

Sliding Mode Control-Based MPPT for Grid-Connected PV Systems with Shunt Active Power Filter

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Abstract - To maximize the energy output of photovoltaic systems it is crucial to implement maximum power point tracking (MPPT). One effective control technique, for MPPT in PV systems in changing operating conditions is sliding mode control (SMC). This research paper introduces an MPPT algorithm based on sliding mode control for grid connected PV (GCPV) systems, where a shunt active power filter is controlled using direct power control theory. By applying the SMC based MPPT algorithm the shunt active power filter can inject power into the grid at the maximum power point (MPP) of the PV system. This helps enhance both efficiency and power quality in GCPV systems. Furthermore, this paper explores comparing scenarios by varying the amount of power injected into the grid. This analysis involves simulating the system under requirements for grid power injection. The results obtained from these simulations shed light on the significance of utilizing sliding mode control to achieve MPPT in operating conditions. The simulation results clearly demonstrate that the SMC based MPPT algorithm exhibits tracking performance and resilience, against parameter changes and disturbances.

Keywords - Maximum power point tracking, photovoltaic system, predictive direct power control, Sliding mode control.

I. INTRODUCTION

Photovoltaic systems as a form of energy technology hold the potential to reduce greenhouse gas emissions and meet the increasing demand, for electricity [1]. However, these systems face variability due, to the nature of solar irradiance and temperature. This variability can lead to decreased energy output if the system fails to track the maximum power point (MPP). To address this challenge maximum power point tracking (MPPT) techniques are employed to ensure that PV systems operate at their MPPs maximizing power generation. Implementing MPPT can enhance both efficiency and power quality in grid connected PV systems [2].

There are MPPT algorithms with popular options including perturb and observe (P&O) incremental conductance (IC) and sliding mode control (SMC).

Photovoltaic (PV) systems have the capability to integrate with the grid enabling them to inject surplus power into the grid for consumers. This integration helps decrease reliance, on fuels and enhances the efficiency of the power system. Fossil fuel power plants are known to emit greenhouse gases like carbon dioxide, which contribute to climate change [3].

By reducing the need for electricity generation from these fossil fuel plants, GCPV systems can play a role in reducing greenhouse gas emissions and mitigating climate change. Moreover, the cost of generating electricity from PV systems has significantly declined in years making them a competitive option for electricity production in parts of the world [4]. Through injecting power into the GCPV systems can contribute to lowering electricity costs, for all consumers. To improve the power quality of systems a shunt active power filter (SAPF) is utilized as a device that uses power electronics technology. SAPFs

are capable of compensating for harmonics, reactive power and voltage imbalances. This compensation aids in enhancing the grids voltage profile and minimizing risks of power outages [5]. The control techniques employed for SAPFs include PQ control [6], DQ control [7], Direct Power Control (DPC) [8]. Control theory has seen advancements with techniques, like Predictive Direct Power Control (PDPC) [9]. PDPC most recent control theory, it is a robust control technique that can be used to control the SAPF in real time to achieve the desired performance objectives.

In times there has been a growing interest, in utilizing SMC for MPPT in grid connected Photovoltaic (PV) systems. The reason behind this is that SMC offers the ability to regulate the PV system and inject power into the grid at its MPP when facing rapidly changing operating conditions. Additionally, SMC is known for its fast tracking capabilities and ease of implementation compared to other techniques [10]. The basic principle behind SMC involves driving the system state onto a predefined sliding surface. Once the system reaches this surface it will remain there regardless of any disturbances or changes in parameters [11].

In a study presented in [12] researchers proposed an SMC based MPPT approach that specifically focused on Incremental Conductance (IC). This controller demonstrated rapid tracking of the MPP under dynamic operating conditions. Another approach, as outlined in [13] involves combining SMC with Artificial Neural Networks (ANN) to create a MPPT solution. The research successfully controlled the state model of a PV system using this method achieving results in terms of MPP tracking while also adhering to IEEE's harmonic limits. Furthermore, an Integral Sliding Mode Control (ISMC) based MPPT method was analyzed in [14]. The study emphasized that selecting a sliding surface greatly influences the performance of ISMC.

