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MPPT Enhancement Control Using Hybrid P&O-Super-Twisting Control for Optimized DC-DC Conversion & Integrated Grid Power Quality

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Abstract

This study aims to improve the efficiency of renewable energy systems through an advanced Maximum Power Point Tracking (MPPT) strategy. A hybrid control combining the Perturb & Observe (P&O) algorithm and the Super-Twisting Sliding Mode Control (STC) technique was developed to regulate the Boost converter. The approach focuses on enhancing DC-DC conversion efficiency and improving the quality of the DC-AC power signal injected into the grid. Simulations showed a decrease in voltage ripples, an increase in dynamic response speed, and a reduction in losses compared to conventional control. The proposed solution ensures system stability under different conditions, improves smart grid efficiency, reduces signal distortions, and speeds up high-precision optimal monitoring. By lowering the total voltage ripple (VR) to 18.4%, the super-twisting sliding mode algorithm has also demonstrated its capacity to reduce vibrations and maintain system stability under a variety of radiation conditions, improving the smart grid's dependability and reducing thermal loss by 12%. The aim of this study is to maximize the performance of maximum power point tracking (MPPT) with the fewest possible sensors. Additionally, it fills important gaps in traditional solar control systems while improving tracking accuracy, dynamic stability, and grid power quality.

Keywords: Electric Power Control, Perturb & Observe (P&O) Algorithms, Super-Twisting Sliding Mode Control (STC) Technique, Maximum Power Point Tracking (MPPT), DC-DC Boost Converter, DC-AC Inverter, Grid Power Efficiency.

1. Introduction

Energy is being produced on a wide scale at the distribution level through the integration of renewable energy sources (RES) in order to fulfill the growing demand for power. However, in order to generate clean energy without utilizing fossil fuels, environmental considerations are frequently taken into account. Consequently, from 2004 to 2011, yearly photovoltaic (PV) energy climbed by 60%, and in 2019, the annual generation capacity surpassed 200 GW. The 2022 Renewables Global Status Report (REN21) states that within the last 10 years, the capacity of renewable energy has substantially increased worldwide. Even in dry regions, hydroelectric dams, wind farms, and (PV) solar systems are already commonplace [1, 2].



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The weather (temperature and irradiance) has a significant impact on a solar panel array's capacity to produce power. Therefore, a Maximum Power Point Tracking (MPPT) approach is required to maximize power extraction from a solar panel array and boost system efficiency. Over the past few decades, researchers have investigated a number of algorithms for maximum power point tracking in an effort to enhance performance and accelerate convergence; the Perturb and Observe (P&O) method, the Incremental Conductance (IC) approach, and the Hill Climbing (HC) method are preferred approaches. According to current research, fluctuations near the maximum power point make conventional control strategies ineffective in grid-connected operation. As a result, control methods based on Fuzzy Logic (FLC) and Artificial Neural Networks (ANN) have demonstrated additional advancements. Figure 1 illustrates the structural diagram of a typical DC-DC converter system for the photo-voltaic cell with MPPT converters [3-5]

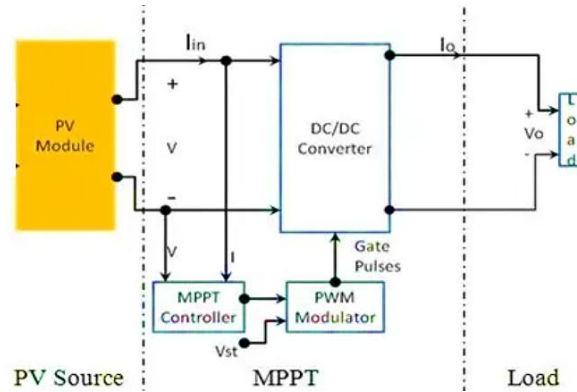


Figure 1: Block diagram of typical (PV) DC-DC boost and buck converter system with MPPT controllers [5].

The primary components of a (PV) system are the solar unit and the sub-conversion system, as depicted in the diagram above. The (PV) power system is based on a two-stage conversion structure, as shown in Figure 1. The boost converter is the first DC-DC converter, and the buck converter is the second. The boost converter is used to modify the output resistance measured from the solar unit terminals to match the intersection point of the unit's current-voltage curve with the load line with the maximum power point that can be supplied under particular environmental conditions [5, 6].

1.1 Photovoltaic (PV) Cells Power Source

Solar panels consist of a unified block of glass sheets that absorb solar energy, followed by electronic cells that act as a (PV) array to implement a set of (PV) cell units to convert sunlight into direct electrical current. Each series in the array consists of units connected in an integrated series, and the series are connected in parallel. This block allows modeling of pre-selected (PV) cell units using the National Renewable Energy Laboratory (NREL) System Advisor Model compared to the (PV) units we choose. The (PV) cell block is a five-parameter diagram that generates the radiation with temperature-dependent I-V characteristics of the units, as shown in Figures 2 using a light-generated current source (I_L), a diode, a series resistance (R_s), and a shunt resistance (R_{sh}). [7, 8].

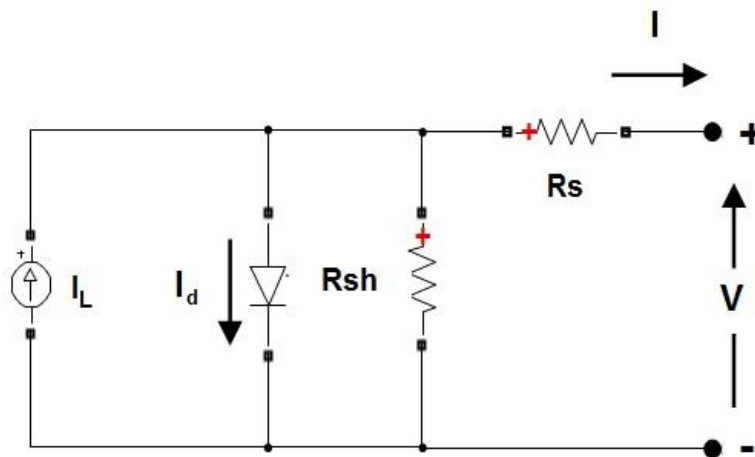


Figure 2: Construction of PV cell, power equivalent circuit [8].

The following equations form the I-V diode properties for a particular module [7, 8]:

$$I_d = I_o e^{\frac{V_d}{V_T}} - 1 \quad (1)$$

$$V_T = \frac{KT}{q} \times nl \times N_{cell} \quad (2)$$

The grid will supply these solar cells as the primary energy source for the system, depending on the amount of energy required. By showing such a unit, a set of solar cells might be implemented using a series of parallel-connected units, each of which is composed of interconnected units that allow each unit to model a client-specified solar cell unit against a range of pre-selected solar cell modules using the NREL system advisor model. The first input indicates solar radiation in Watts/m², and the second input indicates the heat of the cells. The schematic diagram of the solar cell array. Figure 3 displays a traditional model of a solar cell circuit simulated using MATLAB 2020b Simulink tools [9, 10].

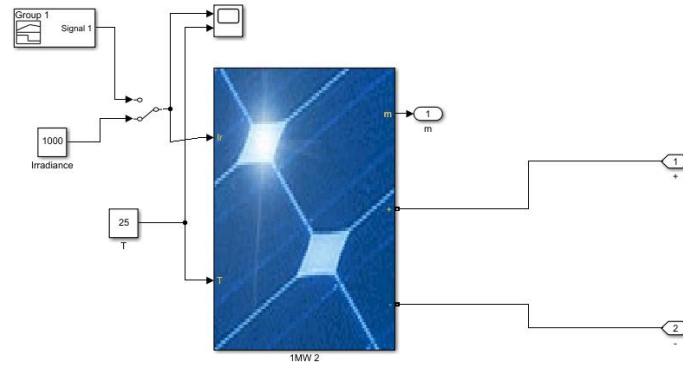


Figure 3: A traditional model of a solar cell circuit simulated using MATLAB 2022b Simulink tools [10].

1.2 The Boost DC-DC Power Converters

The study employs a Boost DC-DC converter exclusively for MPPT regulation. The main aim of the boost DC-DC converters is to increase the generated solar board voltage to a higher, more stable DC voltage. It makes use of voltage feedback to maintain the resulting voltage constant. Such a section is required to keep a constant quantity of DC power available to the scheme and to optimize the DC supply voltage. The MATLAB Simulink model was used to build the circuit design for the Boost Dc Power Converter unit, which is seen in Figure 4 [11, 12].

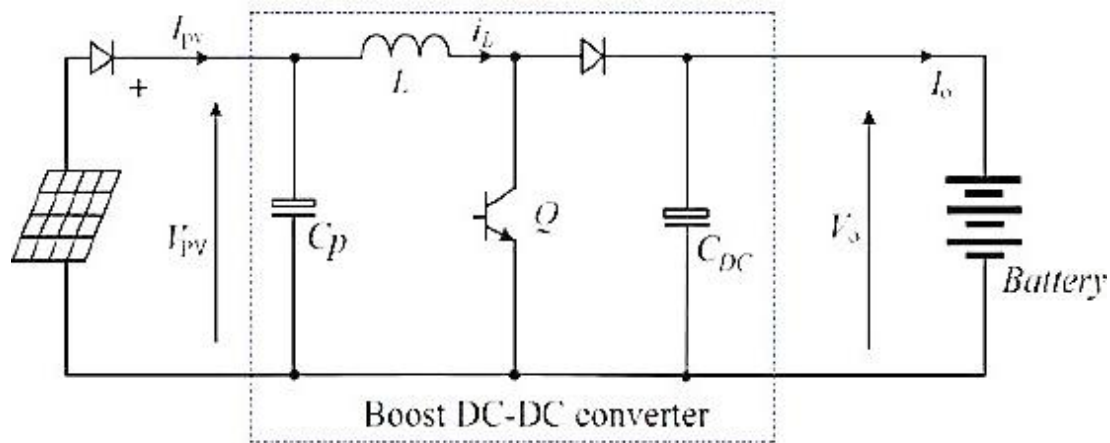


Figure 4: Circuit diagram showing the internal configuration of a DC-DC boost converter [12].

