substitution of Equations (23) and (24) into the Equation (22) gives the control law equation described in (25):

$$D(t) = 1 - \frac{\Psi L}{V_o T_s \left( \frac{2}{dI_{pv}} + I_{pv} \frac{d^2I_{pv}}{dI_{pv}^2} \right)} - \frac{V_{pv}}{V_o}$$  \hspace{1cm} (25)

From Equation (25), we see that the control law generated by the synergetic approach is continuous instead of a switching term by thus the chattering phenomenon can be either reduced or eliminated.

The block diagram of the proposed synergetic strategy is given in Figure 7.
4.3 Stability proof

The system stability is ensured using the Lyapunov’s theory. Let the Lyapunov’s function be defined positive as follows:

\[
V_L = \frac{1}{2} \Psi^2 \leq 0 \tag{26}
\]

We say that the system is stable if the derivative of the Lyapunov’s function is less than zero. The derivative of \( V_L \) is given by:

\[
\frac{dV_L}{dt} = \Psi \left( \frac{d\Psi}{dt} \right) = \Psi \left[ \left( -\frac{1}{T_s} \right) \Psi \right] = \left( -\frac{1}{T_s} \right) \Psi^2 \leq 0 \tag{27}
\]

According to Equation (27), the derivative of the Lyapunov’s function is always negative, which ensures system stability.

5 RESULTS AND DISCUSSION

In order to evaluate the effectiveness of the proposed synergetic controller, the model of the PV system, shown in Figure 1, has been first implemented in Matlab/Simulink environment for simulation. Next, the proposed MPPT controller is implemented in dSPACE RTI 1104 real-time platform and several tests were performed on an experimental test bench to confirm the simulation results obtained.

5.1 Simulation results

To verify the performance of the proposed MPPT controller, the PV model system has been designed in Matlab/Simulink as shown in Figure 8. It includes the PV array, the DC–DC boost converter controlled by the proposed MPPT controller and a resistive load. The PV modules specifications and the system specifications used in the simulation are shown in Table 1 and Table 2 respectively.

The simulation results obtained by the developed controller are compared to that obtained by sliding mode controller at Standard Climatic Conditions SCC (irradiance = 1000 W/m² and temperature = 298 K).

Figure 9(a) shows the output power of all above mentioned methods, these results have confirmed the good performance and the high effectiveness of the proposed controller in transient and steady state. We can note clearly, in a transient state, that the synergetic approach ensures the convergence to the MPP more rapidly compared to sliding mode controller and in the right direction. At the same time, the duty cycle of the proposed technique converges to the optimal value in limited time as shown in Figure 9(b) and the macro-variable is maintained very close to zero as shown in Figure 9(c), by this we guarantee the ability to reach the optimum point (\( \frac{dP_{pv}}{dI_{pv}} = 0 \)). Moreover, in a steady state, once the output power of the PV system is maintained at the maximum, a significant reduce of the oscillation around the MPP is appeared and as result, the power extracted using synergetic approach is much larger compared to the power extracted using SMC technique as shown obviously in attached zoom in Figure 9(a).

In order to evaluate the robustness of the proposed MPPT controller under variable atmospheric conditions, the sun insolation 700 W/m² is applied to the PV system. Then, it is stepped up to 1000 W/m² and finally it is stepped down to 500 W/m² as shown in Figure 10(a). The tracking result of this step change of both techniques is shown in Figure 10(b). While Figure 10(c) and (d) illustrate the duty cycle, the output voltage

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**TABLE 2 System specifications**

| Description | DC–DC boost converter |
|-------------|-----------------------|
| Capacity \( C_{in} \) | 200 \( \mu \)F |
| Capacity \( C_{o} \) | 20 \( \mu \)F |
| Inductance \( L \) | 15e-3 mH |
| Resistive load \( R \) | 25 \( \Omega \) |
| Switching frequency | 10 kHz |

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**FIGURE 7** Simulink block diagram of synergetic controller
(V_{out}), the PV voltage (V_{pv}) and the PV current (I_{pv}) of the proposed synergetic controller at the same step change.

