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Particle Swarm Optimization Based Super Twisting Sliding Mode Controller MPPT Algorithm Design for Solar PV System

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Abstract: To maximise energy harvest while keeping the solar photovoltaic (PV) system stable, proper regulation is essential. In this study, we explore the state-of-the-art in solar PV system management and offer a fresh method: Super Twisting Sliding Mode Controller (STSMC) using Particle Swarm Optimisation (PSO). The suggested method enhances control performance by combining the stability of Sliding Mode Control (SMC) with the optimisation skills of PSO. The goal is to improve solar PV systems' fault tolerance, resilience against uncertainties and disturbances, and Maximum Power Point Tracking (MPPT) accuracy. Results show that the suggested PSO-based STSMC is superior to traditional methods of control. Effective maximum power point tracking (MPPT) is made possible by combining PSO optimisation with the SMC structure. This allows for precise MPPT tracking regardless of the sun irradiation or ambient temperature. The technique also improves the system's fault tolerance and robustness by dealing with uncertainty and disturbances efficiently in real time. The study highlights limitations, such as the use of idealised settings, and provides recommendations for further research to enhance the suggested method. The MATLAB/Simulink Simulation Tool is used for the research.

Keywords: Solar PV System, Control Technique, Particle Swarm Optimization, Maximum Power Point Tracking, Sliding Mode Controller.

1. Introduction

The many benefits of PV systems have led to their increased popularity as a renewable energy option. Semiconductor materials, most commonly silicon-based solar cells, are used to directly convert sunlight into energy in this process. One viable alternative to conventional power generation is the use of renewable energy sources [1]. Increased awareness of the need of protecting the environment has contributed to a dramatic increase in the use of solar photovoltaic systems in recent years. Solar power is free, accessible, and sustainable indefinitely. It produces no greenhouse gases or air pollutants during operation, making it a clean and sustainable power generator. With solar PV systems, electricity may be generated close to where it is needed, cutting down on transmission losses and the need for expansive central power plants. Furthermore, solar PV systems are very dependable and cost-effective over time due to their extended operating lifespan and low maintenance requirements. A solar PV system works by turning solar energy into usable power. An electric current is generated when photons from sunshine impact the surface of a solar cell and transmit their energy to electrons in the semiconductor material. To conform to grid or load specifications, this DC is inverted to AC via an inverter [2]. Figure 1 depicts the basic layout of a PV system.

There are essentially two distinct kinds of solar PV systems: grid-connected and off-grid. Most households use grid-connected systems, which allow electricity to be generated and then fed into the utility grid, with the homeowner receiving credits or payments in exchange for the power created [3]. In regions far from the grid's reach, people often turn to off-grid, or standalone, or independent, systems. To keep functioning during times of low solar irradiance, these devices store energy in batteries. Solar irradiance, temperature, shading, direction, and system efficiency all have a role in how well a solar PV system operates. The amount of sunshine that reaches the solar panels is mostly dependent on a factor called solar irradiation. It changes with factors including latitude, altitude, time of day, season, and climate. Solar cell performance is negatively impacted by increasing temperatures. The output of solar panels can be drastically reduced if neighbouring trees or buildings cast shadows on them. Panel orientation and tilt angle are only two of several installation and design considerations that may improve energy output.

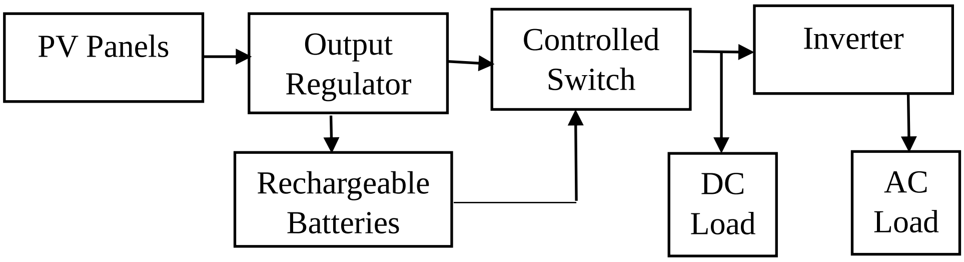

Fig 1: PV System Schematic Diagram

The performance of solar PV systems may be optimised, and they can be integrated into the electricity grid more smoothly, with proper control and administration. To track the maximum power point (MPP) and adjust the voltage and frequency of the output, several control approaches have been devised. Proportional-integral-derivative (PID) control and other conventional techniques of regulation have long been in use. However, given the nonlinear and time-varying nature of solar PV systems, these approaches may not be ideal.

Advanced control approaches for solar PV systems have been studied to solve the shortcomings of conventional methods of control. One such method that has proven effective is called STSMC. STSMC is a reliable control method that can efficiently deal with nonlinearities, disturbances, and uncertainties in the system. The chattering that can occur with conventional sliding mode controls is much minimised while response time and accuracy are improved. STSMC has found useful implementations in several different industries, such as power electronics, robotics, and renewable energy systems. However, STSMC's performance can be improved by tweaking its configuration. The collective behaviour of birds in flocks or schools of fish in groups is the inspiration for PSO, a prominent metaheuristic optimisation technique. Control systems are only one example of the many technical applications that have made use of PSO for parameter optimisation. It is feasible to increase control performance and adaptability to system fluctuations by combining PSO with STSMC.

