Enhancing Grid Integration of Solar Energy: A Novel Approach Employing Sliding Mode Control (SMC) and Direct Power Control (DPC) Strategies

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***Abstract* -** Injecting solar energy from solar power generators into the electric grid is a key strategy to promote clean energy integration. This process is based on innovative control methodologies, primarily the sliding mode control and the direct power control unit. The sliding mode control ensures smooth adjustment in tracking the maximum power point of solar energy flow to match network requirements, ensuring grid stability and reliable power supply. In parallel, the direct power control optimizes the conversion of solar energy, which reduces energy loss and increases efficiency during injection into the network. Collectively, these control technologies facilitate the smooth and efficient integration of solar energy, contributing to sustainable energy practices and reducing reliance on traditional energy sources. The results obtained confirmed that the robustness and effectiveness of the proposed method

***Keywords* –** DPC , Electrical grid, MPPT, PV, SMC.

I. INTRODUCTION

The integration of solar power into the electrical grid is a crucial and transformative step in the global transition toward cleaner and more sustainable energy sources [1]. Solar energy, harnessed from the sun's abundant and renewable resources, has emerged as a leading contender in the effort to reduce greenhouse gas emissions and combat climate change [2]. By connecting solar power systems to the electrical grid, we are unlocking the potential to generate clean electricity on a massive scale, making it accessible to communities, businesses, and industries worldwide [3].

This integration represents a pivotal shift in our energy landscape, as it offers numerous benefits beyond environmental sustainability [4]. Solar power reduces our dependence on fossil fuels, enhances energy security, and creates economic opportunities by fostering innovation and job growth in the renewable energy sector. Moreover, it allows for greater energy independence and resilience in the face of power outages or disruptions [5].

Connecting renewable energy generators to the electrical grid represents a significant exploration due to its profoundly positive impact on the environment [1-6]. However, it involves several complexities and challenges in harnessing these sources efficiently and dynamically, from electricity generation to consumer distribution [7]. Among the challenges faced is the inherent variability of renewable energy sources compared to the electrical grid, resulting in an imbalance in the overall system. This has led researchers to explore effective methods and technologies for injecting, managing, and optimizing energy resources [4, 7-8]. These systems are often referred to as "smart grids.

In this research paper, we proposed an integrated method to improve the performance of solar energy production and its injection into the electrical network. The sliding mode controller SMC worked to track the maximum power point MPP of energy with high efficiency, no matter how the climatic conditions changed. On the other hand, the produced energy is injected into the electrical network through the direct power control DPC unit that is connected to the three-level inverter.

The SMC is a very effective control strategy, widely used in dynamic control systems, including applications in solar energy systems. Its main function is to adjust the system so that it precisely follows a specified reference value. In the context of solar energy, tracking the system's maximum power point is crucial, and the sliding mode controller is key to achieving this.

This controller technology improves the efficiency of solar energy use by optimizing the performance of the solar panels. It does this by regulating the electrical current generated by the solar cells to match the desired target value. The precise energy control facilitated by the sliding mode controller is essential to ensure that the solar energy system operates at its maximum power point, where energy production is most efficient. This level of control is essential to harness the full potential of solar energy and maximize the overall efficiency and performance of solar energy systems.

Direct Power Control (DPC) is a crucial control strategy in power electronics, particularly in the field of renewable energy systems. Its importance lies in its ability to efficiently convert power, providing fast and accurate regulation of active and reactive power in the transfer between the source (such as a renewable energy system) and the load. DPC plays a key role in integrating intermittent energy sources such as solar and wind power into the grid, ensuring optimal energy utilization. Thanks to its fast and dynamic response, DPC is well suited to applications requiring rapid adjustments to maintain system stability. It also minimizes harmonic distortion in the output waveform, contributing to cleaner power transmission. DPC's simplified control structure allows for easier implementation and reduced hardware complexity, potentially reducing costs. It improves network performance by regulating the power factor and ensuring stability under various conditions, thereby supporting the reliability of the power distribution system. In addition, the adaptability of the DPC to different loads makes it versatile and applicable in a variety of contexts, from industrial processes to residential power systems.