In the first step change introduced at 0.1 s we stepped up the irradiance from 700 to 1000 W/m² in short time equal to 0.05 s. On the obtained results we can make a detailed analysis. In transient state, the SMC takes a relatively long time to reach the MPP without an overshoot. The settling time in this case is equal to 0.08 s. While the SC reaches the MPP at the same time that the irradiance settled at 1000 W/m² as it is shown in zoom 1 of Figure 10(b). In steady state, once the power extracted by SMC will be stable, the oscillations around the MPP introduce a power with an average value equal to 86.95 W which creates a static error equal to 0.33 W. On the other hand, the average value of the power extracted by SC is estimated to 87.28 W which provides almost neglected static error. The second step change is distinguished by a stepped down of irradiance at 0.25 s from 1000 to 500 W/m² in relatively long time, compared to the time of the first step change which equals 0.15 s. In this case, SMC shows a fast tracking to the MPP but not with the same accuracy given by Synergetic controller as it is shown in attached zoom of Figure 11(b). In steady state and by using SMC, sizeable oscillations were appeared around the MPP to give a power with an average value equal to 90.75 W, in the first step change, which provides a static error equal to 0.75 W. A power with an average value equal to 75.78 W is obtained in the second step change which provides a static error equal to 0.92 W. On the other hand, the use of the proposed MPPT controller based on synergetic approach makes the extraction of the maximum power possible and with highly reduced oscillations, which achieves almost neglected static error, where the average power value equals 91.5 W in the first step change and 76.7 W in the second step change.

Thus, all the obtained simulation results have confirmed the strong robustness, in transient and steady state conditions, of the proposed synergetic MPPT controller against the SMC technique. The synergetic control ensures the convergence to the MPP quickly under different tests and towards the environment changes without affecting inversely at the output power.

5.2 | Experimental results

An experimental test bench, Figure 12, has been developed in LIAS-ENSIP-laboratory, France, to confirm the validity of the proposed synergetic-based MPPT controller. It consists of the following equipment’s: a programmable DC power supply with
solar array simulation: 62020H-150S manufactured by the company Chroma to simulate two Kyocera KC85T panels (whose specifications are illustrated in Table 1) connected in series to generate 177W at PV peak power, a DC–DC boost converter with a switching frequency of 10 kHz (whose specifications are illustrated in Table 2) and a linear resistive load. The synergetic-based MPPT algorithm is digitally implemented on a dSPACE RTI 1104 system real-time platform through a Matlab/Simulink environment.

The experimental results under standard test conditions (Irradiance = 1000 W/m² and Temperature = 298 K) are presented in Figure 13(b). The proposed synergetic MPPT controller is able to maintain the output power $P_{pv}$, current $I_{pv}$, voltage $V_{pv}$ and the output voltage $V_{out}$ constant. Figures 13(c) and (d) show the experimental results of the duty cycle and the macro-variable respectively.
In order to examine the performance of the proposed MPPT controller, the dynamic behaviour under a step change of irradiance and temperature, in the experimental test, is presented in Figures 14 and 15 respectively.

In Figure 14, the irradiance is increased from 200 to 500 W/m² at 3.5 s and increased from 500 to 1000 W/m² at 7 s. After a very short transient, the output power $P_{pv}$, current $I_{pv}$, voltage $V_{pv}$ and the output voltage $V_{out}$ are maintained constant with good stability.

Figure 15 shows experimental results under a step change of temperature using the proposed synergetic MPPT controller. In this experimental test, the temperature is increased from 298 to 313 K and decreased from 313 to 283 K at constant irradiance of 1000 W/m². From this figure, it can be observed that the stability of the system is successfully achieved by maintaining the output power $P_{pv}$, current $I_{pv}$, voltage $V_{pv}$ and the output voltage $V_{out}$ constant after a very short transient.