1.1. Challenges in Solar PV System Control

There are several obstacles that must be overcome in order for solar PV system control to deliver maximum performance and seamless grid connection. Nonlinear behaviour, climatic fluctuations, and grid integration needs are just a few of the problems that come up while working with solar PV systems. Maximising energy output, enhancing system dependability, and maintaining stable operation all depend on overcoming these obstacles. Among the most difficult aspects of controlling solar PV systems are:

1. Nonlinear Behavior: Because solar cells have a nonlinear current-voltage (I-V) curve, solar PV systems are inherently nonlinear. Because of this nonlinearity, conventional linear control methods may not produce ideal results. Nonlinear dynamics and uncertainties in solar PV systems need the use of sophisticated nonlinear control solutions like SMC.
2. Maximum Power Point Tracking: A solar PV system's MPP shifts because of external factors such shifting sun irradiance and temperature. Algorithms for MPPT are used to keep the system running at its MPP constantly. To get the most out of solar PV systems, it is crucial to create accurate and efficient MPPT algorithms.
3. Shading and Partial Shading: When solar panels are shaded, either whole or partially, by things like clouds or buildings, the system's output suffers. Because of the many peaks and local MPPs created by shading, it is difficult to keep track of the global MPP. To lessen the impact of shading and partial shading, we need cutting-edge control approaches and distributed MPPT algorithms.
4. System Integration and Grid Interaction: To maintain reliable power flow and grid stability, solar PV systems that are linked to the utility grid must be synchronised with the grid. Certain criteria,

including as voltage and frequency regulation, power factor management, and grid synchronisation, are imposed on the system by grid rules and regulations. To enable smooth interaction with the grid, control techniques must handle these integration problems.

5. Fault Detection and Diagnosis: Module failures, wiring problems, and inverter malfunctions are just some of the errors that might occur in a solar photovoltaic system, therefore it's important to be able to detect and diagnose them. Maintenance and peak performance depend on prompt identification and diagnosis of these issues. Advanced signal processing and machine learning underpin fault detection methods that can help pinpoint and localise problems in real time.
6. System Efficiency and Energy Management: In order to maximise energy output and minimise losses, it is crucial to maximise system efficiency. Algorithms for managing energy are employed in hybrid solar PV systems and microgrids to strike a balance between energy production, storage, and consumption. The goal of these algorithms is efficient energy dispatch, load prioritisation, and battery management.

To overcome these obstacles and realise the full potential of solar PV systems throughout the transition to a sustainable energy future, continuous research and innovation in control techniques and system optimisation are necessary. The research presented here proposes utilising a PSO algorithm for maximum power point tracking in solar PV systems, with the goal of optimising STSMC parameters.

1.2. Need for Advanced Control Technique

To maximise energy output, enhance system efficiency, and guarantee dependable operation in the face of complex system dynamics and environmental fluctuations, sophisticated control approaches are required in solar PV systems. PID control, a common form of control, may not be enough for the unique difficulties of solar PV systems. To fulfil the needs of contemporary solar PV systems, cutting-edge control approaches provide improved performance, resilience, and flexibility.

1.3. Introduction to Super Twisting SMC

Power electronics, robotics, and renewable energy systems are just a few of the many technical domains that have found success using SMC, a strong and resilient control technology. Because of its enhanced performance and reduced chattering impact, STSMC is well suited for applications characterised by high levels of dynamicity and nonlinearity. This section presents an overview of STSMC and its key characteristics.

The chattering issue can be mitigated, and control performance boosted with STSMC, an improved type of SMC. To the standard sliding mode control rule, STSMC adds a nonlinear factor known as the super twisting term. SMCs intended robustness and quick convergence features are preserved while the control action is smoothed down near the sliding surface.

1.3.1. Features and Advantages of STSMC

STSMC is ideally suited for regulating complicated and nonlinear systems like solar PV because to its many useful features and advantages. The following are a few of STSMC's many great qualities:

- Robustness: STSMC is resistant to the effects of randomness in the parameters, noise in the environment, and mistakes in the models. It is applicable to real-world situations because it can deal with nonlinearities and uncertainties in the system without needing precise models of the system.
- Reduced Chattering Effect: The super twisting term in STSMC introduces a continuous control action close to the sliding surface, which helps to dampen chattering. This results in less high-frequency oscillation and smoother control signals, which boosts system performance and reduces wear and tear on physical components.
- Finite-Time Convergence: STSMC converges to the sliding surface in a finite amount of time, allowing for quick stabilisation of the system. This quality shines brightest in systems with high rates of change and fluctuating needs throughout time.

1.4. Motivation for Combining PSO and STSMC

By fusing their respective capabilities, PSO and STSMC are better able to address issues with control system design, optimisation, and performance. Several benefits make the combination of PSO and STSMC an appealing strategy for use in a wide range of contexts. In this part, we will discuss the most compelling reasons for merging PSO with STSMC.

- Optimization of Control Parameters: PSO and STSMC optimise control configurations for system performance. Swarm intelligence helps PSO explore solution space and identify optimal parameter values. Using swarm knowledge, it effectively finds the global optimum. Control system design using STSMC is strong, quick, and chatter-free. PSO's global search capabilities may optimise control settings with STSMC, improving performance and robustness.
- Handling Nonlinear and Time-Varying Systems: STSMC can handle system uncertainties and disturbances, making it suitable for nonlinear and time-varying systems. For best performance, sliding mode control gains must be chosen. PSO may be used with STSMC to optimise control gains and adapt the controller's settings to the system's needs. This combination optimises control gains for nonlinear and time-varying systems.
- Improved Optimization Efficiency: With PSO's capacity to search globally, control parameters may be optimised quickly and effectively. By taking the swarm's collective behaviour into account, it can search for optimal solutions more quickly and thoroughly. The computational effort needed to identify optimal values for control parameters is reduced when PSO is combined with STSMC. This increased optimisation effectiveness permits more rapid iterations of design and system rollout.
- System Performance Enhancement: PSO and STSMC work together to boost system performance. STSMC is durable, quick, and reduces chattering, while PSO optimises control configurations for best performance. Integrating the two techniques improves tracking accuracy, convergence, and disturbance rejection in the control system. System performance, stability, and reliability improve.

2. Literature Review

This research intends to improve control performance and resilience by integrating PSO and STSMC for solar PV system control and optimisation, closing the gap between theoretical advances and actual application.

Various methods of controlling the grid-connected PV system's nominal current and DC voltage have been developed in the past. Due to its simplicity, minimal iterative variables, and straightforward implementation, the PI controller has traditionally been employed for optimising electrical variables [4].There are still drawbacks to using a PI controller, however, including a lack of robustness and precision in the face of perturbations of varying degrees and abrupt failures. Nonlinear controllers like the Fuzzy Logic Controller (FLC), the Neural Network (NN), the Sliding Mode Controller (SMC), the model predictive controller (MPC), the deadbeat controller (DC), the repetitive controller (RC), the hysteresis controller (HC), the adaptive controller (ACC), the neuro-fuzzy controller (NFC), the feedback linearization technique (FLT) [5,6], etc. are being studied for their potential to solve these problems.

