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Cryptography algorithms for enhancing security in IoT based Mafly-MPPT system under partial shading conditions

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Abstract

In the realm of renewable energy, the integration of Internet of Things (IoT) technologies with Maximum Power Point Tracking (MPPT) systems has gained significant attention for optimizing photovoltaic (PV) performance, especially under partial shading conditions. However, the increased interconnectivity also introduces substantial cybersecurity risks. This paper presents a comprehensive study on the implementation of advanced cryptography algorithms to enhance the security framework of IoT-enabled Mafly-MPPT systems. By safeguarding data integrity and ensuring secure communication between system components, the proposed cryptographic solutions mitigate potential threats and vulnerabilities. Through extensive simulation and analysis, the study demonstrates the effectiveness of the algorithms in maintaining system efficiency and resilience in dynamic environmental conditions, highlighting the critical role of robust security measures in the future of renewable energy systems.

Subject Classification: *18M35, 32U35.*

Keywords: *Cryptography, IoT, MPPT, Partial Shading, Mayfly algorithm, PV.*

1. Introduction

The integration of IoT technologies in renewable energy systems, particularly in photovoltaic (PV) systems, has become essential for optimizing power generation under variable conditions such as partial shading. One of the most efficient strategies for enhancing energy output in such systems is the Maximum Peak Point technique (MPPT). However, the dynamic nature of solar radiation and the increasing demand for secure data exchange within IoT-based systems pose significant challenges. Ensuring secure communication between IoT devices while maintaining optimal system performance is crucial for the reliability of these systems. Cryptography methodology play a vital role in protecting the integrity and Secrecy of data within IoT-based MPPT systems, especially in harsh environmental conditions like partial shading. This paper focuses on implementing advanced cryptography algorithms to enhance the security framework of IoT-based Mafly-MPPT systems, mitigating risks while ensuring robust performance.

1.1 *Literature Review*

Several research initiatives have focused to improving the performance and security of PV-enabled water pumping systems and grid-connected PV systems under challenging conditions. Iqbal and Ali [1] proposed a novel control system for a PV-enabled water pumping setup, eliminating the need for energy storage while achieving significant operational efficiency. Furthermore, Bellamkonda et al. [2] developed a improvised Grey Wolf Optimization technique for PV water pump method using switched reluctance motors for various partial shading, showcasing improvements in system performance. Kumar et al. [3] and Rath et al. [4] evaluated the performance of grid-tied solar PV systems with DSTATCOM controllers to address dynamic load conditions and partial shading scenarios. These works highlight the importance of control strategies and system optimization for handling environmental variability. Additional studies in Pradhan et al. [5] focused on coordinated power management in standalone PV-hybrid systems using modified IWO-based MPPT techniques, while Pragathi, Poonia, and Nayak [6] and explored soft computing methods to address power quality issues in grid-connected PV systems. These methods enhanced the system's ability to mitigate challenges like voltage instability. Kumar et al. [7] contributed to the domain of secure data transmission by proposing quantum key distribution protocols for authentication, which are integral to ensuring the security of IoT-based systems. Finally, Pragathi, Nayak, and Poonia [8] investigated IoT-based MPPT techniques to improve the performance of Solar PV arrays affected by dispersed shading, emphasizing the role of IoT technologies in advancing renewable energy solutions. The literature underscores the necessity of advanced control mechanisms and secure communication protocols in IoT-enabled PV systems. By building upon these works, this paper proposes a novel cryptography-enhanced security framework for IoT-based Mafly-MPPT systems to address both efficiency and data protection challenges in the Occurrence of partial shading.