Through the results obtained and after analyzing them, we confirmed the effectiveness of the method in improving the system's performance starting from production all the way to injecting the produced energy into the network without any major energy losses.

II. DESIGN OF INEGRATING SOLAR ENERGY INTO THE GRID VIA SMCAND DPC CONTROL METHODS

Figure 1 illustrates the design of the proposed system in the research paper and the two methods employed to enhance the system's performance. This system consists of a solar power generator connected to a DC bus through a DC-DC boost converter, which is later linked to the electrical network via a three-level inverter. Filters are used to reduce harmonics when transferring energy and improve its quality when injected into the grid.

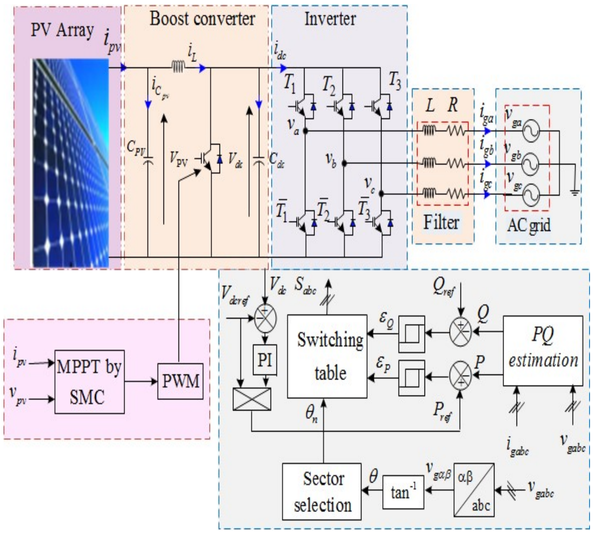


Fig. 1. Scheme of the proposed system

A sliding mode control SMC [9] is adopted to track the maximum power point MPP produced, despite changing weather conditions. The figure shows that the proposed control unit relies on the reference voltage value, which is estimated using an perturb and observe P&O [10] algorithm, then SMC directly influences the switch of the converter, thus affecting its dynamic behavior. After improving the generated power, it is injected into the electrical network with minimal power losses by utilizing a direct power control unit DPC. This unit estimates the active and reactive power values of the grid and compares them with the reference power values for both types. The method will be detailed further in the research paper.

Table 1. PV System Parameters

G(w/m^2)	1000
T(°C)	25
Oen circuit voltage Voc(V)	43.5
Short-circuit current I_{sc}(A)	4.75
Voltage at maximum power point V_{mp}(V)	34.5
Current at maximum power point I_{mp}(A)	4.35
P(w)	150
Ns	16
Np	10
DC-DC Converter	
C_{pv} (F)	200×10-6
L(mH)	10
f(kHz)	20

Table 2. Grid power parameters.

Grid, Filter, Inverter	
eg (V)	220
f(Hz)	50
R_g((Ω)	0.34
L_g(mH)	0.15
C_{dc}(F)	2000×10-6
V_{dc}(V)	800

A) Principal of Sliding Mode Control (SMC)

The sliding mode control method represents a nonlinear controller, which is classified as one of the dynamic control approaches used to develop robust controllers for intricate high-order nonlinear dynamic systems operating in uncertain conditions [9],[12].

Figure 2 illustrates how to use the SMC to track the maximum power point MPP of the photovoltaic system so that the SMC directly affects the dynamic behavior of the DC/DC boost converter, which has been implemented as follows in Fig. 2.

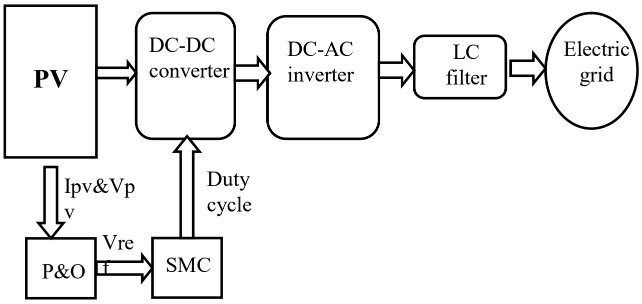


Fig. 2. Block diagram of PV using SMC.