Most MPPT algorithms cannot be implemented without first having a system model created. Instead of using a mathematical model of a system, controllers based on FLC depend on human reasoning. Each controllable variable is evaluated with membership functions [7,8] and given a value between 0 and 1. The rules for mapping input and output values are based on if-else statements. When compared to Incremental conductance, FLC [9] performs better thanks to its resilience when appropriate system knowledge is available. One important drawback of FLC based algorithms is that precise system information is often unavailable. When it comes to adjusting the weights of the neurons, controllers based on artificial neural networks (ANNs) [10] need training data. However, their usefulness depends on how much and how well they are trained.

When it comes to the number of repetitions required to reliably monitor the MPP, the computational weight of bio-inspired algorithms can make them inefficient. Hybridising bio-inspired algorithms with other MPPT methods can circumvent this shortcoming [11].To identify global MPP, PSO is utilised first, and then the perturb and observe method (P&O) [12] is applied. The convergence here is both better and faster than with the basic P&O technique. These bio-inspired and hybridised versions fall short in many applications due to their insufficient reaction to the nonlinear dynamics of power conditioning circuitry, which sits between photovoltaic modules and the loads they supply.

In [13], a system for managing energy that makes use of predictive FLC is presented for use in both off-grid and grid-connected home microgrids. In [14], a neural network controller based on the Legendre transform is presented for use in grid-connected mode to enhance power quality. In [15], a vector controller based on an ANN is developed with the goal of connecting household solar PV systems to the public power grid. The controller lessens the amount of harmonic material, and it increases adaptability in unknown situations. In [16], a Lyapunov-based fast terminal SMC for a grid-connected PV and wind hybrid system is proposed. The converter, inverter, and hybrid system's performance are enhanced in this way when faced with disruptions.

In [17], a fuzzy-SMC is provided that uses a disturbance observer, while in [18], a fuzzy-SMC is presented that uses a sliding-mode voltage observer. The design controllers are quite good at dealing with background noise and unknowns. Improved dynamic and steady-state performance for a PV system linked to the grid is the goal of the MPC controllers developed in [19,20]. In [21], an adaptive backstepping controller is developed for the DC side of a grid-connected Z-source inverter, ensuring consistent and reliable operation regardless of environmental factors like temperature and sun radiation.

Easy tuning, resilience, precision, and insensitivity to uncertainties and external disturbances are only some of the benefits of the SMC's non-linear approach [22]. The primary problems with regular (first order) SMC are chattering and the EMI noise and instability it causes. To cease the chattering, a smooth function is substituted for the sign function in first-order SMC [23], sigmoid function [24], or ideal saturation function [25]. However, their tracking performance and resilience degrade as a result. To combat this, several methods have been devised, with higher order SMC being one of them [26].The STSMC is an example of a higher-order SMC that can function adequately with only the available data [27]. The STSMC is now the gold standard for second-order SMCs because of its strong stabilisation, reduced chattering even in the presence of uncertainties, and finite-time convergence to the sliding surface [28].

After surveying existing MPPT techniques, this research aims to enhance their efficacy and robustness. To achieve this goal, we conducted an analysis of the SMC approach in the hopes of taking use of its resilience while enhancing the MPPT application's efficiency. In this research, we employ a control method that is resilient to parameter variations. First, the STSMC algorithm was developed to reduce the chattering problem, which is a drawback of conventional SMC approach. STSMC's configurations may be fine-tuned with the help of PSO.

3. Proposed Control Technique

This section describes the methodology used in our proposed system.

3.1. Modelling of PV Module

The “International Renewable Energy Agency” estimates that by 2050, renewable sources will provide around 85% of the world's energy requirements. In addition, it’s anticipated that solar energies would account for 20% of global energy production by 2050, further emphasising the significance of electricity generation from solar power. Using a PV array based on semiconductors is one way that solar energy is converted into usable electricity. The study was completed on the assumption that a model of the system already exists, hence no identification procedure was taken into account.

Figure 2 depicts the test module of proposed system, which consists of a PV array, DC-DC boost converter, and resistance load. In Eq. 1, PV is modelled without considering R_{sh} and R_s:

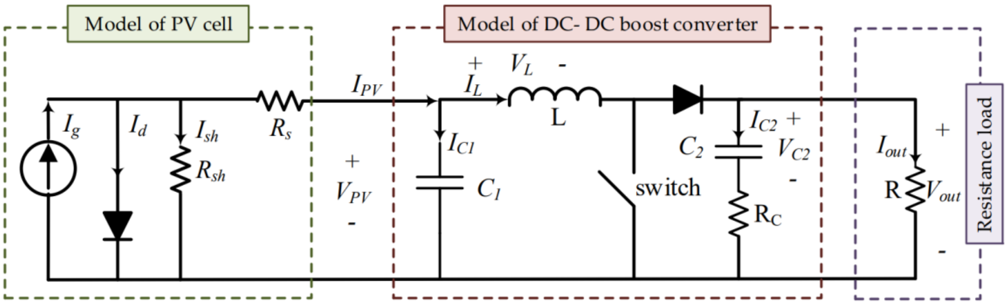

Fig 2: Test Module of proposed system

$$I_{PV} = \left(I_{gen} - I_{sat}\left(e^{\frac{V_{pV}}{N_S V_t}} - 1\right)\right) N_{p,}, \begin{cases} I_{gen} = G\left(I_{sc} + K_I(T - T_r)\right)/1000 \\ I_{\text{sat}} = I_{\text{satref}}\, T^3 T_r^{-3} e^{\left(\frac{qE_g}{AK_B}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right)} \\ I_{\text{satref}} = I_{sc}\left(e^{\frac{V_{OCG}}{N_S A K_B T}} - 1\right)^{-1} \end{cases} \tag{1}$$

where V_{PV} and I_{PV} are the PV panel's output voltage and current, respectively; The numbers Ns and Np represent the number of series and parallel cells, respectively. I_{gen} is the current created by solar radiation. I_{sat} denotes the diode's reverse saturation current. G denotes solar radiation. T is the diode junction temperature, and K_I is the short-circuit temperature coefficient. The standard temperature is T_r. I_{sc} is the short-circuit current under normal conditions; q denotes the electron charge. The photon energy constant is denoted by E_g. The open-circuit voltage is denoted by V_{OC}. I_{satref} is the reference reverse saturation current; K_B is the Boltzmann constant; and A is the pn junction coefficient.