2. System Architecture

The system methodology of the proposed PV-enabled power generation section consists of several key components working together to interface with the utility grid. At the heart of the section is the PV array, which transforms solar energy into direct current (DC). The PV array incorporates blocking diodes to prevent reverse current flow and bypass diodes to safeguard against partial shading effects. The DC output from the PV array is then fed into a boost converter, which increases the voltage to a suitable level for grid connection. The boost converter utilizes an inductor, switch, diode, and capacitor to ensure smooth voltage regulation. Following the boost converter, a constant frequency Pulse Width Modulation (PWM) converter converts the DC voltage into alternating current (AC), which is required for interfacing with the utility grid. The PWM converter is equipped with transistors and controlled switching signals, and it features an LCL filter to suppress harmonics and ensure high-quality power delivery. The system is managed and controlled by a Real-Time Interface (RTI), which is linked to a computer equipped with a DSpace DS1104 card for real-time control and signal processing. This setup enables continuous monitoring of power flow and converter operations. The entire system is integrated to the utility grid through the AC output of the PWM converter. Parameters such as grid voltage and current are monitored to ensure proper synchronization with grid standards. The RTI, together with the DS1104 card, plays a vital role in controlling the switching operations and maintaining the efficiency of the power conversion process. This architecture ensures effective energy conversion from the PV array to the grid while maintaining high system efficiency and stability.

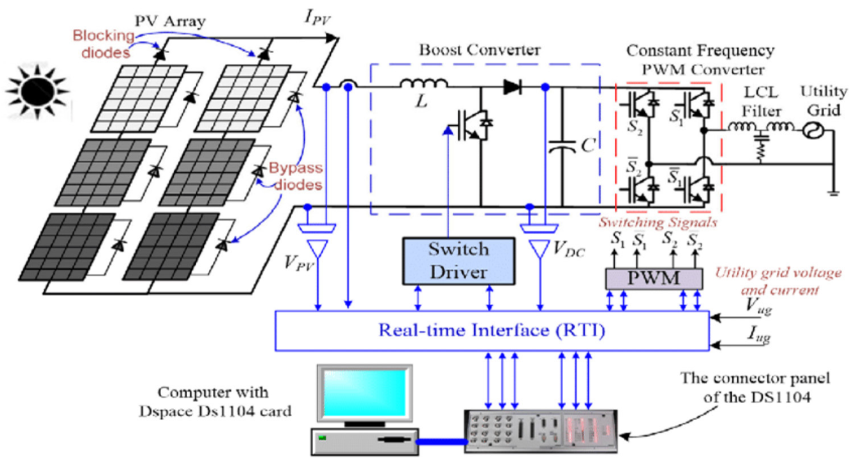

Figure 1

PV system MOPO-MPPT under PSCs with SMC

3. PV system features and modeling

The process of determining the rating of a PV system depends on the specific power needs of the user. In this case, to achieve a power output of 9.6 kW, 32 PV modules, each rated at 302 W, are considered. The PV array is designed to generate the required voltage by connecting 16 modules in series. To ensure sufficient current supply to the load, two of these arrays are connected in parallel. This configuration results in a total of 32 interconnected modules, which increases the likelihood of partial shading conditions (PSCs) occurring. The voltage at the Maximum Peak Point (MPP) for a conventional Perturb and Observe (P&O) algorithm can be calculated mathematically to optimize the power output under various shading scenarios.

$$V_{\max p}(in) = V_{\max p}(in-1) + \Delta V \times sign\left(\frac{dP_{pvv}}{dV_{pv}v}\right) \quad (1)$$

Table I outlines three partial shading condition (PSC) configurations, while Fig. 2 presents their corresponding P-V curves. During PSCs, multiple locally maximum peak points can occur, but only one is the true global maximum (GM). The conventional Perturb and Observe (P&O) method often gets stuck at local maximum points during convergence, failing to accurately locate the GM. To address this, a combination of the P&O technique with a more robust optimization technique is required for fast and efficient tracking of the GM. Several optimization algorithms have recently been proposed to enhance MPPT performance under PSCs. The authors in [9] introduced a genetic algorithm-based MPPT approach, while [10] applied both Particle Swarm Optimization (PSO) and Grey Wolf