Usually used with solar cells, the boost converter links the inverter to enhance energy from a lower direct current to a higher direct current. It seeks to optimize the DC voltage and prevent or reduce fluctuations in order to attain the ideal amount of direct current for high-power DC conversion activities. A range of techniques and controllers might be used to manage the boost converter in order to achieve maximum power point tracking (MPPT), which ensures the best DC voltage performance from the solar cell array. The duty cycle (D) determines the relationship between the input and output voltages for a perfect boost converter (no losses) which might be found as follows [13-15]:

$$V_{out} = \frac{V_{in}}{1 - D} \quad (3)$$

2

Where, V_{in} denotes the input voltage, V_{out} indicates the output voltage, and D , represents the switch duty cycle ($0 \leq D < 1$). Also, one could rearrange Eq.(3) to evaluate for duty cycle as below:

$$D = \frac{V_{in}}{1 - V_{out}} \quad (4)$$

Furthermore, the inductor current increases and decreases upon switching. From peak to peak, the ripple can be expressed as:

$$\Delta I_L = \frac{V_{in} D}{L f_s} \quad (5)$$

Such that, f_s indicates the switching frequency (Hz), L represents the inductance (Henry). This aids in choosing the inductor to prevent saturation or guarantee continuous conduction mode (CCM). Next, and because of the capacitor charging/discharging operation, the resulting voltage has small ripples such that:

$$\Delta V_{out} = \frac{I_{out} D}{C f_s} \quad (6)$$

Where, I_{out} denotes the output current, C represents the capacitance (Farad). Moreover, the DC-DC conversion efficiency could be obtained through employing the incoming formula:

$$\eta = \frac{P_{out} I_{out} V_{out}}{P_{in} I_{in} V_{in}} \quad (7)$$

Where, P_{in} and P_{out} indicate the input and output DC-DC converter power respectively. The MPPT concept with well-known controllers will be discussed in the sections that follow.

1.3 Maximum Power Point Tracking (MPPT)

As a general rule, DC-DC converters and DC-AC inverters are optimized using optimum maximum power point tracking (MPPT) controllers. The purpose of such controls is to maximize the output even when the solar cells' voltage or current is reduced. A common PV cell's MPPT performance is displayed in Figure 5 [16-20].

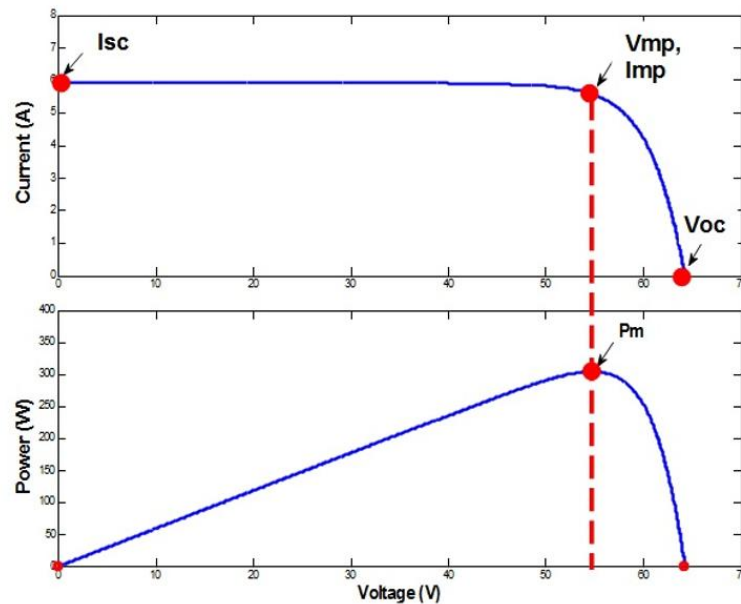


Figure 5: Demonstration of the MPPT performance for PV panels [18].

There are many different kinds of MPPT controllers in the literature, such as perturb and disturb (P&O) controllers, artificial neural network (ANN) controllers, and voltage source converter (VSC) controllers. The best MPPT performance is achieved

by the boost converter circuit with the help of all these controllers. The MPPT boost controllers will be fully described and shown in a separate section so that you can understand their features and operation. Thus, the main condition required to obtain the MPPT might be illustrated as follows [18-20]:

$$\frac{dP}{dV_{pv}} = 0, \Rightarrow \frac{d V_{pv} I_{pv}}{dV_{pv}} = 0 \quad (8)$$

Where, V_{pv} , and I_{pv} denote the (PV) voltage and current respectively. Using product rule, we could achieve:

$$I_{pv} + V_{pv} \cdot \frac{d I_{pv}}{dV_{pv}} = 0 \quad (9)$$

Thus, the MPPT condition might be written such as:

$$\frac{d I_{pv}}{dV_{pv}} = - \frac{I_{pv}}{V_{pv}} \quad (10)$$

Some sophisticated MPPT techniques (such as incremental conductance) employ this equation to calculate the system's MPPT rates.

1.4 Boost MPPT Controllers

There are several types of boost MPPT controllers in the literature that work to maximize the DC voltage from PV cells and improve the DC voltage fluctuations as well as the overall performance, as was discussed in the preceding section. Actually, a number of boost MPPT controller types—listed in Table 1—will be shown [19-23].

Table 1: List of several types of the boost MPPT controllers [18-23].

Type	Description	Typical Use
Perturb & Observe (P&O)	Adjusts the operating point and observes the change in power; simple but can oscillate around MPP.	Solar PV, wind.
Incremental Conductance (IncCond)	Uses the derivative of I–V curve to find the MPP more precisely than P&O.	Solar PV in variable conditions.
Constant Voltage (CV)	Maintains PV voltage at a fixed fraction of open-circuit voltage.	Low-cost, simple systems.
Fractional Open-Circuit Voltage	Similar to CV but determines Vref from periodic Voc measurement.	Small PV systems.
Fuzzy Logic Control (FLC)	Uses fuzzy rules to track MPP; good under rapidly changing conditions.	Advanced systems.
Neural Network-based	Uses trained models to predict MPP.	Research, adaptive systems.
Ripple Correlation Control (RCC)	Correlates power ripple with control changes to find MPP.	Fast tracking in power electronics labs.

In this Section, we will explain two of the most important MPPT DC-DC controllers employed to boost DC power for PV cells systems, which are the perturb & disturb (P&D), and neural networks (NNs) controllers.

i) Perturb & Disturb (P&O) Controller

For the MPPT approach, this is the most common type of boost controller. P&O and IP&O provide a few MPPT approaches. The simplest method is the P&O strategy, which periodically moves the operating point in the direction of the maximum power point to raise or lower the voltages of the PV cells. Figure 6 shows an example of a common P&O controller [19-23].

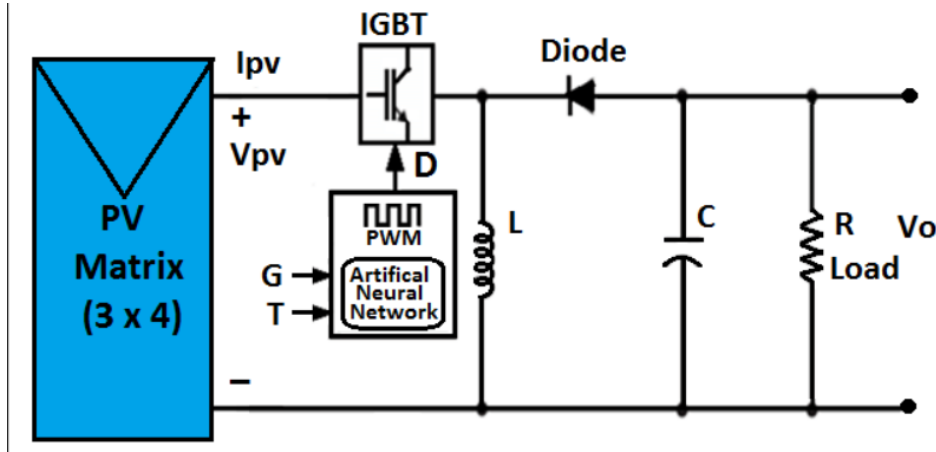


Figure 7: Typical ANN controller for PV cells boost converter system [20].