3.2. Boost Converter

In this configuration, a wide variety of converter circuits can be employed. The popular boost dc-dc converter circuit has been favoured due to its efficiency, simplicity, and widespread application. When a dc voltage is connected to the converter's input, it boosts that voltage to a greater value. The boost dc-dc converter circuit that makes use of a C_{PV} input filter capacitor is seen in Figure 3.

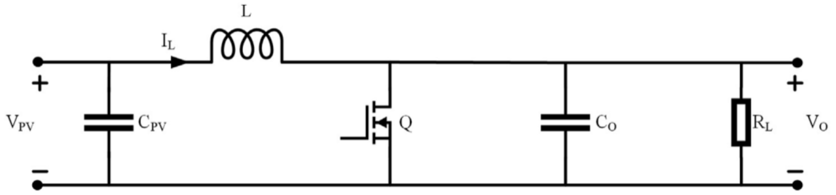

Fig 3: Boost Converter Circuit

The circuit is analysed in two different ways, one when the switch (Q) is engaged and another when it is disengaged. Thus, from Eq. 2 and 3, we derive the characteristic equations for the current through the inductor (I_L) and the voltage across the output capacitor (V_O).

$$\frac{dI_L}{dt} = \frac{V_{PV} - Vo}{L} + \frac{V_0}{L}u \tag{2}$$

$$\frac{dVo}{dt} = \left(-\frac{Vo}{RCo} + \frac{I_L}{Co}\right) - \frac{I_L}{Co}u \tag{3}$$

When these equations are combined, the state space equation of the dc-dc boost converter circuit (assuming $I_L = I_{PV}$) is derived in matrix form at Eq. 4.

$$\frac{d}{dt}\begin{bmatrix} I_{PV} \\ V_O \end{bmatrix} = \begin{bmatrix} 0 & -1/L \\ 1/C_0 & -1/RC_0 \end{bmatrix}\begin{bmatrix} I_{PV} \\ V_O \end{bmatrix} + \begin{bmatrix} V_O/L \\ -I_{PV}/C_0 \end{bmatrix} u + \begin{bmatrix} 1/L \\ 0 \end{bmatrix} V_{PV} \tag{4}$$

3.3. Maximum Power Point

In the case we're dealing with, we use the MPP PV voltage as the reference voltage, V_{ref}, and the MPP PV current, I_{ref}. The target operating voltage of the PV system must be maintained within a certain control range. In Eq. 5, the reference voltage is calculated by taking out the derivative of the PV system's power with regard to its current.

$$\left.\frac{dP_{PV}}{dI_{PV}}\right|_{MPP} = V_{PV} + I_{PV}\frac{dV_{PV}}{dI_{PV}} = 0 \tag{5}$$

Using Eq. 1 as an evaluation tool, we can derive the derivative of V_{PV} with regard to I_{PV} as:

$$\frac{dV_{PV}}{dI_{PV}} = \frac{-V_t}{I_{gen} - I_{PV} + I_{\text{sat}}}, V_t = \frac{AK_B}{q}T \tag{6}$$

By putting Eq. 6 into Eq. 5, the reference voltage at MPP is determined as follows:

$$V_{\text{ref}} = V_t \ln\left(\frac{I_{\text{gen}} - I_{\text{ref}} + I_{\text{sat}}}{I_{\text{sat}}}\right) \tag{7}$$

3.4. STSMC for MPPT

The SMC is frequently used as a robust controller in nonlinear and uncertain parameter systems. The chattering phenomenon arises in the extensively used SMC method for controlling DC-DC converters. This issue can be mitigated by employing varying frequency of switching. In general, however, scholars tend to use a specific frequency for switching in systems based on microcontrollers. Illustration of SMC in graphical form is shown in Figure 4.

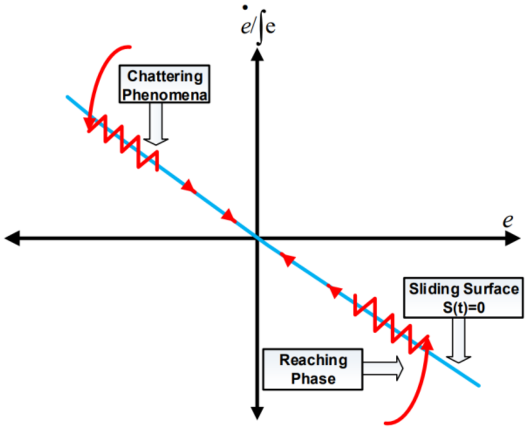

Fig 4: Graphical Representation of SMC

There are several methods available for addressing the chattering issue. In this strategy, the objective is to achieve maximal power point with minimal chattering phenomenon. In addition, the second order SMC based on the STSMC is favoured for maximising PV panel power while minimising chattering. This method eliminates the need for time-based derivations of the sliding variable and preserves the benefits of the traditional SMC. On the sliding surface, the trajectories oscillate with twisting rather than chattering.

SMC development requires a two-stage process. To get the required behaviour from the dc-dc converter, one must first construct a sliding surface for it to operate on. The next stage is to create a control law that will keep the system pushed along the sliding surface. The selected sliding surface, S(x,t), and its initial derivation must both equal zero.

$$S(x,t) = 0, \dot{S}(x,t) = 0, \qquad (8)$$

We may maximise our strength by navigating to and remaining on the sliding surface of the system trajectories. To achieve this goal, we can apply the sliding surface equation Eq. 9.

$$S(\mathrm{x},\mathrm{t}) = \frac{\partial \mathrm{P_{PV}}}{\partial \mathrm{V_{PV}}} = \mathrm{V_{PV}}\left(\frac{\partial \mathrm{I_{PV}}}{\partial \mathrm{V_{PV}}} + \frac{\mathrm{I_{PV}}}{\mathrm{V_{PV}}}\right) = 0 \qquad (9)$$

The u(t) control law used by ST-SMC is a two-term expression. The first component is defined by the discontinuous time derivative, whereas the second term is a continuous function of the accessible sliding variable that appears only during the reaching phase.

