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Moth flame optimization based super twisting sliding mode MPPT controller for grid connected PV system

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ABSTRACT

Maximizing energy extraction while maintaining the stability of solar photovoltaic (PV) systems requires an effective and robust control strategy. This study proposes a novel control approach by integrating a super twisting sliding mode controller (STSMC) with the moth-flame optimization (MFO) algorithm to enhance battery energy management, power quality, and maximum power point tracking (MPPT) in grid-connected PV systems. The proposed MFO-STSMC controller combines the robustness of sliding mode control with the adaptive optimization capabilities of MFO, resulting in improved MPPT accuracy, reduced oscillations, and enhanced resilience to environmental disturbances and nonlinearities. Simulation results validate that the proposed method significantly outperforms conventional MFO-PI controllers, achieving accurate MPPT tracking under varying irradiance and temperature conditions, and ensuring stable operation. Moreover, the total harmonic distortion (THD) is reduced to 0.17% with MFO-STSMC, compared to 0.72% with MFO-PI, highlighting substantial improvement in power quality. The system is modeled and validated using MATLAB/Simulink, confirming the effectiveness of the proposed strategy in enhancing energy efficiency and grid stability.

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1. INTRODUCTION

In recent years, enhancing the reliability and efficiency of grid-connected photovoltaic (PV) systems has been a major focus of research, especially under rapidly changing environmental conditions. While Super-twisting sliding mode control (ST-SMC) has shown strong potential for reducing chattering and improving transient response, and metaheuristic algorithms like moth-flame optimization (MFO) have proven effective for maximum power point tracking (MPPT) under partial shading, most existing works treat these solutions separately. This paper addresses the critical gap in integrating nonlinear control with intelligent optimization by proposing a hybrid MPPT controller that combines ST-SMC with MFO. The proposed method leverages the robustness of ST-SMC and the adaptive tuning capability of MFO to achieve faster convergence, better disturbance rejection, and enhanced power quality in grid-connected PV systems. Unlike prior studies, this work presents a unified control framework that dynamically adjusts controller parameters in real-time for improved performance.

Simulation results confirm that the hybrid approach outperforms conventional controllers by achieving higher tracking efficiency, lower total harmonic distortion (THD), and better power regulation under varying irradiance and grid conditions. Sami *et al*. [1] and Mohapatra *et al*. [2] proposed ST-SMC techniques for grid-connected PV systems, demonstrating superior stability and disturbance rejection. Similarly, Dunna *et al*. [3] and Dardouri *et al*. [4] developed super-twisting-based MPPT controllers that enhance power tracking and efficiency under varying environmental conditions. Further refinements in ST-SMC strategies were made by [5]-[7], who implemented ST-SMC in multifunctional PV inverters, achieving improved transient response and robustness. In addition, the study in [8], [9] investigated optimally tuned ST-SMC controllers for active and reactive power regulation in grid-connected PV systems, ensuring enhanced power quality.

Simultaneously, optimization-based MPPT techniques, particularly MFO, have gained significant attention due to their capability to handle nonlinearities and partial shading conditions. The study in [10], [11] introduced hybrid MPPT controllers integrating MFO with chaos quantum particle swarm optimization and other bio-inspired techniques, improving tracking efficiency and convergence speed. The study in [12], [13] further explored MFO-based MPPT schemes for optimal power flow and power dispatching, ensuring minimal power loss. The effectiveness of MFO in renewable energy applications was also demonstrated by [14], [15], who applied modified MFO algorithms incorporating chaotic maps and Gaussian mutation to optimize grid power management. Moreover, Hussien *et al*. [16] extended the application of MFO to wind energy conversion systems, validating its performance in different renewable energy scenarios. The combination of ST-SMC with metaheuristic optimization algorithms has been another area of focus.