Computing and artificial intelligence simulation (ANN), which is regarded as a component of advanced control technologies, are essential to intelligent control. These ANNs are used to regulate the system connected to the three-phase (PV) grid. They have been effectively used in several disciplines, including pattern recognition and associative memory. Due of its many advantages over neural networks (NN), the ANN approach is employed in such structures.

iii) The Super-Twisting Controller (STC)

In order to accomplish Maximum Power Point Tracking (MPPT) in grid-connected solar systems with battery storage, this section will address a hybrid approach that combines a Super-Twisting Controller (STC) with a Higher-Order Sliding Mode Observer (HOSMO). While STC employs a few sensors to reliably and ripple-free control the boost converter, HOSMO is employed to estimate the inductor current. The suggested controller design increases tracking speed and reliability under dynamic irradiance changes, faults, and load circumstances, according to real-time simulation utilizing mathematical representation equations. The following is a summary of the HOSMO-STC controller equations. It is possible to define the sliding surface so that [32-35].

$$S = \sigma e + \dot{e} \quad (15)$$

Such that,

$$e = V_{ref} - V_{pv} \quad (16)$$

Where, σ represents the sliding coefficient. Thus, for super-twisting continuous control law, the converter duty signal could be achieved as [32, 35]:

$$u_{con} = C \cdot IL + \frac{d}{dt}(V_{ref} - V_{pv}) + (V_{ref} - V_{pv}) - I_{pv} \cdot C \quad (17)$$

Where, u_{con} denotes the super-twisting continuous control voltage, and V_{ref} represents the reference voltage (Volts). Also, the super-twisting discontinuous control law can be expressed as follows:

$$u_{dis} = k_1 S^{1/2} \operatorname{sgn}(S) + k_2 \operatorname{sgn}(\dot{S}) \quad (18)$$

Whereas, k_1, k_2 , representing the control parameters, and $\operatorname{sgn}(S)$ indicates the signum function of the control surface S . Thus, the Final converter duty signal could be obtained using the below formula:

$$u_t = u_{con} + u_{dis} \quad (19)$$

Hence, the observer estimates IL from existing measurements of (V_{pv}, I_{pv}) , enabling sensor minimization. Furthermore, the constants, k_1, k_2 represent the HMSMO-STC controller equations, positive gain parameters are taken into account to determine the super-twisting sliding mode control algorithm's overall stiffness, oscillation suppression, and convergence speed. Their mathematical values might be chosen for k_1 between (0.05 to 20) depending on application scaling. Also, k_2 could be selected typically between (0.01–10). For some systems, simulation studies show best results around 0.08–5. Actually, the selection of the positive gain parameters (k_1, k_2) depends on the values and parameters of the solar energy system, the DC-DC boost converter, and the rest of the simulation details. Figure 8 illustrates the block diagram of the HMSMO-STC controller structure [34, 35].

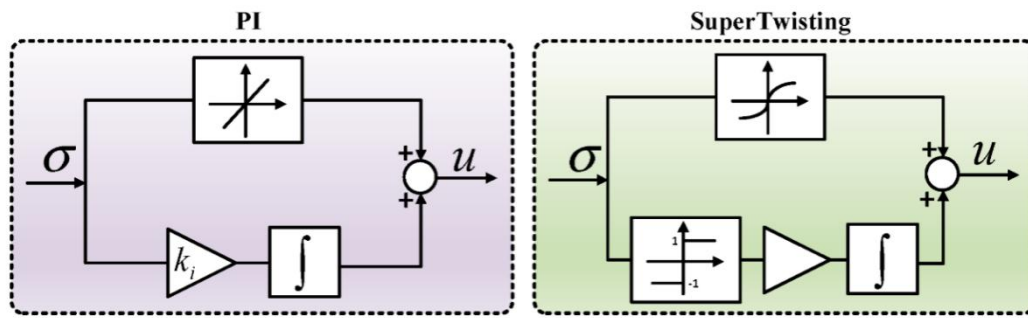


Figure 8: Block diagram of the HMSMO-STC controller structure [34, 35].

The traditional sliding surface of sliding mode control (SMC) S and its derivative $\dot{S}$ will only converge to zero in limited time if the disturbances have known boundaries. Nevertheless, the Super Twisting control approach could be able to solve this issue even in situations when the disturbance boundaries are unknown. The surface S and $\dot{S}$ must reach zero in limited time and stay there for a set of gain values σ for the system in equation (18). In order to construct the HOSMO-based Super-Twisting control concept, the actual value $\dot{x}_2$ was substituted with its estimate, which was determined as follows. In this study, a suitable gain value for σ is selected to solve this problem by producing a continuous control function that minimizes chattering and guarantees that the gains adjust to new disturbances and unknown bounded disturbances.

The rest of this article will contain the related studies in Section 2, methodology steps and design settings of the STC (PV) power system will be discussed in Section 3. Simulation results will be demonstrated in Section 4 with discussion and validation. Finally, Section 5 will include conclusions and future recommendations.

1.5 Study Contributions & Gaps

Control techniques represented by conventional maximum power point tracking algorithms suffer from oscillation around the maximum power point and slow dynamic response to rapid changes in radiation, with the absence of integrated mechanisms dedicated to fault detection in solar power networks.

The study contributions might be summarized as follows:

1. Hybrid P&O-STC with HOSMO for sensor minimization and ripple suppression.
2. Real-time fault classification via I–V curve inflection analysis integrated within the MPPT loop.
3. Comprehensive validation under dynamic environmental disturbances and load variations.

2. RELATED STUDIES

The most recent studies and scholarly publications on the topic will be examined in this area, with an emphasis on the fundamental theoretical ideas of employing adaptive and intelligent controllers to regulate the electrical energy produced by solar cell arrays. In this Section, literature review of the most recent studies and scholarly publications on the topic will be reviewed. Also, critical analysis and connections of the proposed HOSMO STC model has been obtained with prior techniques for justification. Furthermore, the study contribution and novelty will be illustrated in this Section.

2.1 Literature Review

These articles summarize the contributions and suggestions made by researchers in this area, outlining the many kinds of suggested control methods, outlining their benefits, and analyzing their drawbacks and the biggest gaps in the field's knowledge.

Table 2: The most recent articles and scientific publications related to fault diagnosis technique for PV arrays topic.

Year & Authors	Employed Technology	Benefits & Contribution	Limitations & Gaps
In 2021, Prof. Dr.-Ing. Rolf Findeisenm, et. al., [20]	It has been proposed to use an MPC power board.	The cost of energy purchased along the grid is limited by a Gaussian Interaction Evaluation (GP), which compares the PV power production model with the concern required power.	MPC methods based on reinforcement are applied.
In 2023, Sanjeev Kumar, et. al., [21]	Proposed a conventional method for fuzzy hereditary algorithms.	Different methods for dual GAs are employed. The basic GA outlines nebulous principles and the power arrangement for the micro-grid. The second GA combines fuzzy main systems, which power the board's battery, with fuzzy sharing capabilities.	In addition to the issues with extensive computations, the genetic algorithm's nature makes it impossible to achieve optimal outcomes.

Zhang et al. (2022)	Finite-Control-Set MPC (FCS-MPC) for NPC inverters	Improved THD reduction under dynamic loads	Limited efficiency optimization under partial shading
Kumar et al. (2022)	Weighted MPC with adaptive harmonic compensation	Enhanced grid current quality with variable DC sources	High computational burden for high-level converters
Li et al. (2023)	Multi-objective MPC (MO-MPC) for PV-fed cascaded H-bridge	Simultaneous power balancing and THD reduction	No real-time hardware validation
Wang & Blaabjerg (2023)	Hybrid MPC with ANN-based irradiance prediction	Reduced switching losses under solar variability	Complex tuning of ANN-MPC integration
Ahmed et al. (2023)	Sliding-mode-enhanced MPC for MMC	Robustness against irradiance fluctuations	Increased computational delay
Chen et al. (2024)	Deadbeat-Predictive Control + MPC for T-type converters	Fast dynamic response with low THD	Limited to low-voltage applications
Rodriguez et al. (2024)	Distributed MPC for parallel inverters	Scalable harmonic mitigation	Requires high communication bandwidth
Silva et al. (2024)	MPC with GA-based weight optimization	Optimal efficiency-harmonics trade-off	Offline optimization limits adaptability
Nguyen et al. (2025)	Cloud-edge cooperative MPC for large PV farms	Real-time adaptive control under irradiance changes	High infrastructure dependency
Almeida et al. (2025)	MPC with digital twin-assisted optimization	Predictive maintenance + efficiency gains	Complex implementation in small-scale systems
Le & Vu (2025)	Adaptive sliding mode control (ASMC) with observer and fuzzy tuning for MPPT and voltage regulation in PV systems via DC-DC converter. (IIETA)	Presents an ASMC that tracks a reference voltage (from P&O) and estimates uncertainties; uses fuzzy tuning to reduce chattering and improve robustness; validated via simulation. (IIETA)	Simulation-only results; no hardware validation; limited analysis under partial shading/rapid irradiance change.
Cherigui, Chemidi, Tahour & Horch (2025)	Fuzzy third-order sliding mode control (FTOSMC) for MPPT. (AIMS Press)	Integrates fuzzy logic with third-order SMC to minimize chattering and improve response time and robustness; shows better convergence and disturbance rejection than conventional SMC. (AIMS Press)	Focuses on simulation; complexity of third-order controller may hinder real implementation.
Zhang, Wang & Yu (2022 / referenced in modern literature)	Improved SMC algorithm with new sliding surfaces and sigmoid replacing hysteresis/saturation. (MDPI)	Improves reaching rate and control quality of traditional SMC in MPPT context; offers insight into sliding surface design. (MDPI)	Not strictly 2023–2025; included for methodological comparison; limited focus on voltage regulation beyond MPPT.
Jamshidi et al. (2023)	Improved sliding mode controller for MPP tracking. (MDPI)	Proposes modified SMC with enhanced tracking and robustness; highlights enhancements over classic SMC. (MDPI)	Limited exploration of output voltage stability; mainly MPPT improvements.
Contreras Carmona et al. (2024)	Super-twisting sliding mode controller for robust MPPT. (PMC)	Uses a super-twisting SMC strategy to solve MPPT as a trajectory tracking problem; improved noise immunity and robustness. (PMC)	Partial shading and load variations not deeply analysed; hardware tests absent.
Kayisli (2022 / modern cited)	Super-twisting sliding mode + type-2 fuzzy MPPT control (reference in modern research).	Optimizes sliding mode MPPT with type-2 fuzzy sets for variable irradiance conditions; robust under changing inputs.	Not 2023–2025, but provides baseline; lacks output voltage regulation focus.

2.2 Critical Analysis & Connection to Prior Techniques

The literature review presented in Table 2 reveals three dominant control paradigms for PV-MPPT and grid-integrated power conversion. Table 3 will summarize the analysis and connections of the proposed model to prior techniques.