3.5. PSO based STSMC

Particle swarm optimisation (PSO) is a well-known metaheuristic optimisation method that takes its cues from the herd mentality of animals like birds and fish. In the 1990s, Eberhart and Kennedy created it, and ever since then, it's gotten a lot of interest in areas including optimisation, machine learning, and control systems. For many optimisation situations, PSO may provide near-optimal solutions quickly and with little effort on the part of the developer. By fusing their respective capabilities, PSO and STSMC are better able to address issues with control system design, optimisation, and performance. Several benefits make the combination of PSO and STSMC an appealing strategy for use in a wide range of contexts. Parameters for the STSMC's design are listed in Eq. 10.

$$X_{STSMC} = [k_1 k_2\ a\ b] \qquad (10)$$

We're on the lookout for MPP since we want to maximise our use of solar energy. We adjust our PV system such that the power deficit between PV and MPP is minimised. This signifies that the PV power level approaches the PV power level at MPP, also known as the PV maximum power level, P_{max}. Minimising the average absolute variance among the PV panel output and the maximum power is thus the goal. Eq. 11 provides a brief description of the optimisation issue.

$$\min f(x) = mean(|P_{max} - P_{PV}|) \tag{11}$$

$$Subjected\ to \begin{cases} a > 0 \\ b > 0 \\ k1 > 0 \\ h(k1 - k2) > \dfrac{1}{4} \end{cases}$$

In conclusion, PSO is used to find the best values for a few of the proposed controller's parameters, values that can be chosen arbitrarily.

4. Simulations and Results

The effectiveness of the suggested controller is tested in the MATLAB/Simulink simulation platform. Gains in a controller can be set to their ideal levels using a variety of approaches, such as those based on machine learning, artificial neural networks (ANN), optimisation techniques, etc. Gain levels for the controller were chosen to get the required response using the PSO approach in this study. Starting at 800 W/m^2, the irradiance is adjusted down to 600 W/m^2, then up to 1000 W/m^2, and finally back down to 800 W/m^2. Figure 5 depicts the planned PV array's current-voltage and power-voltage characteristics under varying irradiance.

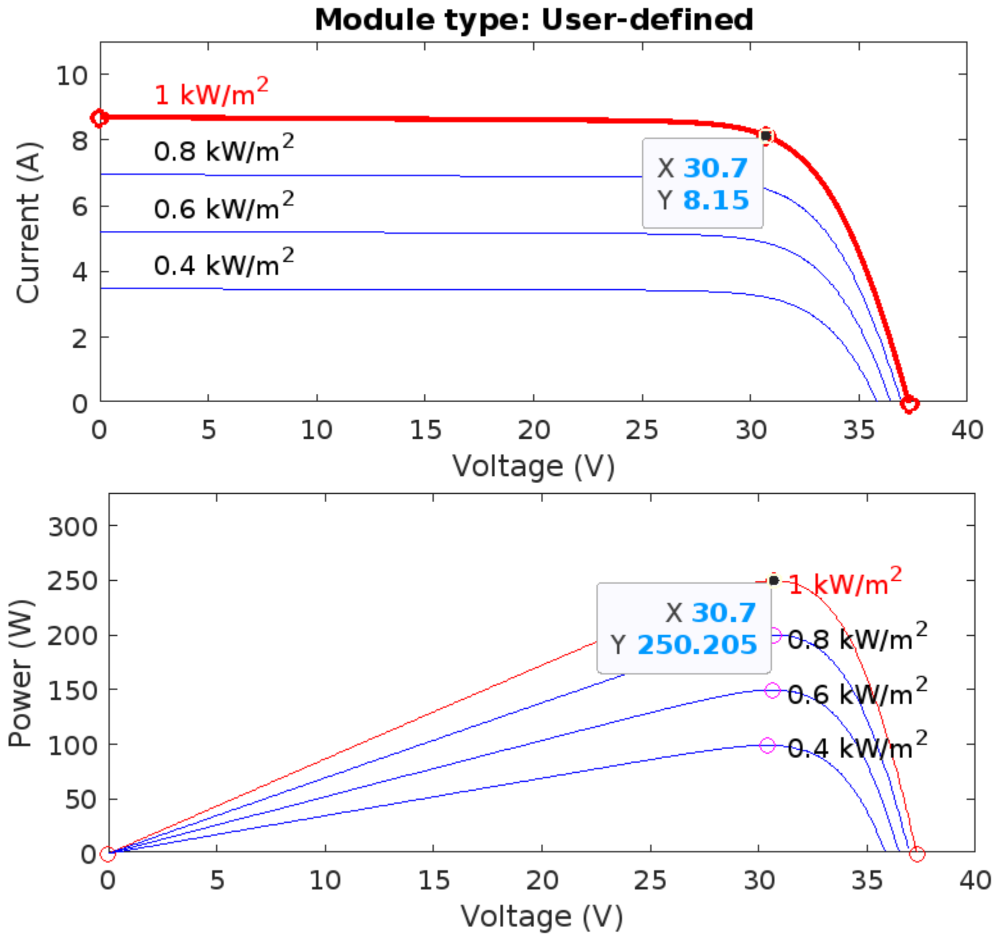

Fig 5: Current-Voltage & Power-Voltage Characteristics of PV Array

Parameters for the SMC and STSMC algorithms are optimised with PSO optimisation after the simulation environment has been set up. The MPPT system, which is powered by a PV panel with all components simulated. The effectiveness of both traditional SMC and STSMC techniques for MPPT is compared. The Simulink model for SMC and STSMC is shown in Figure 6&7 respectively.