The study in [17], [18] explored hybrid control strategies incorporating genetic algorithms and particle swarm optimization into ST-SMC-based MPPT controllers, enhancing the convergence rate and steady-state accuracy of PV power tracking. Similarly, Ahmed [19] integrated artificial neural networks with ST-SMC-based nonlinear MPPT controllers, significantly improving the adaptability of PV systems to rapid irradiance changes. The study in [20], [21] designed advanced ST-SMC controllers incorporating differential flatness-oriented observer techniques and improved sliding mode control, leading to better fault tolerance and disturbance rejection. Furthermore, recent studies have focused on real-time energy management and grid interaction of PV-battery hybrid systems. The study in [20], [21] designed [22] investigated economical operation modeling and super-twisting MPPT control for grid-connected PV/battery systems, demonstrating efficient energy utilization and cost optimization. Additionally, Carmona *et al*. [23] and Kantas *et al*. [24] proposed novel sliding mode-based MPPT strategies that ensure high-speed convergence and maximum power extraction under dynamic conditions. Overall, the integration of ST-SMC and MFO-based MPPT techniques has significantly improved the reliability and efficiency of PV systems. The literature demonstrates that hybrid control approaches, combining nonlinear control with intelligent optimization algorithms, offer promising solutions for addressing the challenges of grid integration, power stability, and energy management in modern renewable energy systems.

2. METHOD

On-grid 100 kW PV systems utilize multiple commercial PV modules, as illustrated in Figure 1. The proposed system comprises a grid-connected solar PV system integrated with a battery energy storage system (BESS) and an advanced control scheme to enhance power quality, stability, and energy efficiency. The PV array generates DC power, which is processed through a DC-DC boost converter controlled by a MFO-based MPPT algorithm. A super-twisting based controller (STBC) further refines the nonlinear MPPT control for rapid convergence and robustness under dynamic environmental conditions. The regulated DC power is fed into a three-phase voltage source converter (VSC), which injects controlled AC power into the grid via an LCL filter to reduce switching harmonics. The BESS is connected to the DC-link through a bidirectional converter and managed using a super twisting sliding mode controller (STSMC), which ensures stable battery charging and discharging while maintaining current balance. The entire system is coordinated to ensure optimal energy flow, improved dynamic response, and significantly reduced THD, thereby ensuring effective operation in grid-connected conditions while supporting load variations and renewable intermittency.

2.1. Design and implementation of super twisting sliding mode controller

In SMC, the system states are guided toward the sliding surface (SS). A graphical representation of SMC is shown in Figure 2. Once the states reach the SS, SMC ensures they remain within its close vicinity. The design of SMC comprises two key components: the SS and the control law. The SS form is given by (1).

$$\sigma = e^k + \sum_{i=0}^{k-1} C_i e^i \tag{1}$$

Where $k = r - 1$, with r representing the relative degree between u and y. The constant C_i can be chosen as any positive value. The parameter σ must be selected such that the differential equation remains stable when σ=0. For various values of k, the corresponding state-space (SS) representations are given by (2).

$$K = 1\ \sigma = \dot{e} + \lambda e \tag{2}$$
$$K = 1\ \sigma = \ddot{e} + 2\lambda\dot{e} + \lambda^2 e$$

The development of SMC involves a two-step process. To achieve the desired performance in a DC-DC converter, a sliding surface must first be designed for the system to operate on. The next step is to formulate a control law that ensures the system remains confined to the sliding surface. The chosen sliding surface, $S(x,t)$, along with its initial derivative, must both be equal to zero given by (3).

$$S(x,t) = 0, \dot{S}\,(x,t) = 0 \tag{3}$$

We can optimize system performance by guiding the trajectories toward and maintaining them on the sliding surface. To accomplish this, we utilize the sliding surface (4).

$$S(x,t) = \frac{\partial P_{PV}}{\partial V_{PV}} = V_{PV}\left(\frac{\partial P_{PV}}{\partial V_{PV}} + \frac{I_{PV}}{V_{PV}}\right) = 0 \tag{4}$$

2.2. Moth-flame optimizer

Mirjalili *et al.* [25] developed a meta-heuristic optimization algorithm called MFO. The principle of MFO originates from the way moths use transverse orientation for navigation, which enables them to navigate in darkness. These insects maintain a constant angle of flight relative to the moonlight's position, guiding their movement. When the light source, or "flames," is distant, moths will travel in a straight line. In the presence of closed, non-uniform flames or lights, moths follow a specific path to navigate and exploit the global minimum solutions. The MFO flowchart can be given in Figure 3.