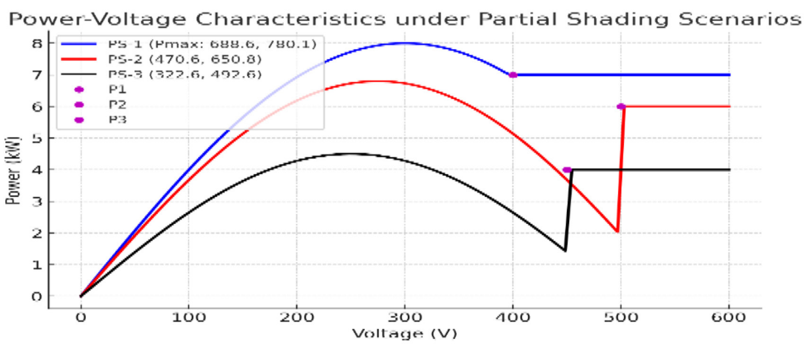

Figure 2

P-V for various PSCs

Optimization (GWO) to MPPT. However, compared to GWO, PSO, GA, and other algorithms, the Mayfly Optimization Algorithm (MOA) has demonstrated superior accuracy in tracking the GM. [6] Therefore, this study employs MOA in combination with P&O to effectively locate the GM under both normal and partial shading conditions.

4. MOA algorithm

Male adult mayflies attract females through a distinctive nuptial dance, which involves swarming up and down over the water's surface in a rhythmic pattern. This characteristic up-and-down motion, along with the rapid increase in population, provides inspiration for finding the global optimal point of a PV system's MPPT. In this context, the breeding process begins when the most optimal mayflies (male and female) are drawn to each other, mimicking the natural selection process. The eggs are then deposited in the water, initiating the next generation and promoting population growth. This biological behavior forms the foundation for the Mayfly Optimization Algorithm (MOA), a novel technique introduced by Zervoudakis and Tsafarakis to address complex multi-objective problems. The algorithm mirrors the natural dynamics of mayflies and is particularly useful for optimizing intricate systems. The following steps outline the process involved in the Mayfly algorithm.

Male Mayfly Motions*:*

The motion of male mayflies in the optimization algorithm is modeled to represent their search for optimal solutions within a solution space. Male mayflies are typically attracted towards the best-performing male and female mayflies in the swarm, simulating a natural behavior of competitive nuptial dance. Their movements are influenced by both exploration (seeking new potential solutions) and exploitation (moving towards known good solutions).

The velocity of a mayfly (male) is improved based on its current coordinates, the coordinates of the best-performing male mayfly, and its attraction to female mayflies. The velocity update equation can be expressed as follows:

$$vki(m)(t+1) = vki(m)(t) + a1 \cdot r1 \cdot (xki(best_m)(t) - xki(m)(t)) \\ + a2 \cdot r2 \cdot (xki(f)(t) - xki(m)(t))$$

Where

$v_{ki}^{m}(t+1)$ is the updated velocity of the k_{th} male mayfly in the j_{th} dimension at time period t+1,

$v_{ki}^{m}(t)$ is the current velocity of the male mayfly,

$x_{ki}^{(best\_m)}(t)$ is the coordinates of the best mayfly- male in the swarm at time t

$x_{ki}^{f}(t)$ is the coordinates of the attracted mayfly- female in the j_{th} dimension,

a_1 and a_2 are attraction coefficients representing the influence of the best male and female mayflies, respectively,

r_1 and r_2 are randomized value between [0, 1] introducing stochastic behavior.

This movement allows male mayflies to balance between local search around promising solutions (exploitation) and global exploration of new regions in the solution space, helping the algorithm avoid local optima. The interactions between male and female mayflies, as well as their stochastic movements, contribute to a diverse search process and ensure convergence toward optimal solutions.

The coordinates of the j_{th} component with the k_{th} mayfly is represented by x_i^j. This term can represent either x_{kj}^{m} the coordinates of the k_{th} mayfly-male in the j_{th} component or x_{kj}^{f} the coordinates of the k_{th} female mayfly in the j_{th} component. A stochastic path is typically provided to the algorithm by the best-performing mayflies executing the nuptial dance at a given time. The expression for this can be mathematically represented by the following equation:

$$v_{kij}^{t+1} = g \times v_{kij}^{t} + di \times r \tag{6}$$

The nuptial dance coefficient is denoted by di. The value of r is chosen randomly from the range [-1, 1]. The parameter di is progressively reduced as d=d0×(1−δ), where d0 represents the baseline value of the nuptial dance value, δ represents the iteration number in progress, and δr is a randomized number between [0, 1]. This reduction in di helps in fine-tuning the movement of mayflies as the iterations progress.