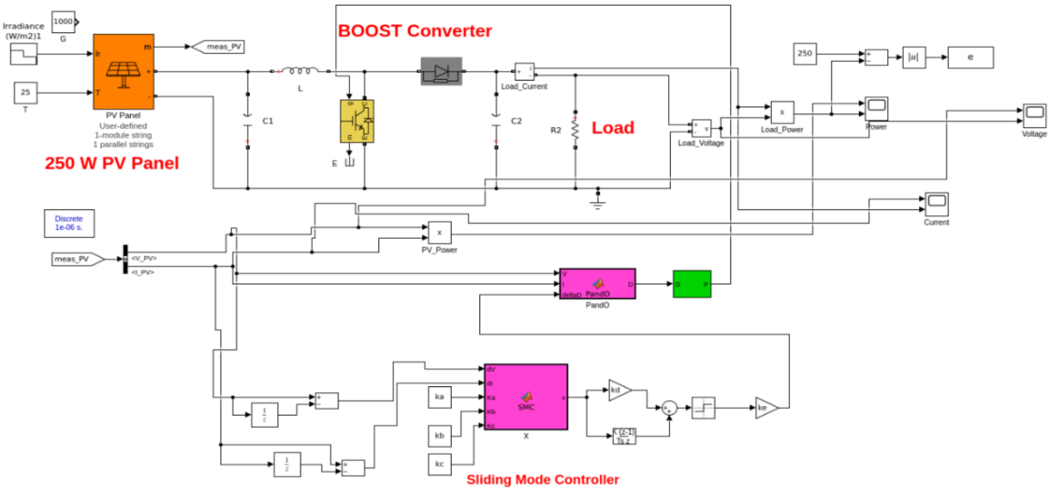

Fig 6: SMC Simulink Model

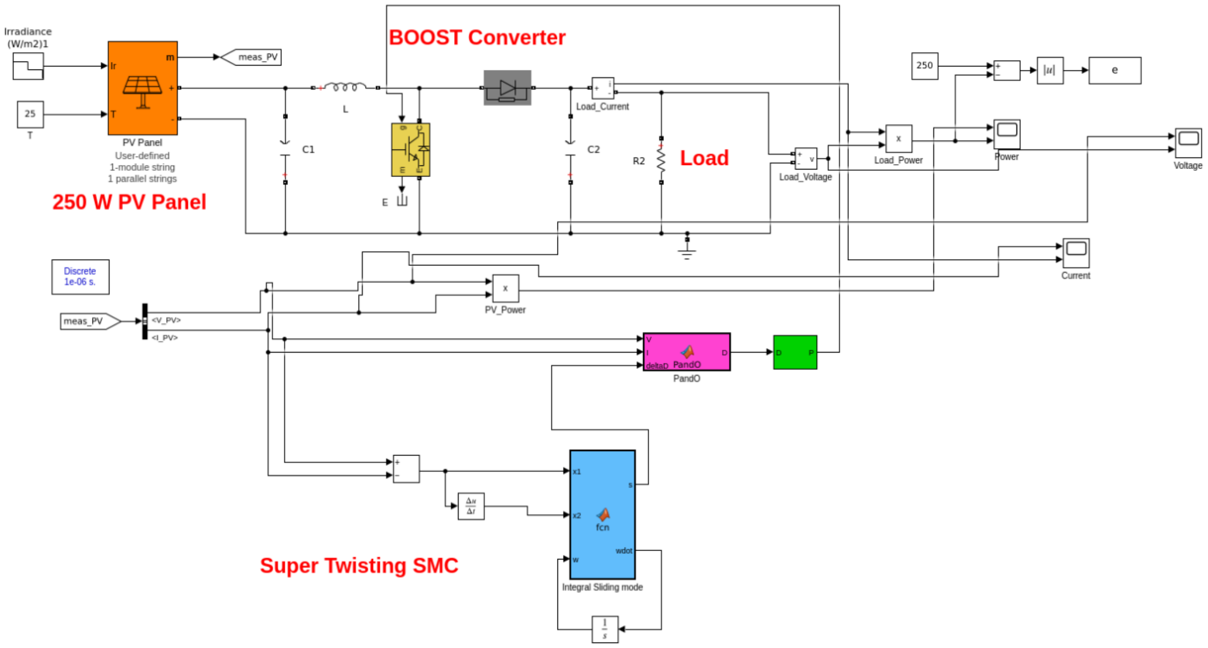

Fig 7: STSMC Simulink Model

The increased MPPT capacity of the suggested method is one of the most important findings of the research. MPP tracking accuracy and speed are greatly improved by the PSO-based optimisation of the STSMC in response to changing solar irradiance and temperature. Compared to conventional MPPT techniques as the P&O algorithm and the Incremental Conductance (INC) algorithm, the obtained findings show that the suggested methodology provides superior tracking efficiency, reaction time, and steady-state accuracy. Figures 8 and 9 depict the simulated PV power output for SMC and STMC, respectively.