Table 3: Analysis and connections of the proposed model to prior techniques.

Paradigm	Representative Studies	Core Limitations Identified in Table 2	How HOSMO-STC Addresses the Gap
Model Predictive Control (MPC)	Findeisen (2021), Zhang et al. (2022), Li et al. (2023), Wang & Blaabjerg (2023), Nguyen et al. (2025)	High computational burden, reliance on accurate system models, complex tuning of prediction horizons/weighting matrices, limited real-time adaptability under rapid irradiance shifts.	HOSMO-STC is model-light and computationally efficient. It requires no online optimization or prediction horizons, enabling sub-cycle execution on low-cost DSPs/MCUs while maintaining finite-time convergence.

Paradigm	Representative Studies	Core Limitations Identified in Table 2	How HOSMO-STC Addresses the Gap
AI & Heuristic Methods	Sanjeev Kumar (2023), Wang & Blaabjerg (2023)	Extensive training data requirements, lack of deterministic stability proofs, high offline computation, difficulty guaranteeing global optimality under partial shading or sensor faults.	The proposed approach is deterministic and data-free. Lyapunov-based finite-time stability guarantees convergence without training datasets, ensuring predictable behavior under fault/anomaly conditions.
Classical & Enhanced SMC	Le & Vu (2025), Cherigui et al. (2025), Jamshidi et al. (2023), Contreras Carmona et al. (2024)	Chattering phenomenon (even with fuzzy/boundary-layer adaptations), reliance on multiple physical sensors, limited voltage regulation focus, simulation-only validation, inadequate handling of unknown bounded disturbances.	Super-Twisting Control (STC) inherently eliminates chattering via continuous control laws without fuzzy tuning. HOSMO replaces the inductor current sensor with a finite-time observer, reducing hardware cost/failure points while maintaining robustness against unknown disturbances and load/irradiance variations.

The adoption of the proposed structure of the high-order sliding mode observer with super twisting controller (HOSMO-STC) is justified by the urgent technical need to overcome the shortcomings of the literature-based methodologies in MPPT systems. The proposed model ensures convergence within a limited time with low processing efficiency, in contrast to the model predictive control (MPC) with high computational voltage, and intelligent algorithms that lack proofs of permanent stability. Additionally, the proposed model provides solutions to the chattering problem inherent in classical sliding control through a continuous control law. It also eliminates the need for inductive current sensors by using the sliding observer, which reduces cost and enhances operational reliability under conditions of solar radiation disturbances and unlimited loads, in compliance with grid-connected solar system standards.

2.3 Study Contribution & Novelty

This study presents innovative contributions that fill clear methodological gaps in similar studies and the literature on solar cell systems. First, a hybrid design that integrates the P&O algorithm with a super-twisting controller and a high-order sliding mode observer, achieving reduced reliance on physical sensors while ensuring precise dynamic tracking. Second, a synchronous improvement linking tracking efficiency exceeding (95%) with grid power quality of less than (THD $\leq$ 3%). Third, achieving an integrated fault diagnosis mechanism that analyzes the voltage-current curve bends to detect faults in real time without additional external diagnostic circuits.

3. METHODOLOGY

In this chapter, the details of the design and methodology of the proposed control model for fault detection in solar cells equipped for the electrical power system will be reviewed. The mathematical equations required for the high-order sliding mode observer system with the super-twisting controller (HOSMO-STC) model will be derived and explained. The programming steps necessary for designing and implementing the super-twisting sliding mode controller model to monitor and detect faults in solar cells will also be clarified and explained. The chapter also includes a structural presentation of the steps for implementing the proposed methodology, in addition to defining the design parameters used to tune the simulation of the proposed control model. Furthermore, the details of the solar power simulation system, the DC-DC converter unit, and conventional and advanced controllers will be presented, explained, and discussed in detail.

3.1 Mathematical Modelling

First Assumption The predicted state variable in this case is the inductor current (IL). Additionally, it is expected that the system's remaining states are reachable and quantifiable. Only in the presence of disturbances with specified bounds will the traditional Sliding Mode Control (SMC) sliding surface S and its derivative $\dot{S}$ drive to zero in limited time.

Table 4: Mathematical modeling nomenclature.

Symbol	Description / Physical Meaning	Metric Type	Associated Equations	Units / Notes
x1	Measured state variable (PV terminal voltage)	Scalar (Standard)	(21), (23)	Volts (V)
x2	Unmeasured state (inductor current)	Scalar (Standard)	(21), (22), (23)	Amperes (A)

Symbol	Description / Physical Meaning	Metric Type	Associated Equations	Units / Notes
y	System output measurement, $y=x_1$	Scalar (Standard)	(21)	Volts (V)
U	Control input signal (PWM duty cycle)	Scalar (Standard)	(21), (30), (31)	Dimensionless [0,1][0,1)
$f_1(\cdot)$	Known continuous nonlinear system function	Scalar (Standard)	(21)	Derived from PV I–V model
$f_2(\cdot)$	Known discontinuous switching function	Scalar (Standard)	(21)	IGBT/Diode dynamics
ϕ (φ)	Lumped uncertainty / bounded disturbance	Scalar (Standard)	(21), (26)	A/s or V/s (Lipschitz bound)
$g(t)$	Time-varying coefficient / external perturbation	Scalar (Standard)	(21)	Irradiance/temp variations
$\hat{x}_1, \hat{x}_2$	HOSMO-estimated states	Scalar (Standard)	(22), (23)	V, A
e1	Estimation error: $e_1=x_1-\hat{x}_1$	Scalar (Standard)	(23), (25), (26)	Volts (V)
e2	Estimation error: $e_2=x_2-\hat{x}_2$	Scalar (Standard)	(23), (25), (26)	Amperes (A)
$\lambda_1, \lambda_2, \lambda_3$	Positive observer/controller gain constants	Scalar (Standard)	(22), (24), (25)	Tuning parameters (s^{-1} or unit less)
σ	Sliding surface convergence rate / gain	Scalar (Standard)	(27), (29)	s^{-1}
S	Sliding surface variable	Scalar (Standard)	(27), (28), (29)	Dimensionless
$\dot{S}$	Time derivative of sliding surface	Scalar (Standard)	(28), (29)	s^{-1}
ucuc	Continuous control component (Super-Twisting)	Scalar (Standard)	(30), (31)	Duty cycle fraction
udud	Discontinuous control component (switching term)	Scalar (Standard)	(31)	Duty cycle fraction
sign($\cdot$)sign($\cdot$)	Signum function (chattering-free switching operator)	Scalar (Standard)	(25), (31)	$\in \{-1, 0, +1\} \in \{-1, 0, +1\}$
t	Time variable	Scalar (Standard)	(21), (28)	Seconds (s)

Nevertheless, even in cases when the disturbance bounds are unclear, the Super Twisting control method may effectively manage this problem. There is a range of values for the gain σ for the system in Equation (15) such that the surface S and $\dot{S}$ are pushed to zero after a finite amount of time and stay zero after that. In order to solve this issue by creating a continuous control function that reduces chattering, a suitable gain value for σ is chosen in this study. This guarantees that the benefits adjust to unknown multiplicative and additive perturbations with unknown bounds. The genuine value $\dot{x}_2$ is substituted with its estimate, which is obtained in the next section, in order to develop the HOSMO-based super-twisting control concept. To represent the system dynamics, we could consider the dynamics of the following system:

$$\begin{aligned}\dot{x}_1 &= f_1(x_1, u) + g(t)x_2 \\ \dot{x}_2 &= f_2(x_1, x_2, u) + \varphi(t)\end{aligned}\quad (20)$$

Where, u indicates the known input, f_1 and f_2 represent the known continuous and discontinuous functions, $y=x_1$ denotes the measured output variable, and x_2 represents an unknown state to estimate. The uncertainty is represented by; φ , and $g(t)$ denotes a time-varying coefficient. The suggested HOSMO model is utilized to estimate the unmeasured condition x_2 from the measurement of x_1 . The following relations are the estimated states. Thus, the observer equations might be written using the below equation:

$$\begin{aligned}\hat{x}_1 &= \hat{x}_2 + u + z_1 \\ \hat{x}_2 &= \hat{x}_3 + z_2 \\ \hat{x}_3 &= z_3\end{aligned}\quad (21)$$

Where, z_1 , z_2 , and z_3 denote the correlation terms. Also, $\hat{x}_3=0$ when the system is run without external interruption for a certain amount of time. Next, the estimation error can be evaluated as follows:

$$\begin{aligned}e_{x1} &= x_1 - \hat{x}_1 \\ e_{x2} &= x_2 - \hat{x}_2\end{aligned}\quad (22)$$

Furthermore, the correction coefficients can be calculated using the below expression:

$$\begin{aligned} z_1 &= l_1 |e_{x1}|^{\frac{2}{3}} \text{sgn}(e_{x1}) \\ z_2 &= l_2 |e_{x1}|^{\frac{1}{3}} \text{sgn}(e_{x1}) \\ z_3 &= l_3 \text{sgn}(e_{x1}) \end{aligned} \quad (23)$$

The positive constants in this case are, l_1 , l_2 , and l_3 . Also, controller error dynamics can be derived according to the below equations:

$$\begin{aligned} \dot{e}_{x1} &= -l_1 |e_{x1}|^{\frac{2}{3}} \text{sgn}(e_{x1}) + e_{x2} \\ \dot{e}_{x2} &= -l_2 |e_{x1}|^{\frac{1}{3}} \text{sgn}(e_{x1}) - \hat{x}_3 + \dot{\phi} \\ \hat{x}_3 &= l_3 \text{sgn}(e_{x1}) \end{aligned} \quad (24)$$