Comparative analysis with Proportional Integral (PI) controllers indicated performance, in terms of tracking accuracy and MPP identification. A modified version of the Finite Time SMC based MPPT was also suggested in

reference [15]. An PSO optimization technique was used to define the surface parameters of the SMC, the proposed method implemented in two modes: offline mode to define the gains and online mode to driving the variable step of P&O. the proposed method performed better in all aspects with low oscillation, low ripple, low overshoot and low convergence time.

This paper presents a SMC-based MPPT algorithm for GCPV systems with shunt active power filter (SAPF) controlled by predictive direct power control (PDPC) theory. MATLAB\SIMULINK results demonstrate that SMC-based MPPT algorithm has excellent tracking performance and is more robust to parameter changes and disturbances. In addition to the above, the paper also compared the case of changing the amount of power that will be injected to the grid. This can be done by simulating the system under different grid power injection requirements.

The paper is divided into four sections; Section II focuses on Systems Modeling Section III presents the simulation results and subsequent discussion and Section IV provides a summary of the research conclusions.

II. SYSTEMS MODELING

A) PV system model

A PV model refers to a depiction of the properties of a photovoltaic (PV) device or system. his paper uses the single diode model as depicted in Fig. 1 [16].

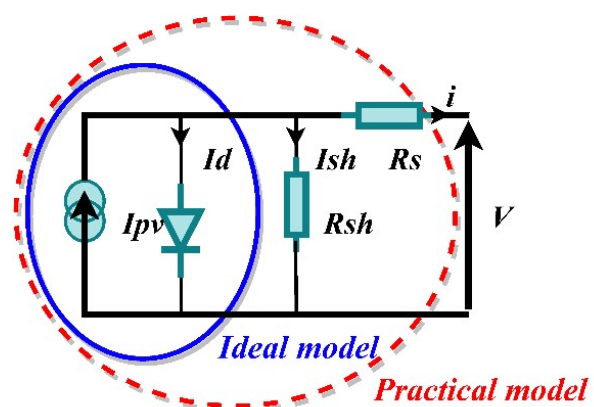


Fig. 1. Single diode PV model.

The general equation of the PV array is presented as follows :

$$I = I_{pv}N_p - N_p I_o \left[e^{\frac{V+IR_{s.eq}}{N_s \alpha V_T}} - 1 \right] - \frac{V + IR_{s.eq}}{R_{sh.eq}} \quad (1)$$

Where :

I_{pv} : is the photocurrent generated by the PV array

I_o : is the reverse saturation current of the diode

V_T : is the voltage across the diode

$R_{s.eq}$: is the series resistance of the PV array

$R_{sh.eq}$: is the shunt resistance of the PV array

α : is the ideality factor of the diode

N_s : is the number of series module

N_p : is the number of shunt module

B) Maximum Power Point Tracking

MPPT is a method employed to ensure that a photovoltaic (PV) system operates at its power point (MPP) where it generates the amount of power. The MPP refers to the point, on the PV curve where the multiplication of voltage and currents at its peak. Fig. 2 shows the PV curve and the MPPT of PV array. MPPT holds significance for PV systems as it can significantly enhance their power output. According to research conducted by the National Renewable Energy Laboratory (NREL) employing MPPT can boost a PV systems power output by, up to 30% [17].