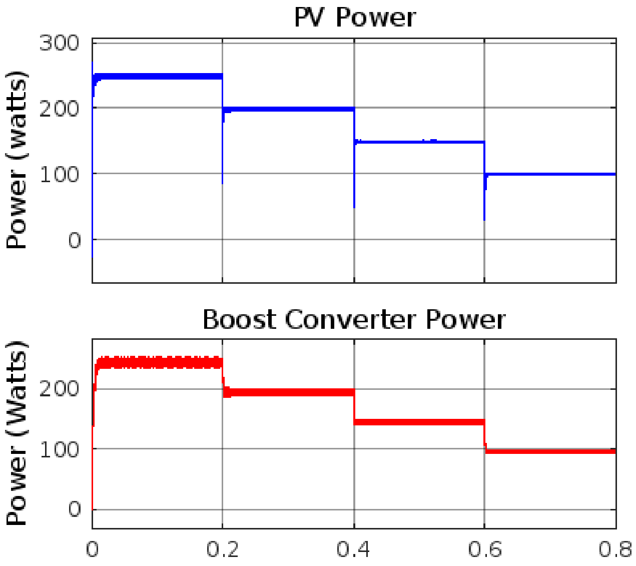

Fig 8: PV Power Curve for SMC Simulation

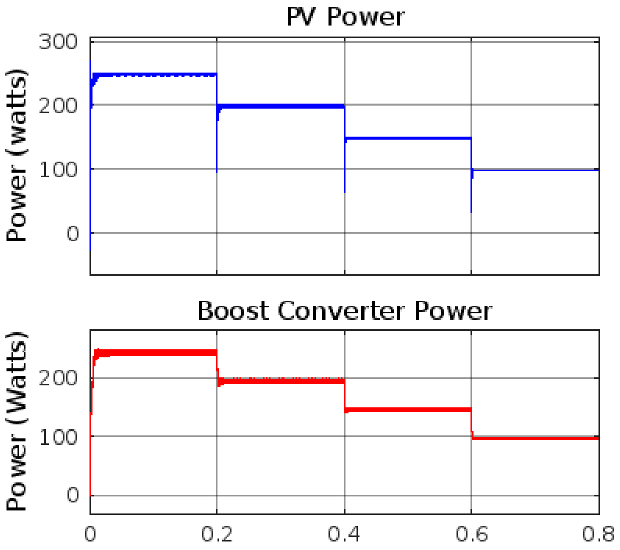

Fig 9: PV Power Curve for STMC Simulation

The outcomes show that when PSO is combined with STSMC, performance is enhanced in comparison to traditional control methods. By efficiently optimising the STSMC's control settings using the PSO method, the STSMC's tracking accuracy, settling time, and resilience against uncertainties and disturbances are all improved.

Table 1: Performance Comparison Between SMC and STSMC

	SMC	STSMC
Mean Efficiency	98.56%	99.28%
Fluctuations (min-max)	96%-100%	93%-100%
Fluctuation (Vo)	125v-128.2v	126v-127.5v

The SMC's chattering and fluctuations are more than the STSMC MPPT algorithm, as is evident. The chattering issue is lessening because of the high-order structure's adaptability. These graphs also show how reliable the SMC-based MPPT approaches are when exposed to varying levels of sunlight. The created approaches are then compared in terms of their performance by exploring and measuring a few factors. Table 1 displays average efficiency, variation in efficiency, and minimum and maximum values of VO.

5. Conclusion

In conclusion, PV system control is essential for maximising energy harvesting, preventing instability, and guaranteeing effective operation. This study evaluated the current state of solar PV system control methods and recommended a PSO-based optimisation of STSMC as a next-generation method of control. After reviewing the relevant literature and comparing the suggested PSO-based STSMC to existing methods, it becomes clear that it provides significant benefits and boosts to the control performance of solar PV systems. When contrasted against the standard SMC control method, PSO-based STSMC is shown to be superior in terms of resilience and tracking accuracy. Control performance is enhanced in a wide range of settings because to the combination of PSO optimisation and the sliding mode control structure. Higher energy yields may be achieved from solar panels thanks to the suggested method's improved MPPT capacity. The results demonstrate the effectiveness of PSO adaptation to STSMC by demonstrating a decrease in the supported fluctuations from the chattering problem for selected parameters.

While the outcomes show that the proposed method works, several restrictions are also shown. The research may not reflect all real-world considerations, such as component deterioration, partial shade, and system age, because it is based on idealised settings. The performance of the suggested strategy should be further validated in future study by include these elements under more realistic settings. Furthermore, the study only addresses a limited number of control goals; more work is required to determine whether or if the suggested technique can be successfully applied to additional control tasks in solar PV systems, such as grid integration and energy management.

References

[1] M. Asim, M. Tariq, M. A. Mallick, I. Ashraf, S. Kumari, and A. K. Bhoi, “Critical Evaluation of Offline MPPT Techniques of Solar PV for Stand-Alone Applications,” in Lecture Notes in Electrical Engineering, vol. 435. Singapore: Springer Singapore, 2018, pp. 13–21. doi: 10.1007/978-981-10-4286-7_2.

[2] M. Raugei et al., “A multi-disciplinary analysis of UK grid mix scenarios with large-scale PV deployment,” Energy Policy, vol. 114, pp. 51–62, Mar. 2018, doi: 10.1016/j.enpol.2017.11.062.

[3] B. Azzopardi and J. Mutale, “Life cycle analysis for future photovoltaic systems using hybrid solar cells,” Renewable and Sustainable Energy Reviews, vol. 14, no. 3, pp. 1130–1134, Apr. 2010, doi: 10.1016/j.rser.2009.10.016.

[4] P. Manoharan et al., “Improved Perturb and Observation Maximum Power Point Tracking Technique for Solar Photovoltaic Power Generation Systems,” IEEE Systems Journal, vol. 15, no. 2, pp. 3024–3035, Jun. 2021, doi: 10.1109/JSYST.2020.3003255.

[5] M. Lasheen and M. Abdel-Salam, “Maximum power point tracking using Hill Climbing and ANFIS techniques for PV applications: A review and a novel hybrid approach,” Energy Conversion and Management, vol. 171, pp. 1002–1019, Sep. 2018, doi: 10.1016/j.enconman.2018.06.003.

[6] V. Subramanian, V. Indragandhi, R. Kuppusamy, and Y. Teekaraman, “Modeling and Analysis of PV System with Fuzzy Logic MPPT Technique for a DC Microgrid under Variable Atmospheric Conditions,” Electronics, vol. 10, no. 20, p. 2541, Oct. 2021, doi: 10.3390/electronics10202541.

[7] D. Remoaldo and I. Jesus, “Analysis of a Traditional and a Fuzzy Logic Enhanced Perturb and Observe Algorithm for the MPPT of a Photovoltaic System,” Algorithms, vol. 14, no. 1, p. 24, Jan. 2021, doi: 10.3390/a14010024.

[8] M. Ahmed, I. Harbi, R. Kennel, J. Rodriguez, and M. Abdelrahem, “An improved photovoltaic maximum power point tracking technique-based model predictive control for fast atmospheric conditions,” Alexandria Engineering Journal, vol. 63, pp. 613–624, Jan. 2023, doi: 10.1016/j.aej.2022.11.040.