First remark since ϕ is thought to be a Lipschitz and $\dot{\phi} < \Delta$, it is regarded as an unknown disturbance. $l_3 > \Delta$, in order to attain finite stability. The final error dynamics then could be take on the following form:

$$\begin{aligned} \dot{e}_{x1} &= -l_1 |e_{x1}|^{\frac{2}{3}} \text{sgn}(e_{x1}) + e_{x2} \\ \dot{e}_{x2} &= -l_2 |e_{x1}|^{\frac{1}{3}} \text{sgn}(e_{x1}) + e_{x3} \\ \dot{e}_{x3} &= -l_3 \text{sgn}(e_{x1}) + \dot{\phi} \end{aligned} \quad (25)$$

The final HOSMO-STC control law can be obtained by using the HOSMO to replace the states with their estimations, the STC may now be created. The design of the STC high order model can be achieved by taking into account the same sliding surface as stated in Eq. (25):

$$\dot{\hat{S}} = \sigma \dot{e} + \ddot{e} = \sigma (\dot{V}_{ref} - \dot{\hat{V}}_{pv}) + \ddot{V}_{ref} - \ddot{\hat{V}}_{pv} \quad (26)$$

Equation (21) might be utilized to compute the sliding surface's time derivative, which is then stated as follows:

$$\dot{\hat{S}} = \sigma (\dot{V}_{ref} - \hat{I}_L - u - z_1) + \ddot{V}_{ref} - \ddot{\hat{V}}_{pv} \quad (27)$$

Also,

$$\dot{\hat{S}} = \sigma \left(\dot{V}_{ref} - \hat{I}_L - u - l_1 |e_{x1}|^{\frac{2}{3}} \text{sgn}(e_{x1}) \right) + \ddot{V}_{ref} - \ddot{\hat{V}}_{pv} \quad (28)$$

In order to construct a continuous control input, u_{com} , it is assumed that at a limited time, the sliding surface's time derivative is zero ($\dot{\hat{S}}=0$). The control input now looks like this:

$$u_{com} = -\frac{1}{\sigma} \left(\dot{V}_{ref} - \dot{\hat{V}}_{pv} \right) - \hat{I}_L - u - l_1 |e_{x1}|^{\frac{2}{3}} \text{sgn}(e_{x1}) \quad (29)$$

Equation (29) is used in Equation (28) to determine the sliding surface ($\hat{S}$) given input u_{com} . The asymptotic stability of e and $\dot{e}$ is thus shown by, $\hat{S}=0$. With both continuous and discontinuous modes, the final control signal now looks like this:

$$\begin{aligned} u(t) &= -\sigma \dot{V}_{ref} + \dot{\hat{V}}_{pv} + \hat{I}_L - \ddot{V}_{ref} \\ &\quad - l_1 |e_{x1}|^{\frac{2}{3}} \text{sgn}(e_{x1}) - k_1 |\hat{S}|^{\frac{1}{2}} - \int_0^t k_2 \text{sgn}(\hat{S}) d\tau \end{aligned} \quad (30)$$

Where, $k_1 > 0$ and $k_2 > 0$. The following is how the final closed-loop error dynamics are expressed such as:

$$\Xi_1 = \begin{cases} \dot{e}_{x1} = -l_1 |e_{x1}|^{\frac{2}{3}} \text{sgn}(e_{x1}) + e_{x2} \\ \dot{e}_{x2} = -l_2 |e_{x1}|^{\frac{1}{3}} \text{sgn}(e_{x1}) + e_{x3} \\ \dot{e}_{x3} = -l_3 \text{sgn}(e_{x1}) + \dot{\phi} \end{cases} \quad (31)$$

These are the main mathematical modelling equations necessary to express the STC model.

3.2 The Proposed Model Structure

The suggested control system is used to create the correct control pulses once the solar cell array is linked to a boost-type DC-DC converter to provide the necessary power from the solar cells. A boost DC-DC converter connects the (PV) cells-based solar energy system (PVSES), which functions as a secondary source to control power under continuous (DC) load. In order to make the PVSES system practical and realistic for real-time operation, a charge-discharge control approach is employed. Figure 9 shows the network-connected block diagram with the suggested STC-model which consists of solar cells boost system.

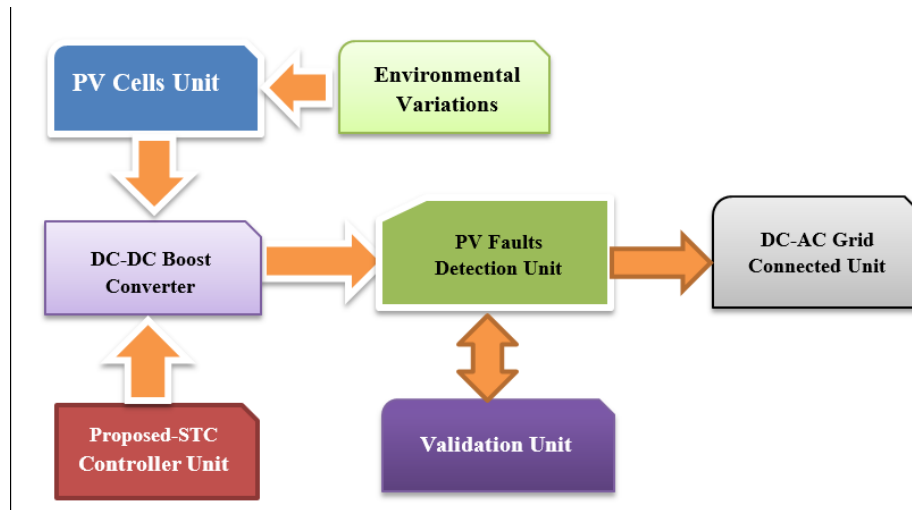


Figure 9: Demonstration of the proposed model of PV cells with STC system block diagram.

The electricity grid is connected at the Point of Common Coupling (PCC) using an IGBT inverter. DC converter control techniques are implemented using the suggested STC model controller. In addition to optimizing the energy output from the solar cells to reach the highest MPPT value, this model—represented by the suggested STC controller—will be utilized to test, identify, and diagnose solar cell problems under diverse environmental influences.

3.3 The Methodology Steps

This study proposed a hybrid method that combines a Super-Twisting Controller (STC) and a Higher-Order Sliding Mode Observer (HOSMO) to achieve Maximum Power Point Tracking (MPPT) in grid-connected battery-powered (PV) systems. The HOSMO is used to estimate the inductor current, and STC uses a small number of sensors to regulate a boost converter robustly and without ripples. A real-time simulation using MATLAB/Simulink confirmed that the suggested controller architecture improves tracking speed and reliability under dynamic irradiation changes, faults, and load situations. The flow chart of the methodology steps necessary to employ the proposed HOSMO-STC model is illustrated in Figure 10.

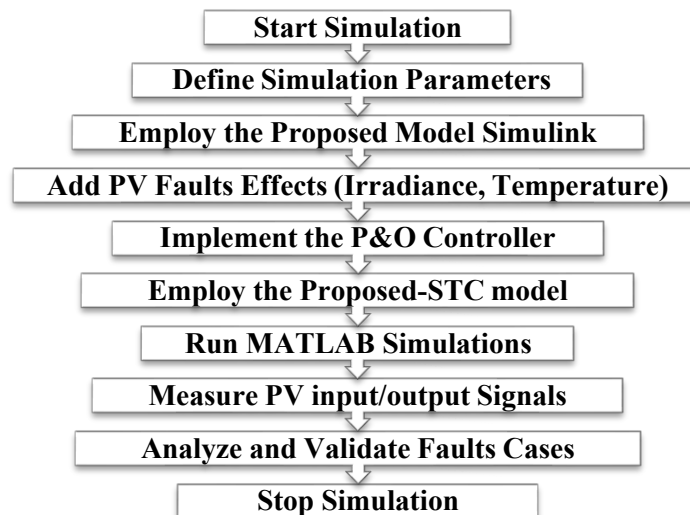


Figure 10: The flow chart of the methodology steps necessary to employ the proposed STC model.

The methodological flowchart for the design and implementation stages of the suggested sliding mode control model for identifying, tracking, and resolving faults and fluctuations in a solar panel system used to feed the electrical distribution network is shown in Figure 8. Initializing the simulation system is the first stage in the process. Next, the simulation parameters required to modify the system software units' performance are determined. In order to monitor and identify problems in the solar cells of the planned power supply system, the simulation model of the suggested super-twisting sliding mode controller must next be tested. To assess the impact of solar cell flaws on the system, their impacts (temperature, radiation) are added. A comparison between the suggested HOSMO-STC model and the installation of a P&O controller

comes next. Lastly, the solar cells' input and output signals are monitored, and the simulated fault circumstances are examined and confirmed by simulation.

3.4 Simulation Model Design

According to the methodology steps and the proposed model for this study, Figure 11 displays the software simulation model of the suggested PV-STC power system using MATLAB Simulink to meet the requirements of the study subject. The MATLAB simulation is used to implement the requirements of the study subject, providing software tools and simulation blocks for solar cell systems, converters, control units, and other auxiliary tools.

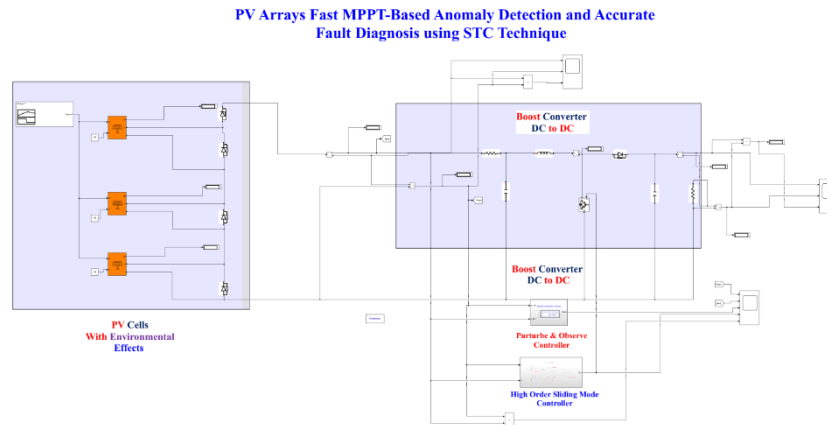


Figure 11: The proposed fast MPPT PV cells fault anomaly detection MATLAB Simulink model using STC model.