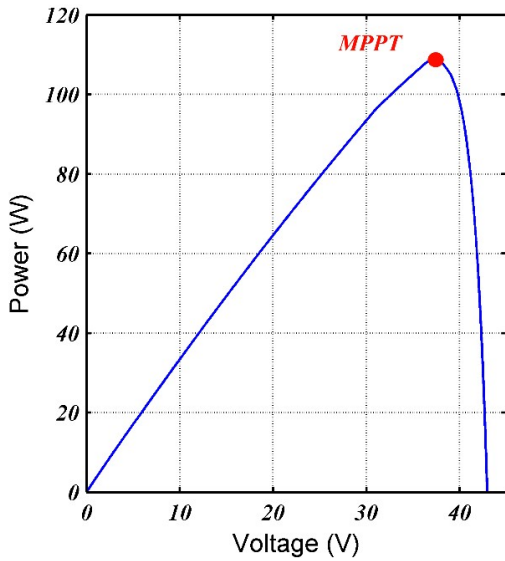


Fig. 2. PV curve and the MPPT of PV array

C) SMC-based MPPT

One robust control technique called SMC can effectively implement MPPT in PV systems when facing changing operating conditions. The SMC based MPPT algorithm aims to guide the system state towards a predefined sliding surface. On this surface regardless of disturbances or parameter changes the system will remain there. The mathematical representation of this SMC based MPPT algorithm is as follows:

$$\sigma = \frac{\Delta I_{pv}}{\Delta V_{pv}} V_{pv} + I_{pv} \quad (2)$$

σ represents the sliding surface that acts as a conductance condition.

The control signal used in the SMC based MPPT algorithm is determined by:

$$d = \begin{cases} d + \Delta d & \text{for } \sigma > 0 \\ d - \Delta d & \text{for } \sigma < 0 \end{cases} \quad (3)$$

The equivalent control signal's derived based on the condition ($\dot{\sigma}=0$):

$$d_{eq} = 1 - \frac{V_{pv}}{V_{dc}} \quad (4)$$

The control signal provided as discontinuous:

$$d_{dis} = -K \cdot \sigma \quad (5)$$

The equation that governs the duty cycle of the Step-up converter can be expressed as follows:

$$d = \begin{cases} 1 & \text{for } d_{eq} + d_{dis} \geq 1 \\ d_{eq} & \text{for } 0 < d_{eq} + d_{dis} < 1 \\ 0 & \text{for } d_{eq} + d_{dis} \leq 0 \end{cases} \quad (6)$$

The Lyapunov stability criterion is used to prove the stability of the SMC-based MPPT algorithm. The Lyapunov function is defined as follows:

$$V = \frac{1}{2} \sigma^2 \quad (7)$$

System stability is affirmed when the derivative of the Lyapunov function remains consistently negative, indicating diminishing deviations from equilibrium over time:

$$\dot{V} = \dot{\sigma} \leq 0 \quad (8)$$

III. SIMULATION RESULTS AND DISCUSSION

Matlab/Simulink was used to simulate a low-voltage grid-connected SAPF with PV system, and the effectiveness of the PDPC control method in raising the power factor and reducing harmonic currents in the grid was verified. Three cases of the amount of power injection generated by the PV were investigated, corresponding to three P-V curves exposed to three levels of light irradiation at 200, 700, and 1000 W/m². The amount of injection and its effect on the electrical current and the amount of active power consumed from the grid were compared.

Fig. 3 shows the current and source voltage waveforms before and after turning on the SAPF. It can be observed that the current waveform is transformed into a sinusoidal waveform with a low THD value of 1%. Fig. 4 shows the accurate tracking of the DC-side voltage to the reference value of 80 V, as well as the stability of the active power at 100 W. These results confirm the effectiveness of the PDPC method in achieving effective monitoring and improving the power quality of the system.