PV system

Figure 3 represents the circuit equivalent of PV generator:

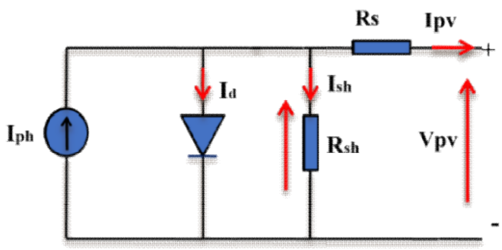


Fig. 3. Circuit of PV generator.

The characteristic of PV cell (the current-voltage I-V) as given in [13] :

$$I_{PV} = N_p I_{ph} - N_p I_o \left[exp\left(\frac{q(V_{pv} + \left(\frac{N_S}{N_p}\right) R_S I_{pv}}{N_S AKT} \right) - 1 \right] - \frac{V_{pv} + \left(\frac{N_S}{N_p}\right) R_S I_{pv}}{\left(\frac{N_S}{N_p}\right) R_{sh}} \quad (1)$$

Where: I_{pv}, $V_{pv:}$ PV generator current and voltage respectively

I_{ph}, I_o: are the photo current and reverse saturation current

N_p, N_s: number of parallel modules and series cell

R_s, R_{sh}: the series and the shunt resistance

q: the electron charge (1,602×10^{-19}C)

K: Boltzmann constant (1,380649×10^{-23}J.K^{-1})

A: the diode ideality factor

T: the junction temperature in Kelvin (K)

The photo current and reverse saturation current can be expressed by the following equations:

$$I_{ph} = \left[I_{sc} + K_i (T - T_{ref}) \right] \frac{G}{G_{ref}} \quad (2)$$

$$I_o = I_{res}\left(\frac{T}{T_{ref}}\right)^3 \exp\left[\frac{qE_g}{AK}\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)\right] \quad (3)$$

I_{sc}: *Short*-circuit current at reference conditions
K_i : Short circuit current temperature coefficient
E_g: Band-gap energy of the PV cell semiconductor
I_{res}: Saturation current at the reference temperature
G_{ref}: Reference conditions (1000W.m^{-1}) and T_{ref} (25°C)

Perturb and observe algorithm P&O was illustrated in [10], So that the value of the reference voltage Vref is estimated by tracking the maximum power point to be later compared with the actual voltage of the solar power generator under varying environmental conditions. Then, use the sliding mode controller SMC to generate a signal for turning the converter on (1) or off (0).

The analysis of SMC's dynamic behavior:

The sliding surface proposed is:

$$S = \frac{dP}{dV} = \frac{P_{pv} - P_{ref}}{V_{pv} - V_{ref}} = 0 \quad (4)$$

With:

$$P_{ref} = I_{pv}.V_{ref} \quad (5)$$

This sliding surface enables us to define the duty cycle of the PV system's boost converter, as illustrate by [14]:

$$D = \begin{cases} 0 & , for \quad Deq + Dn \leq 0 \\ D_{eq} + D_n & , for \quad 0 < Deq + Dn < 1 \\ 1 & , for \quad Deq + Dn \geq 0 \end{cases} \quad (6)$$

With:

$$D_{eq} = 1 - \frac{V_{ref}}{V_{out\_pv}} \quad (7)$$

D_n represent a discrete control:

$$D_n = K.Sat(s) \quad (8)$$

While: $$Sat(s) = \begin{cases} \frac{S}{\varepsilon}, & if\,|s| < \varepsilon \\ sign(S), Otherwise \end{cases} \quad (9)$$

Where K is a positive constant and ε is the boundary layer thickness.

B) Principal of Direct Power Control (DPC)

Fig.1 allows explaining the main idea of how a direct power controller works where the instantaneous values of the active Pg and reactive power Qg of the electrical grid are measured and compared to the reference values Pg-ref and Qg-ref, Then the difference between their values are linked to the inputs of two "hysteresis" comparators. These comparators, with the assistance of a "switching table" and considering the mains voltage, determine the switching states of the switches [15-16].