MFO is classified as a population-based optimization technique that defines an "M" matrix representing moths, where "n" denotes the number of moths [1, ..., n] and "d" represents the search-space dimension [1, ..., d]. The objective functions of the moths, denoted as "OM," are arranged in an OM matrix [1, ..., n], which helps generate optimal solutions. Similarly, the flames "F" are evaluated in the same manner. The MFO technique follows a step-by-step process involving an initialization function "I," three approximation functions, a population function "P," and a termination criterion "T."

The "I" function initializes a random population of moths by generating "rand" values for their corresponding objective functions while considering the upper ("ub") and lower ("lb") limits. These functions can be represented as follows given in (5).

$$M(i,j) = \big(ub(i) - lb(i)\big)\, rand(n,d) + lb(i) \tag{5}$$
OM = fitness function (M)

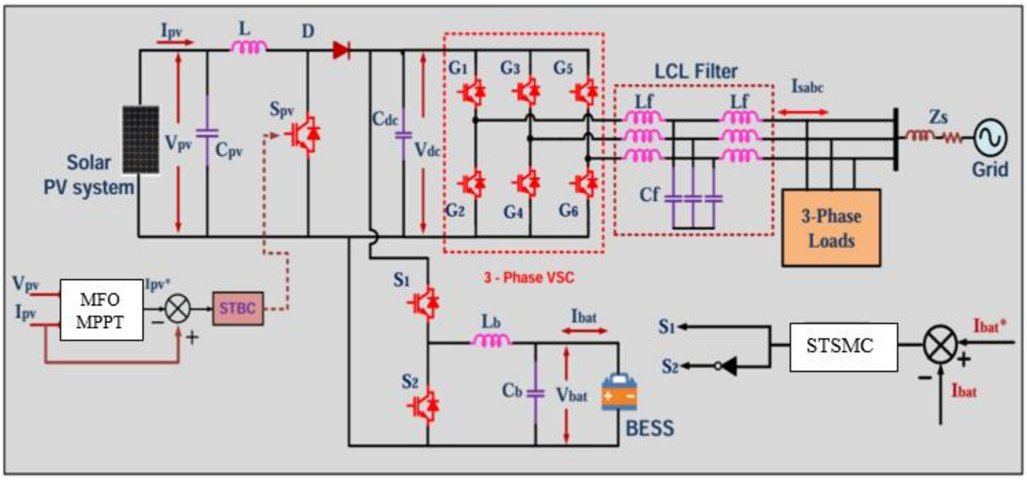

Figure 1. Block diagram of STSMC

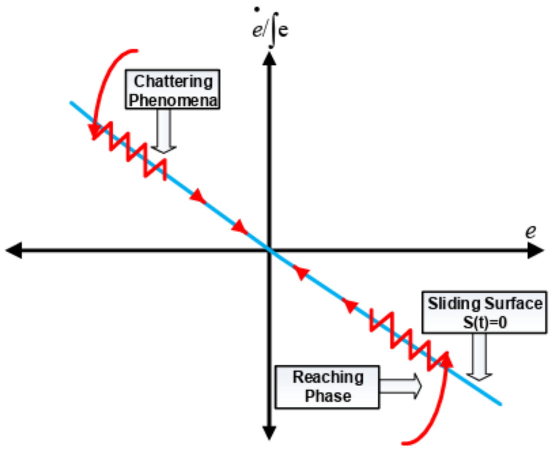

Figure 2. Graphical representation of SMC

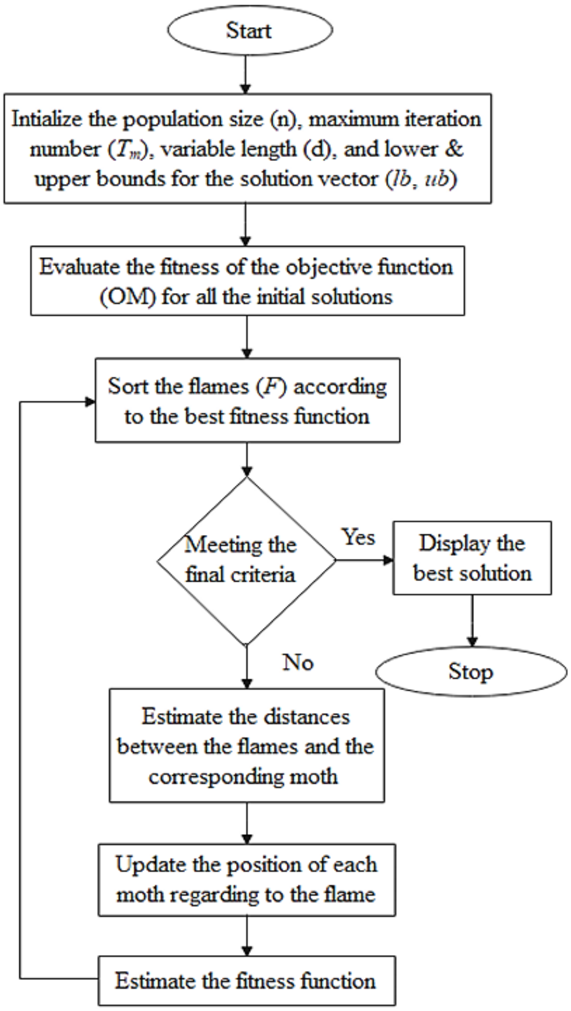

Figure 3. The evaluation process of MFO

Hence, the ‘P’ function begins after the completion of ‘I’ and continues until the ‘T’ criteria are met. It guides the moths throughout the search space. The logarithmic spiral function serves as the primary updating mechanism for each moth’s position relative to the flame. The location of the flame is updated using the following expression given in (6).

$$M_i = H(M_{i,}F_j) \quad (6)$$

The MFO optimizer utilizes the following expression to define the logarithmic helix given in (7).

$$H(M_{i,}F_j) = DI_i.e^{bt}.cos2\pi t + F_j \quad (7)$$