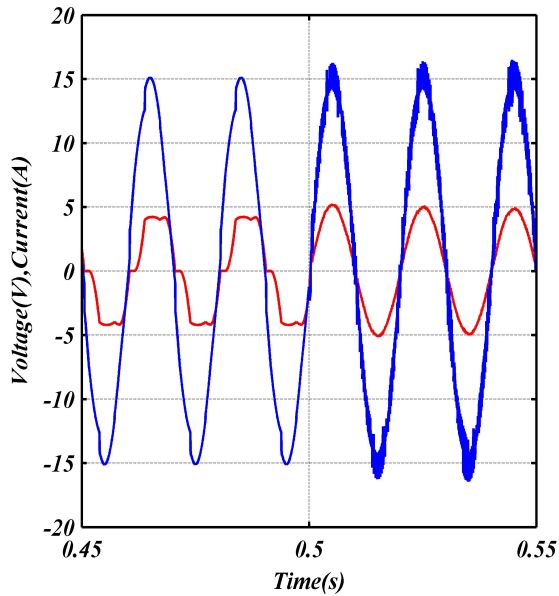


Fig. 4. Source current and voltage waveforms before and after turning on the SAPF.

Fig. 5 shows the three P-V curves used for injection into the grid, and Table 1 shows the characteristics of these P-V curves.

In Case 1, Fig. 6 shows the excellent tracking of the SMC method resulted in a higher MPP (MPP1=61W) for injecting active power into the

grid, which led to a decrease in the grid current consumption and active power. This is because the SAPF was able to compensate for the reactive power and harmonic currents generated by the load, which improved the power factor and reduced the overall load on the grid.

In Case 2, Fig. 7 shows the identifying of highest power value corresponding to the light radiation of 700 W/m², which is 112 W, resulted in a decrease in the grid current consumption to almost zero ampere, meaning that the load consumed almost all of its power from the PV. This is because the SAPF was able to inject the maximum amount of power from the PV into the grid, which reduced the need for power from the grid.

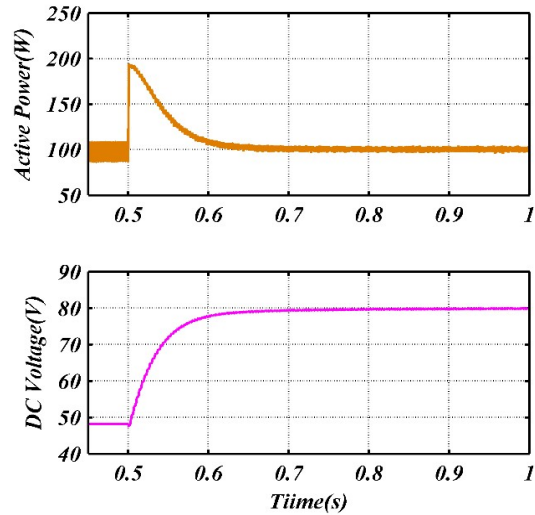


Fig. 5. Active power and DC-side voltage

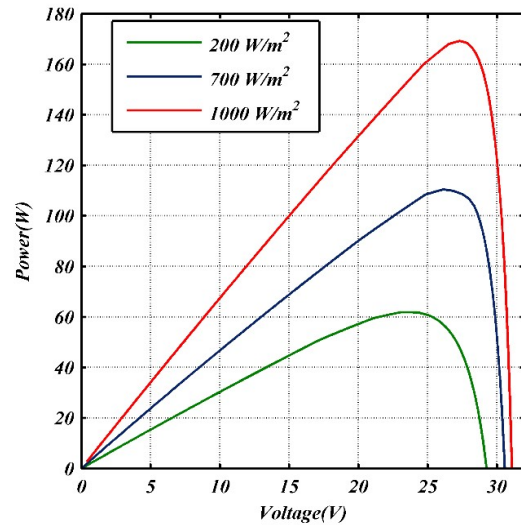


Fig. 6. P-V curves for injection into the grid.

In Case 3, Fig. 8 shows the injection of a higher power value of 170W from the PV resulted in the reverse injection of current from the PV to the grid. This is because the SAPF was able to inject more power into the grid than the load consumed. This can be useful for applications where the PV generates more power than the load consumes, such as in net-zero energy buildings.