[9] M. Raghappriya, K. M. Devadharshini, and S. Karrishma, “Fuzzy Logic Based Maximum Power Point Tracking of Photovoltaic System,” JIIP, vol. 4, no. 1, pp. 49–60, May 2022, doi: 10.36548/jiip.2022.1.006.

[10] A. Arora and A. Singh, “Design and implementation of Legendre-based neural network controller in grid-connected PV systems,” IET Renewable Power Generation, vol. 13, no. 15, pp. 2783–2792, Nov. 2019, doi: 10.1049/iet-rpg.2019.0269.

[11] P. Gaisse, J. Muñoz, A. Villalón, and R. Aliaga, “Improved Predictive Control for an Asymmetric Multilevel Converter for Photovoltaic Energy,” Sustainability, vol. 12, no. 15, p. 6204, Aug. 2020, doi: 10.3390/su12156204.

[12] S. A. Mohamed, A. M. Hamada, and S.E. Abdellatif “Comparative Analysis of the Modified Perturb & Observe with Different MPPT Techniques for PV Grid Connected Systems,” IJRER, no. v10i1, 2020, doi: 10.20508/ijrer.v10i1.10375.g7850.

[13] A. Belkaid, I. Colak, K. Kayisli, and R. Bayindir, “Improving PV System Performance using High Efficiency Fuzzy Logic Control,” in 2020 8th International Conference on Smart Grid (icSmartGrid), Paris, France: IEEE, Jun. 2020, pp. 152–156. doi: 10.1109/icSmartGrid49881.2020.9144817.

[14] M. Awais, L. Khan, S. G. Khan, Q. Awais, and M. Jamil, “Adaptive Neural Network Q-Learning-Based Full Recurrent Adaptive NeuroFuzzy Nonlinear Control Paradigms for Bidirectional-Interlinking Converter in a Grid-Connected Hybrid AC-DC Microgrid,” Energies, vol. 16, no. 4, p. 1902, Feb. 2023, doi: 10.3390/en16041902.

[15] D. R. Aryani, F. S. Adi, J.-S. Kim, and H. Song, “An improved model-based interlink converter control design in hybrid AC/DC microgrids,” Energy Reports, vol. 8, pp. 520–531, Nov. 2022, doi: 10.1016/j.egyr.2022.10.146.

[16] S. Li, S. Zhou, and H. Li, “Harmonic Suppression Strategy of LCL Grid-Connected PV Inverter Based on Adaptive QPR_PC Control,” Electronics, vol. 12, no. 10, p. 2282, May 2023, doi: 10.3390/electronics12102282.

[17] R. M. Asif et al., “Design and analysis of robust fuzzy logic maximum power point tracking based isolated photovoltaic energy system,” Engineering Reports, vol. 2, no. 9, Sep. 2020, doi: 10.1002/eng2.12234.

[18] K. Zeb et al., “Design of Fuzzy-PI and Fuzzy-Sliding Mode Controllers for Single-Phase Two-Stages Grid-Connected Transformerless Photovoltaic Inverter,” Electronics, vol. 8, no. 5, p. 520, May 2019, doi: 10.3390/electronics8050520.

[19] X. Zhang and R. W. Longman, “Stability of Sliding Mode ILC Design for a Class of Nonlinear Systems with Unknown Control Input Delay,” IEEE Trans. Neural Netw. Learning Syst., vol. 33, no. 9, pp. 4346–4360, Sep. 2022, doi: 10.1109/TNNLS.2021.3056680.

[20] M. A. G. De Brito, E. H. B. Dourado, L. P. Sampaio, S. A. O. Da Silva, and R. C. Garcia, “Sliding Mode Control for Single-Phase Grid-Connected Voltage Source Inverter with L and LCL Filters,” Eng, vol. 4, no. 1, pp. 301–316, Jan. 2023, doi: 10.3390/eng4010018.

[21] P. Vu, Q. Nguyen, M. Tran, G. Todeschini, and S. Santoso, “Adaptive backstepping approach for dc-side controllers of Z -source inverters in grid-tied PV system applications,” IET Power Electronics, vol. 11, no. 14, pp. 2346–2354, Nov. 2018, doi: 10.1049/iet-pel.2018.5763.

[22] Liao, D. Luo, X. Luo, H. Li, Q. Xiang, and G. Huang, “Nonlinear Model and Dynamic Behavior of Photovoltaic Grid-Connected Inverter,” Applied Sciences, Vol. 10, 2020, pp. 1-14, doi:10.3390/app10062120.

[23] Y. Chaibi, M. Salhi, and A. El-jouni, “Sliding Mode Controllers for Standalone PV Systems: Modeling and Approach of Control,” International Journal of Photoenergy, vol. 2019, pp. 1–12, Mar. 2019, doi: 10.1155/2019/5092078.

[24] V. Utkin, A. Poznyak, Y. Orlov, and A. Polyakov, “Conventional and high order sliding mode control,” Journal of the Franklin Institute, vol. 357, no. 15, pp. 10244–10261, Oct. 2020, doi: 10.1016/j.jfranklin.2020.06.018.

[25] S. Roy and I. N. Kar, “Adaptive sliding mode control of a class of nonlinear systems with artificial delay,” Journal of the Franklin Institute, vol. 354, no. 18, pp. 8156–8179, Dec. 2017, doi: 10.1016/j.jfranklin.2017.10.010.

[26] S. Benhadouga, A. Belkaid, R. Farhan, I. Colak, M. Meddad and A. Eddiai, “Experimental Comparative Study Mppt Between P&O and Sliding Control of a Small PV System,” IJRER, no. v12i2, 2022, doi: 10.20508/ijrer.v12i2.13091.g8470.

[27] Q. Cao and X. Su, “Generalized Super-Twisting Backstepping Sliding Mode Control for Electro-Hydraulic Servo Systems Considering the Coexistence of Matched and Mismatched Uncertainties,” Applied Sciences, vol. 13, no. 8, p. 4931, Apr. 2023, doi: 10.3390/app13084931.

[28] R. Seeber and M. Horn, “Stability proof for a well-established super-twisting parameter setting,” Automatica, vol. 84, pp. 241–243, Oct. 2017, doi: 10.1016/j.automatica.2017.07.002.