In this regard, M_i represents the "i-th month," while F_j denotes the "j-th flame." The function H represents the helix function. DI_i defines the distance between the "i-th moth" and the "j-th flame." The parameters ‘b’ and ‘t’ are defined as a constant and a random value, respectively, given by (8). Therefore, DI_i can be determined by (8).

$$DI_i = |F_j - M_i| \quad (8)$$

Exploration takes place when the moth’s next position is calculated at the outer limit of the region separating it from the flame. In contrast, exploitation happens when the next position is selected within that region. In (9) shows that the number of flames F_{no} is reduced progressively as the iterations proceed, helping maintain a proper balance between exploration and exploitation. Consequently, toward the final iterations, the moths adjust their positions with respect to the best-performing flame.

$$F_{no} = round\left(N_f - t_i * \frac{N_f - 1}{T_m}\right) \quad (9)$$

Where N_f is the flame's maximum number at the iteration ‘t_i’ and T_m is the maximum iteration number. As mentioned earlier, the “P” function is carried out after the completion of the “T” function. At this stage, the best-performing moth is identified, which serves as the closest estimate of the optimal solution. In this work, the duty cycle (D) of the DC–DC converter is treated as the decision variable, and its values correspond to the positions of the moths.

3. RESULTS AND DISCUSSION

The simulation results in Figures 4 and 5 demonstrate that distortions are more pronounced when using a PI controller compared to a sliding mode controller with STSMC. The PI controller, while simple and widely used, struggles to handle nonlinearities and rapid dynamic changes effectively, leading to higher harmonic distortions, overshoots, and oscillations in the output. This is primarily due to its fixed gains, which lack the adaptability required for varying system conditions.