The excellent MPP tracking of the SMC method helps to achieve high efficiency of the overall system, which leads to a significant reduction in grid current consumption and, consequently, financial costs for the consumer.

Table 1. Characteristics of these P-V curves

Curve	V _{mpp}	I _{mpp}	P _{mpp}
MPP1 200 W/m ²	23V	2.65A	61W
MPP2 700 W/m ²	26V	4.22A	112W
MPP3 1000 W/m ²	27V	6.2A	170W

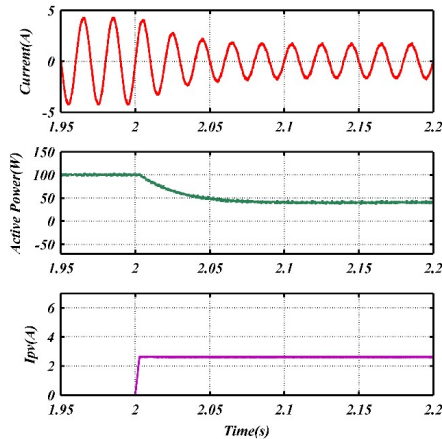


Fig. 7. Source current, active power and I_{pv} for case 1 (200W/m²)

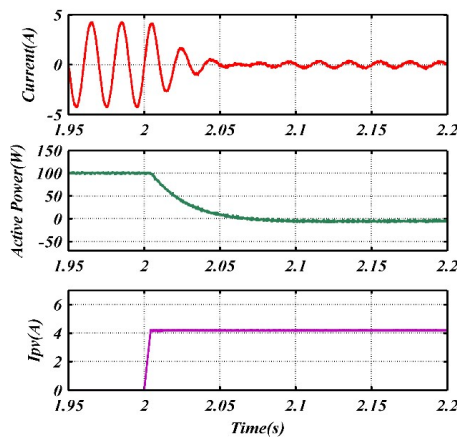


Fig. 8. Source current, active power and I_{pv} for case 2 (700W/m²)

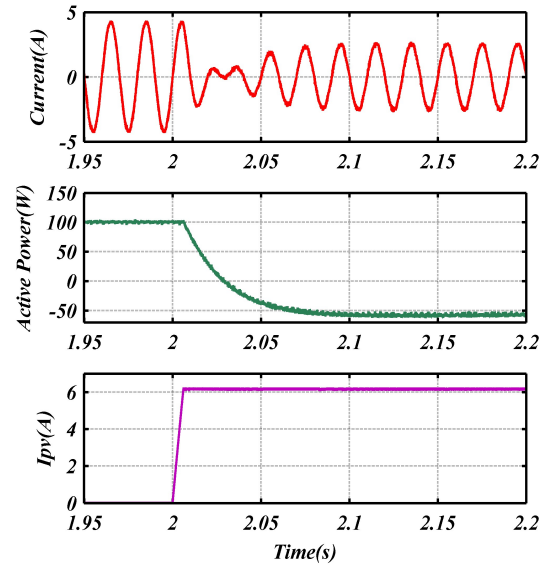


Fig. 9. Source current, active power and I_{pv} for case 3 (1000W/m²)

IV. CONCLUSION

The SMC technique proves to be highly effective, in tracking the MPPT and injecting power into the grid. This study showcases its capabilities by injecting power outputs of 61, 112 and 170 W into the grid for Cases 1 2 and 3 respectively. Consequently, this reduces the need for power from the grid (Case 2). Can also inject reverse current into the grid (Case 3) resulting in cost savings for consumers.

Further advancements can be made to enhance MPP tracking efficiency and power injection efficiency of the SMC method. Additionally, conducting tests under real-world conditions in GCPV systems can provide insights. It would also be valuable to explore the benefits associated with implementing the SMC method in systems.

Overall this technology holds promise in enhancing the efficiency of GCPV systems while lowering electricity costs, for consumers.

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