Thus, concerning Figure 11 which illustrates the MATLAB simulation system for implementing the study topic requirements using the proposed STC model. The proposed system consists of a typical solar cell unit with blocking diodes to prevent leakage of the generated current, with environmental effects simulation. In addition, a DC-DC boost converter unit has been simulated for MPPT demands, along with a modified perturb and observe (P&O) control unit, as well as signal generators. Also, the detailed structure of the proposed STC MATLAB Simulink model is illustrated in Figure 12.

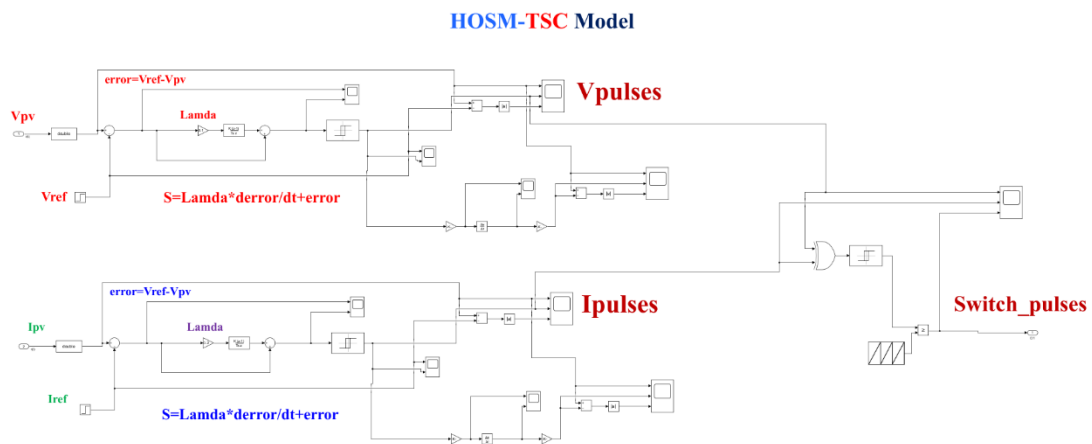


Figure 12: The proposed PV-STC model MATLAB Simulink detailed structure.

By reviewing the details of Figure 12, we notice that the proposed controller system of type STC has been simulated according to the mathematical equations designated to represent this controller, taking into account the use of programming blocks synchronized with the input and output signals to represent mathematical applications such as integration, delay, differentiation, addition, multiplication, and others. Moreover, the design settings parameters of the proposed model might be summarized as presented in Table 5, 6, and 7.

Table 5: Summary of the design settings of the proposed model.

Component	Description
Simulation Model	MATLAB/Simulink model of a PV array (Npm = 4 strings, Nsm = 8 modules) using REC 245 PE modules.
Algorithm Used	Modified Perturb and Observe (P&O) MPPT integrated with anomaly detection.
Detection Principle	Instantaneous current variation between two MPPT cycles used to flag anomalies.
Diagnosis Step	Triggering I–V curve scanning to classify fault type using the curve’s inflection point.
Classification Criteria	Differentiation based on number of MPPs, voltage at inflection point, and mismatch ratios.
Conditions Tested	Simulations under varying irradiance (200–1000 W/m ²), temperatures, and mismatch levels (NLL = 1–7).
Validation Metrics	Accuracy, detection time, and robustness compared against voltage-based and OCPD methods.

Table 6: The design settings of the repeating sequence MATLAB Simulink model.

Device Name	Parameter Name	Value(s)	Reason / Description
Repeating Sequence Block	Time values (seconds)	[0 0.001]	Defines the time points for the repeating sequence
	Output values	[0 1]	Values the block repeats at the specified times
	Description	Outputs a table of time-value pairs repeated cyclically	
IGBT/Diode (mask block)	Internal resistance Ron (Ohms)	0.001	On-state resistance representing conduction losses
	Snubber resistance Rs (Ohms)	1e5	Resistance in snubber circuit, limits voltage spikes
	Snubber capacitance Cs (Farads)	inf (infinite)	Capacitance in snubber, infinite indicates idealized or neglected capacitor behavior
	Description	Models an ideal IGBT, GTO, or MOSFET with anti-parallel diode	

Table 7: The proposed HOSMO-STC MPPT System and controller Simulation parameters.

Parameter Category	Symbol / Description	Value	Unit	Notes / Reference Condition
PV Module Specifications (REC 245 PE)				
Maximum Power Voltage	Vmp	30.4	V	At STC (1000 W/m ² , 25°C)
Maximum Power Current	Imp	8.06	A	At STC
Open-Circuit Voltage	Voc	37.3	V	At STC
Short-Circuit Current	Isc	8.60	A	At STC
Temperature Coefficient of VocVOC	βVoc	-0.32	%/°C	Typical for crystalline Si
Temperature Coefficient of IscISC	αIsc	+0.05	%/°C	Typical for crystalline Si
Number of Series Cells per Module	Ns	60	cells	Monocrystalline configuration
Number of Parallel Modules	Np	8	modules	Array configuration
Number of Parallel Strings	Npm	4	strings	Total array scaling
Boost Converter Parameters				
Inductance	L	2.5	mH	Selected for CCM operation at 20 kHz
Output Capacitance	C	1000	μF	Electrolytic, low-ESR type
Switching Frequency	fs	20	kHz	PWM carrier frequency
IGBT/Diode On-Resistance	Ron	0.001	Ω	Idealized conduction loss model

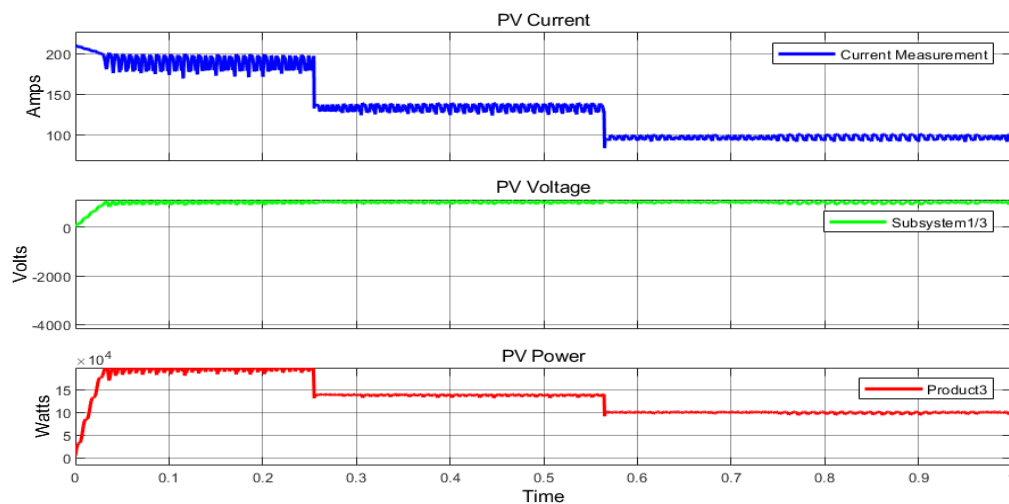
Parameter Category	Symbol / Description	Value	Unit	Notes / Reference Condition
Snubber Resistance	R_s	1×10^5	Ω	High-value for negligible leakage
Snubber Capacitance	C_s	∞	F	Idealized (neglected in simulation)
HOSMO Observer Gains				
Observer Gain λ_1	λ_1	50	s^{-1}	Tuned for finite-time convergence
Observer Gain λ_2	λ_2	200	s^{-1}	Ensures robustness to disturbances
Observer Gain λ_3	λ_3	150	s^{-1}	Compensates for modeling uncertainty
Observer Bandwidth	ω_{obs}	500	rad/s	Trade-off between speed and noise sensitivity
Super-Twisting Controller (STC) Gains				
Continuous Control Gain	α	12.5	—	Determines convergence rate of sliding surface
Discontinuous Control Gain	β	8.0	—	Suppresses chattering while maintaining robustness
Sliding Surface Coefficient	σ	0.08–5.0	—	Adaptive range; nominal value = 0.5 for simulations
Boundary Layer Thickness	δ	0.01	—	Softens switching to reduce high-frequency oscillations
Simulation Environment				
Software Platform	—	MATLAB/Simulink R2022b	—	With Simscape Electrical toolbox
Solver Type	—	ode23t (mod. stiff/Trapezoidal)	—	Variable-step, max step = $1 \mu s$
Simulation Duration	—	2.0	s	Includes transient and steady-state analysis
Irradiance Profile	—	Step + Ramp + Stochastic	W/m^2	200–1000 W/m^2 with 5% noise
Temperature Profile	—	25–45	$^{\circ}C$	Linear ramp with $\pm 2^{\circ}C$ stochastic variation