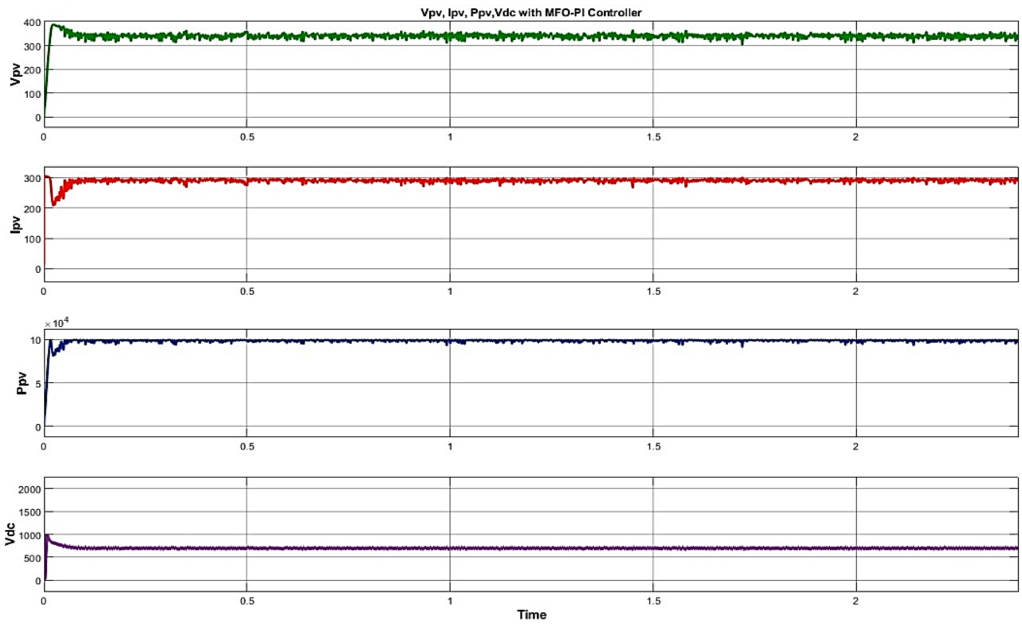

Figure 4. Vpv, Ipv, Ppv, Vdc using MFO-PI controller

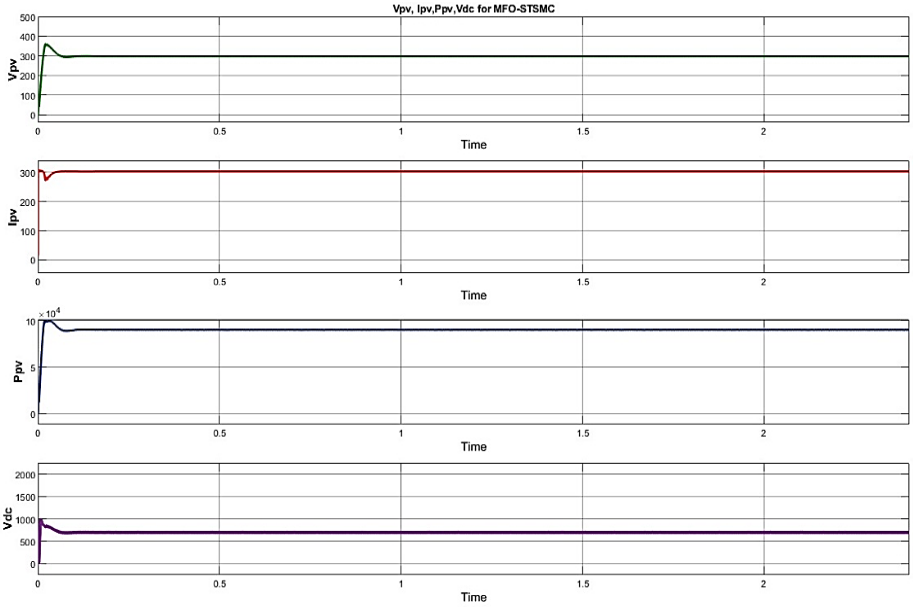

Figure 5. Vpv, Ipv, Ppv, Vdc using MFO-STSMC controller

In contrast, the STSMC excels in reducing distortions by leveraging its robustness against disturbances and parameter variations. Its ability to manage nonlinearities and external disturbances more effectively results in smoother and more stable control, as evidenced by the lower distortion levels in the simulation output. Figure 6 illustrates the THD of the grid current for both the MFO-STSMC and MFO-PI controllers.