All experimental results are in concordance and very close to the previous simulation results. Thus, confirm the validity and the feasibility of the proposed synergetic-based MPPT controller. This approach provides high efficiency 99.97% at standard test conditions, as shown in Figure 13(a), with correct and fast tracking as shown in Figure 13(b). Oscillations around the MPP are approximately eliminated and the variable is maintained very close to zero (see Figure 13(d)). At the same time, the duty cycle converges to the optimal value to reach the MPP as shown in Figure 13(c). Moreover, the experimental results show the effectiveness and the good robustness of the PV system with the proposed MPPT against the variation of external conditions, irradiance (Figure 14) and temperature (Figure 15).

5.3 The EN 50530 MPPT efficiency test

To further evaluate the developed strategy, the EN 50530 standard test of dynamic MPPT efficiency is used [38]. It is implemented by providing triangular irradiance waveforms sequentially but with different ramp gradients values from 0.5 W/m²/s to 100 W/m²/s, so thus covered a comprehensive set of irradiance changes from the slow to the very fast.
In this work, we use the EN50530 standard test with two different irradiance levels from 300 to 1000 W/m² (medium to high irradiance), but without repeating the same triangular waveforms as mentioned in the original document [38], because MPPT techniques as agreed keep the same responds during the same ramp (up and down). We applied three sequences with different ramp gradients: 10, 35 and 70 W/m²/s (slow, fast, and very fast) respectively, the irradiation remains constant for a certain period of time at the high level as well as the low as shown in Figure 16. The power tracking result of the proposed strategy and the sliding mode controller is presented in Figure 17, certain parts are zoomed in to be clearer.

During a slow solar irradiance change (10 W/m²/s); the tracking power obtained by the proposed strategy is almost perfect and the ability to extract the maximum power is very high compared to sliding mode controller as shown in Zoom 1. The SMC also provides a good performance when the irradiance changes slowly as shown in zoom 2, it is true that the tracking power deviate from the right direction compared to synergetic controller but after each relatively large period which makes the disturbances along the tracking smaller. In the second sequence, the solar irradiance changes faster: 35
FIGURE 16  Triangular irradiance waveforms for the EN 50530 standard test of dynamic MPPT efficiency

FIGURE 17  Power tracking result of the synergetic controller and the sliding mode controller
The MPPT efficiency is measured using the following formula \[ \eta_{\text{MPPT}} = \frac{P_{\text{out}}(t)}{P_{\text{max}}(t)} \] (28)

So the average efficiency is calculated according to equation (29):

\[ \eta_{\text{MPPT,avg}} = \frac{\int P_{\text{out}}(t) \, dt}{\int P_{\text{max}}(t) \, dt} \] (29)

where \( P_{\text{out}} \) is the output power extracted from the PV array and \( P_{\text{max}} \) is the theoretical maximum power. Although the efficiency is volatile in certain parts of the approved profile in the EN 50530 standard test especially in low irradiance and fast changes, the proposed strategy achieves an average tracking efficiency of 99.93 % under all stages of changing weather whereas the SMC achieves 99.12 % as shown in Figure 18.

6 Conclusion

This paper presents a new nonlinear MPPT controller based on the synergetic control theory applied to a stand-alone PV system. A DC–DC boost converter is used as an interface between the PV array and the load. The proposed controller was tested both in simulation and experimentally. The EN 50530 standard test was used with different gradients values to calculate the MPPT efficiency under irradiance changes.

The simulation results, obtained using Matlab/Simulink tools, prove the good performance in transient and steady state of the proposed synergetic-based MPPT controller, under different temperature and solar irradiance. Moreover, it is much better than sliding mode-based MPPT controller. The synergetic MPPT controller overcomes the problems that exist in the conventional and intelligent algorithms, not only regarding to the fast and accurate tracking but also regarding to the oscillations around the MPP. These features are confirmed by experimental results obtained using dSPACE RTI 1104 real-time platform. In fact, various atmospheric conditions are tested to prove the high efficiency of the proposed synergetic MPPT controller.

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