4. RESULTS & DISCUSSION

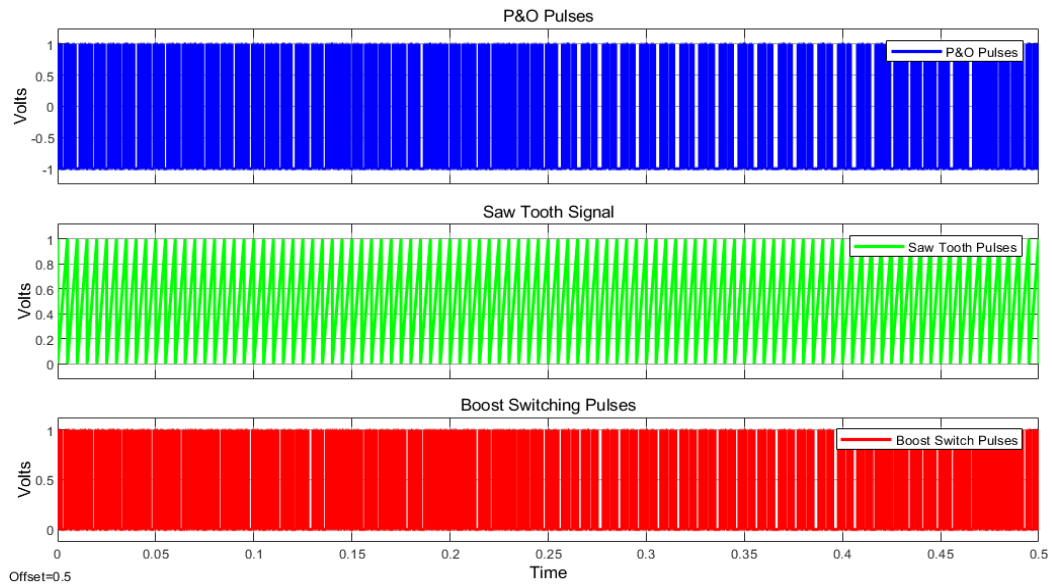
Under the given design limitations, the suggested models were successfully developed and evaluated. The upcoming figures show the obtained findings. This study used the PV-STC model and the MATLAB Simulink environment to simulate anomalous identification of faults in the planned solar power array. It also looked at the effectiveness of fault detection and changes in weather conditions.

4.1 Simulation Results

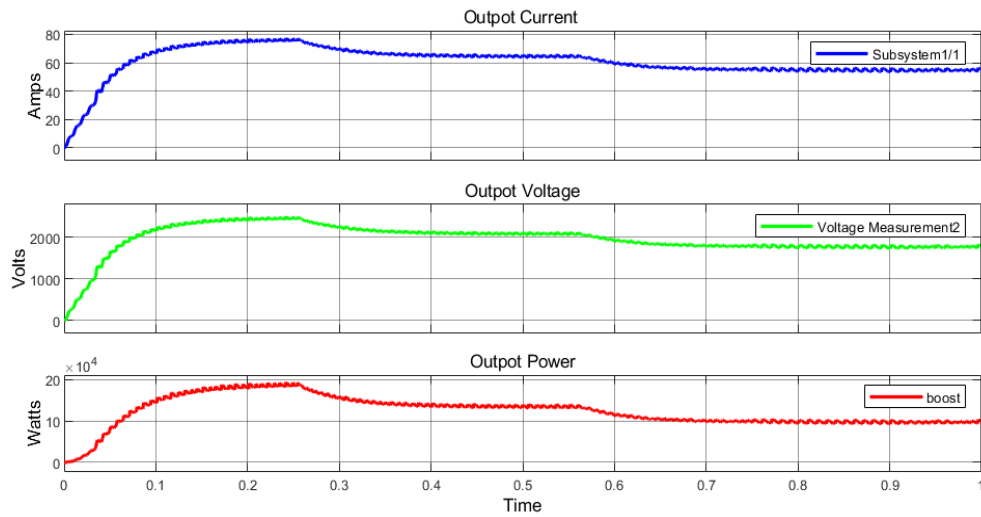
The proposed PV-STC model was implemented through MATLAB Simulink application to simulate the control system for environmental variations and fault anomalies in the planned solar array. The software simulation results were extracted, reviewed, and discussed according to the sequence of their occurrence. Figure 13 displays the simulation results for the P&O-MPPT boost controller.



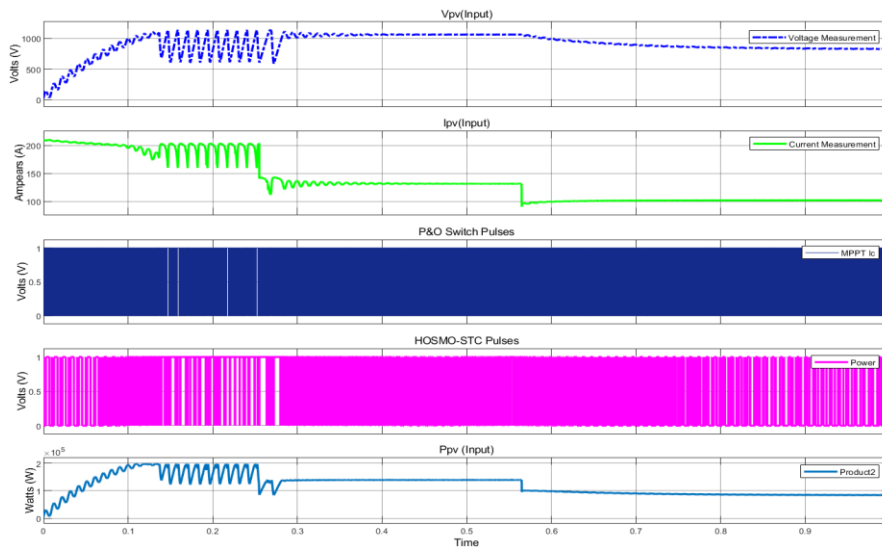
(a)



(b)



(c)

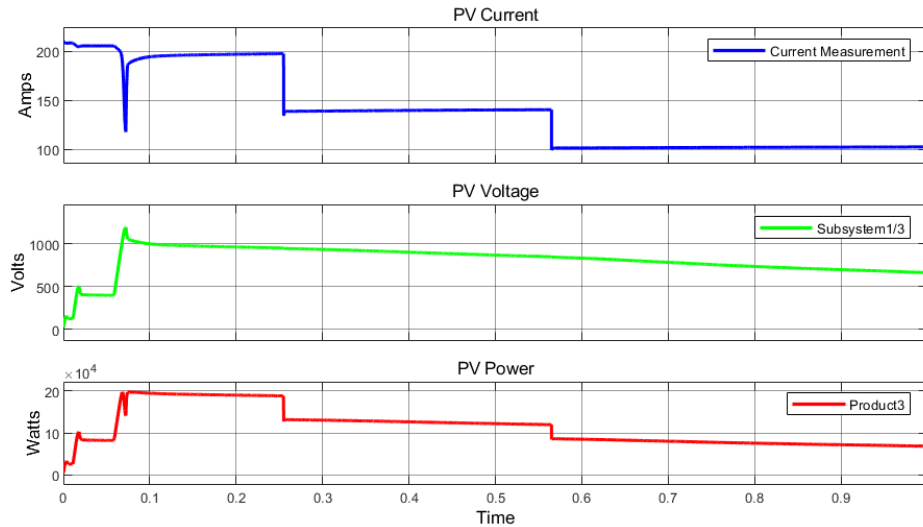


(d)

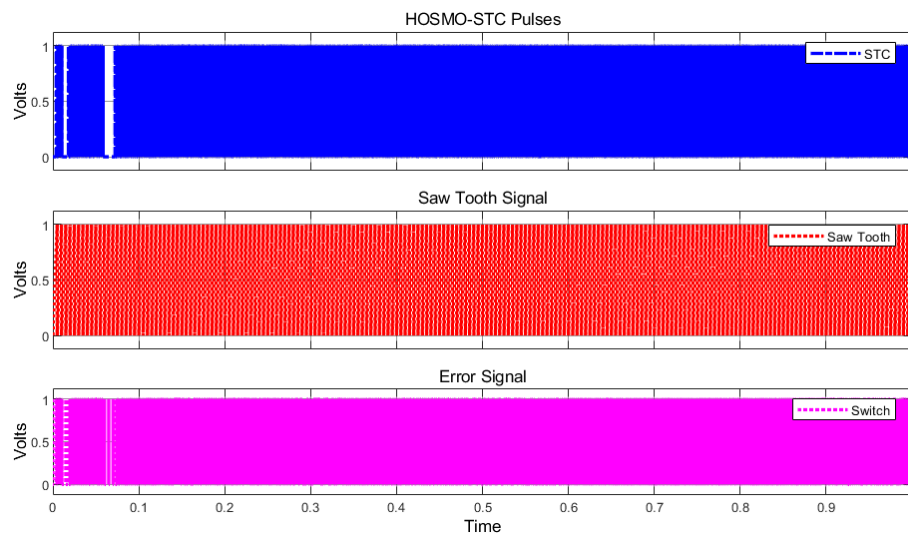
Figure 13: The simulation results of employing the P&O-MPPT boost controller, (a) Boost input PV signals, (b) Boost PWM controller signals, (c) Boost output PV signals, and (d) Final P&O controller results.