(a)

(b)

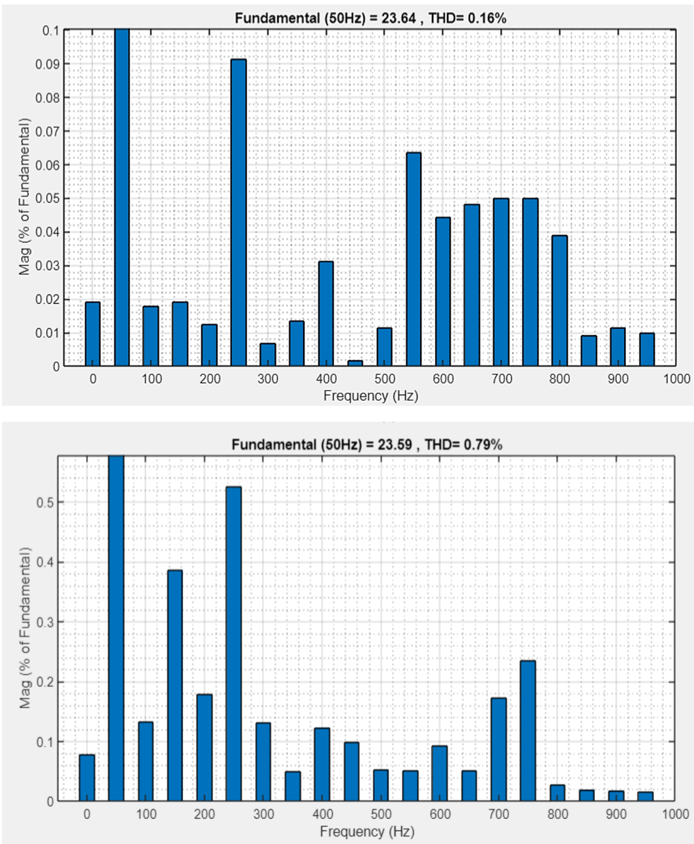

Figure 6. THD of grid current with (a) MFO-STMC and (b) MFO-PI

4. CONCLUSION

This study introduced an advanced control strategy combining the STSMC with MFO for grid-connected solar PV systems with integrated battery energy storage. The proposed MFO-STSMC approach outperforms conventional MFO-PI controllers by ensuring rapid and accurate MPPT under dynamic environmental conditions, while simultaneously improving power quality and battery management. Simulation results confirm superior transient performance, reduced oscillations, and enhanced grid current quality. Most notably, the THD is drastically reduced to 0.16%, compared to 0.79% in conventional MFO-PI systems, demonstrating a 79.7% improvement in harmonic reduction. This significant reduction directly correlates to improved power quality and system stability. Additionally, the proposed method exhibits robust resilience against environmental disturbances and nonlinearities, ensuring stable and efficient operation across varying conditions. These results validate the effectiveness and applicability of the MFO-STSMC controller for modern smart grid and renewable energy systems.

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AUTHOR CONTRIBUTIONS STATEMENT

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Gouthami Eragamreddy		✓				✓		✓	✓	✓	✓	✓		
N. Malla Reddy	✓		✓	✓			✓			✓	✓		✓	✓
Remala Geshma Kumari		✓				✓			✓					
Veeranjaneyulu Gopu	✓				✓		✓			✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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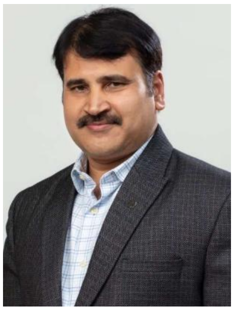

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