To estimate the instantaneous values of active and reactive power, we resort to applying the following two equations [17]:

$$P = V_a i_a + V_b i_b + V_c i_c \quad (10)$$

$$Q = \frac{1}{\sqrt{3}}\left[(v_b - V_c)i_a + (V_c - V_a)i_b + (v_a - v_b)i_c\right] \quad (11)$$

Depending on the output data “Sp” and “Sq” of the hysteresis comparator, the selected vectors must provide the increase or decrease of the active and reaction power [18], given the switching Table 3:

Table 3. Switching for DPC.

Sp	Sq	θ1	θ2	θ3	θ4	θ5	θ6
1	0	V_5	V_6	V_1	V_2	V_3	V_4
	1	V_3	V_4	V_5	V_6	V_1	V_2
0	0	V_6	V_5	V_4	V_3	V_2	V_1
	1	V_1	V_2	V_3	V_4	V_5	V_6

III. SIMULINK RESULT

This research paper processes a method to inject a power solar into electric grid. Sliding mode control was used to improve the tracking performance of the maximum power point of the solar power generator. This was done due to its instantaneous responsiveness, despite the random nature of weather conditions. As shown in Fig.6, the accuracy of the results obtained in solar energy production was confirmed according to instantaneous changes in solar irradiance Fig.4

Figure 5 illustrates the dynamic characteristics associated with the solar power generator. We can observe that the electric current also varies according to the recorded changes in solar irradiance. However, the voltage value stabilizes at 560V.

Solar energy was injected into the electrical grid using the direct power control unit, which was connected to the inverter. The analysis of the results in Fig.7 demonstrates the effectiveness of the method by showing the alignment of the energy produced by the solar power generator with the amount of energy injected into the grid, Despite the slight loss of injected energy compared to the generated energy.

Figure 9 represents the current (Ig) and voltage (V_g), we observe that THD over all modes is maintained at less than 5%, achieving healthy operation. However, the THD value is better in the case of power injection to the grid ($G = 1000\ W/m^2$)

Figure 10 illustrates the tracking performance of the DC bus voltage. The continuous voltage remains steady throughout the simulation period at a value of 800 V, despite some minor fluctuations at moments 0.27 s, 0.5 s, and 0.78 s. This indicates the accuracy of the proposed controller and the effectiveness of the overall system.

After analyzing the obtained results, it can be said that the sliding controller played a fundamental role in tracking the maximum power point generated by the solar system, despite changing weather conditions, to be injected into the electrical grid using direct energy control technology. The integration of these two methods together significantly improved the system's performance and efficiency.

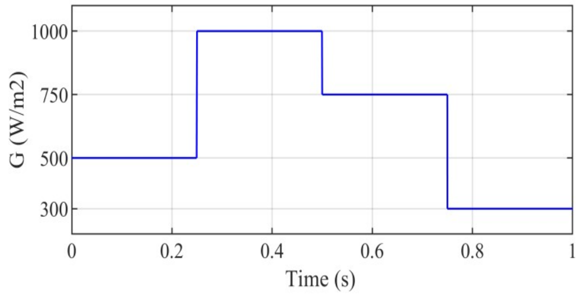
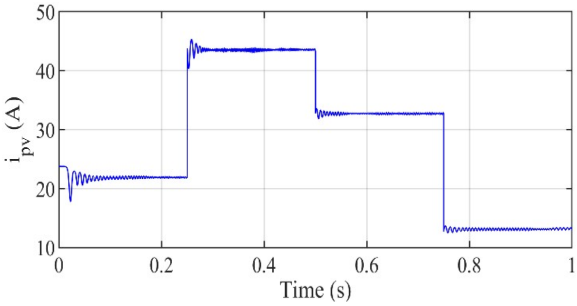
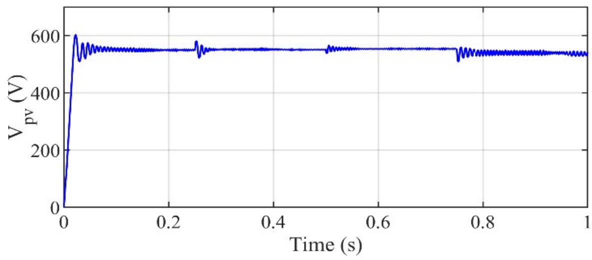


Fig. 4. Solar irradiance.