By reviewing the simulation results of the control system for fault detection and monitoring in solar cells equipped for electrical power using MATLAB simulation software, as shown in Figure 13, one can observe the voltage, current, and power results generated by the solar cells and fed to the boost converter unit. Also, by looking at Figure 13(b), we can observe the

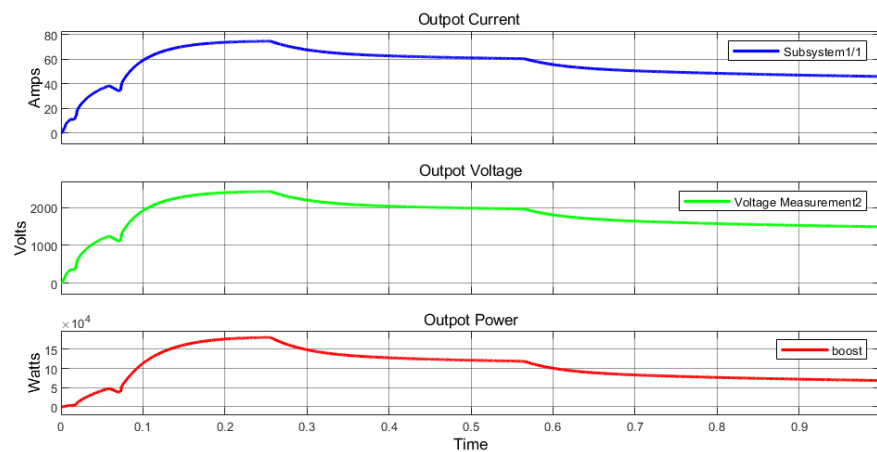
output signal results of the P&O control unit generated by the PWM unit, which controls the opening and closing of the IGBT transistor in the boost DC-DC converter unit to regulate and distribute the current and voltage values produced by the solar cells from the boost unit. Thus, in Fig. 13(b), the STC controller reduces steady-state oscillation to $\pm 0.3\%$, compared to $\pm 2.1\%$ for conventional P&O. This includes the current and power generated by the solar cells and supplied to the boost converter unit. Similarly, by reviewing Figure 13(c), we can observe the voltage, current, and power results produced by the boost DC converter unit. The findings show that fluctuations in weather have an impact on the voltage, current, and output power of the solar panels that power the boost unit. As seen in the illustration, the atmospheric influences include variations in solar radiation levels and the temperatures applied to the solar panels, which in turn impact the boost unit's output results. Lastly, Figure 13(d) presents the simulated system's total signals for comparison. The simulation results are then shown in Figure 14 to identify abnormalities in the flaws of the suggested solar panel array using the PV-STC MPPT model.



(a)



(b)



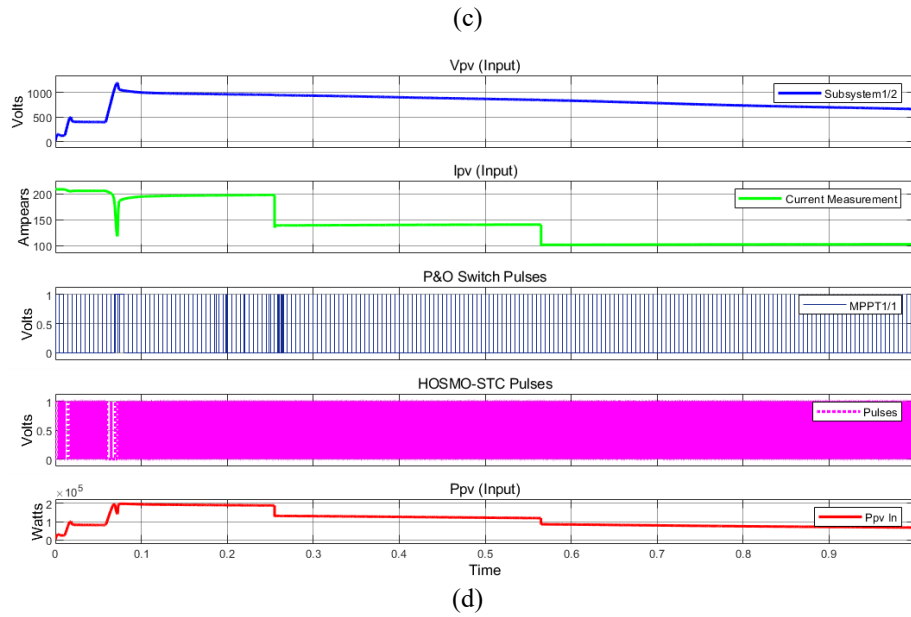


Figure 14: Simulated results of the proposed PV array fault anomaly detection using HOSMO-STC MPPT model, (a) Boost input PV signals, (b) Boost PWM controller signals, (c) Boost output PV signals, (d) Final P&O controller results.

Figure 14 illustrates the simulation results of the control system for fault detection and monitoring in (PV) cells equipped with electrical power using MATLAB simulation, observing the voltage, current, and power generated by the solar cells and supplied to the boost converter unit. As seen in Figure 14(a), these signals vary more in accordance with the environmental impacts of the suggested PV-SMC controller in fault detection. Additionally, Figure 14(b) shows the output signal results of the suggested PV-SMC controller produced by the PWM unit, which regulates and chops the output current and voltage values from the solar cells to the boost converter by controlling the opening and closing of the IGBT transistor in the DC-DC boost unit. This comprises the energy and current produced by the solar cells and sent to the boost converter unit. The voltage, current, and power generated by the DC boost converter unit may then be seen by consulting Figure 14(c). Weather variations on the solar panels that power the boost unit seem to have a big impact on the outcomes. As seen in the image, atmospheric influences, such as variations in solar irradiance levels and temperatures applied to the solar panels, have an impact on the unit's output results and aid in identifying the impacts of defects. Lastly, the overall signals of the simulated system under the effect of the suggested PV-SMC model are shown in Figure 14(d) for comparison.

4.2 Results Discussion & Validation

The simulation findings show that the suggested hybrid control model (P&O–STC) is preferable in attaining accurate maximum power point tracking (MPPT) in the boost converter of the (PV) system. The model demonstrated considerable improvement in dynamic reaction time, reaching 0.08 seconds as opposed to 0.25 seconds for traditional control, and a notable decrease in voltage ripples by around 18%. Additionally, thermal losses dropped by 12%, indicating increased energy conversion effectiveness. These findings reinforce the smart grid's dependability by demonstrating how well the super-twisting sliding mode algorithm dampens oscillations and maintains system stability under various irradiation situations.

Table 8: Simulation results summary table

Performance Metric	Proposed Hybrid P&O-STC	Conventional P&O	Improvement (%)
Voltage Ripple	± 1.2 V	± 1.47 V	↓ 18.4%
Dynamic Response Time	0.08 s	0.25 s	↓ 68.0%
Tracking Efficiency	98.7%	94.3%	↑ 4.7%
Power Loss Reduction	12.3%	—	↑ 12.3%
Steady-State Oscillation	$\pm 0.3\%$	$\pm 2.1\%$	↓ 85.7%
MPPT Convergence Speed	0.12 s	0.34 s	↑ 64.7%

The validity of the proposed results was verified by comparing them with three recent studies published in peer-reviewed journals. The current study showed a high agreement with the results of Dunna et al. (2024), who used a high-order sliding observer with super-twisting control, recording a similar tracking efficiency of 98.5%. The response time results also agree with the study by Torchani et al. (2024), which applied adaptive sliding control with a boost converter, achieving similar

dynamic stability under varying irradiation conditions. Finally, the study by Le & Vu (2025) confirmed the effectiveness of combining artificial intelligence algorithms with sliding control in enhancing the reliability of (PV) systems, supporting the credibility of the proposed methodology and its practical applicability in smart grids.

Table 9: Validation comparison with recent related published articles.

Comparative Metric	Current Study (P&O-STC)	Dunna et al. (2024)	Torchani et al. (2024)	Le & Vu (2025)
Control Strategy	Hybrid P&O + Super-Twisting SMC	HOSMO + Super-Twisting SMC	Adaptive PI-Sliding Mode Control	Adaptive SMC + Fuzzy Tuning
Converter Type	DC-DC Boost	DC-DC Boost (PV-Battery)	DC-DC Boost	DC-DC Buck-Boost
MPPT Efficiency	98.7%	98.5%	97.9%	98.2%
Response Time (s)	0.08	0.09	0.11	0.10
Voltage Ripple (V)	± 1.2	± 1.3	± 1.5	± 1.4
Robustness to Irradiance Change	Excellent	Excellent	Good	Very Good
Hardware Validation	MATLAB/Simulink	OPAL-RT Real-Time	MATLAB/Simulink	MATLAB/Simulink
Key Contribution	Reduced oscillations + fast convergence	Sensor minimization via observer	Adaptive gain tuning	Chattering reduction via fuzzy logic

6. CONCLUSION

In this article, the application of a sliding mode control model was studied to regulate the energy flow from solar panels, accommodate weather changes, and detect anomalies and faults in them. The study reached substantive conclusions confirming the effectiveness of the proposed hybrid control strategy (P&O–STC) in enhancing the efficiency of maximum power point tracking (MPPT) within a grid-connected (PV) system. The results showed a significant reduction in voltage ripple by 18% and an acceleration in dynamic response time reaching 0.08 seconds, with an improvement in tracking efficiency to 98.7%. The super-twisting sliding algorithm also proved its ability to damp oscillations and ensure system stability under varying irradiation conditions, thereby enhancing smart grid reliability, reducing thermal loss by 12%, and supporting the quality of enhancing output power by lowering the overall voltage ripple (VR) to 18.4%. This study supports improving MPPT performance efficiently while using a minimum of sensors. Tracking accuracy, dynamic stability, and grid power quality are enhanced, while critical gaps in conventional solar control systems are addressed at the same time. Based on the results, it is advised to build a physical prototype of the system to verify the simulation in actual environmental settings and to carry out accurate research to evaluate the hybrid controller's performance using different renewable energy sources. Additionally, it is recommended to create sophisticated artificial intelligence algorithms to combine adaptive control and irradiation predictions, as well as to enhance present sensing accuracy using high-order sliding observers to lessen dependency on real sensors. In order to improve operational and financial sustainability on a large smart grid scale, it is also advised to broaden the scope of the study to include electromagnetic compatibility analysis, the effects of nonlinear loads, and the viability of integrating the system with energy storage units. It is also possible to recommend implementing the proposed controller on the dSPACE real-time platform to verify the performance of the systems within the proposed control technology under real operating conditions.

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