(a)



(b)

Fig. 5. (a) Current of PV generator. (b) Voltage of PV generator.

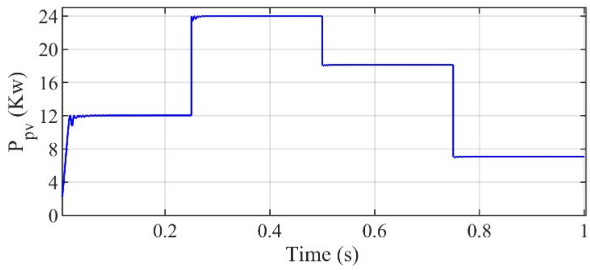


Fig. 6. Solar power.

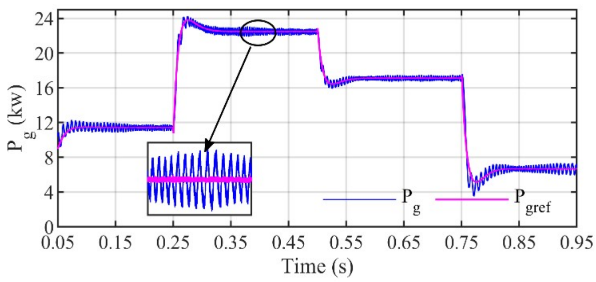


Fig. 7. Active power of grid.

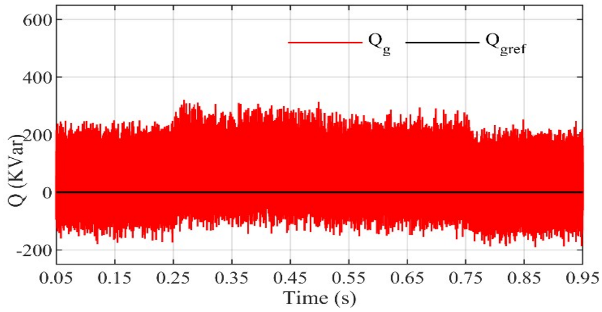


Fig. 8. Reactive of grid power.

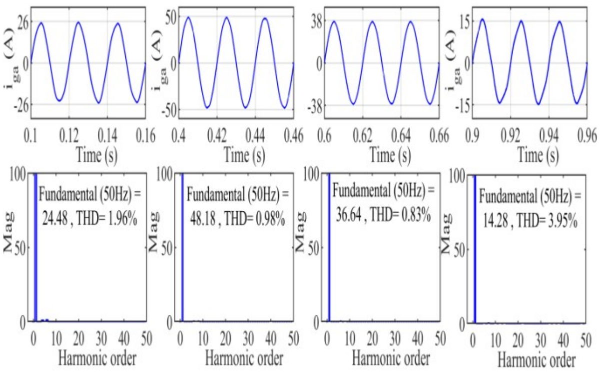


Fig. 9. THD of current grid.

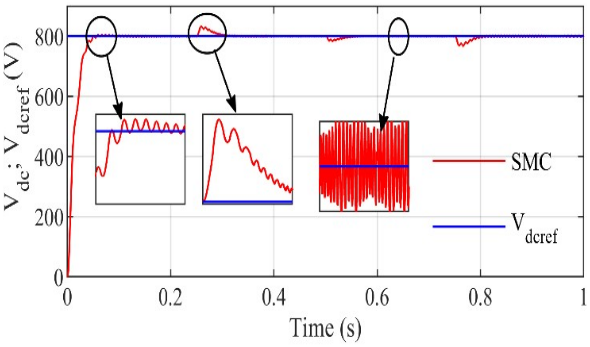


Fig. 10. DC bus voltage.

IV. CONCLUSION

In the proposed system for injecting solar energy into the electrical grid, two effective methods have been suggested for its success. The sliding control unit efficiently tracked the maximum electrical power point, regardless of changes in regulatory conditions, while the direct energy control unit estimated the value of the energy generated from the electrical grid. In turn, it provided operation commands to the transformer.

The results obtained confirmed the effectiveness and accuracy of both techniques, as well as their rapid response.

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