Female mayflies motions: The way that female flies are positioned in relation to males for breeding can be shown by

$$z_{in}^{t+1} = z_{in}^{t} + u_{in}^{t+1} \tag{7}$$

The z_{in}^{t} is the female element coordinates at time 't_n' and upgraded across velocity v_{in}^{t+1}

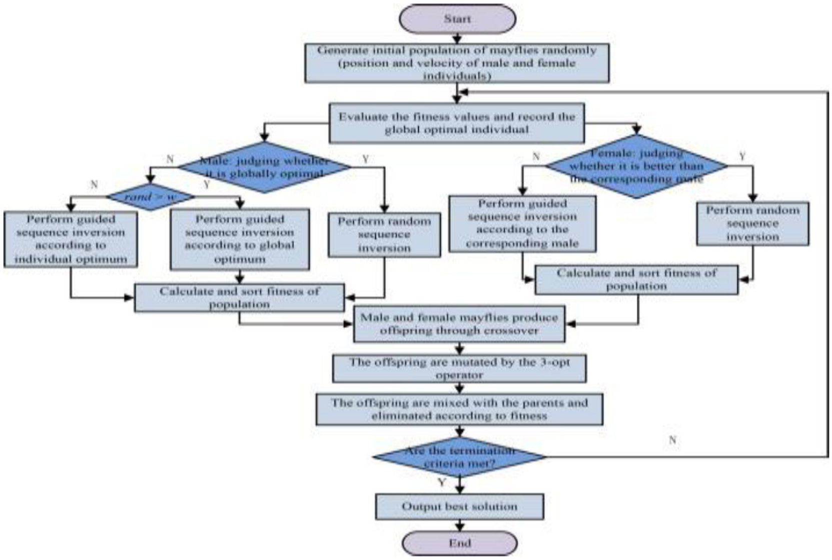

Figure 3

Flowchart for MOPO

To update a female's velocity, apply the following equation.

$$u_{kij}^{t+1} = \begin{cases} \text{if } fitns(z_{ik}) > fitns(x_{ik}) \\ g \times u_{kij}^{t} + a_{22} \times e^{-\beta r_{mf}^{2}} \times (x_{kij}^{t} - z_{kij}^{t}) \\ \text{else if } fitns(z_{ik}) \le fitns(x_{ik}) \\ g \times u_{kij}^{t} + fl \times r \end{cases} \tag{8}$$

Here, $v_{ki}^{f}(t)$ represents the velocity of the k_{th} mayfly's- female j_{th} element at time period t, $x_{ki}^{m}$is the position of the k_{th} mayfly's- male j_{th} element, and $x_{ki}(f)$ denotes the position of the k_{th} mayfly's- female j_{th} element in the i_{th} dimension at time period t_i.

$$\text{offspring value } 1 = (1 - r_{oif}) \times \text{female value} + r_{oif} \times \text{male value} \tag{9}$$

$$\text{offspring value } 2 = r_{oif} \times \text{female value} + (1 - r_{oif}) \times \text{male value} \tag{10}$$

$$\text{offspring value}'_{in} = \text{offspring value}_{in} + k \tag{11}$$

$$V_{\max p}^{t+1} = V_{\max p}^{t} \pm \Delta V \times \times \text{offspring value}'_{in} \tag{12}$$

5. Cryptographic technique in IoT Security

The security of the Internet of Things (IoT) relies heavily on robust cyber security techniques to protect data during transmission. These techniques aim to safeguard the confidentiality, integrity, and availability (CIA) of information across networks. Cryptographic algorithms play a key role in securing IoT networks by ensuring data integrity through detecting any unauthorized alterations during transmission, providing authentication to restrict access to authorized users, and encrypting data to prevent unauthorized access. Cryptography, the practice of securing information through encryption, uses various methods to protect network communications. There are three main categories of cryptographic techniques: Symmetric algorithms, employing the same key for encryption and decryption, and asymmetric algorithms, involving a public-private key pair; and cryptographic protocols, which combine these methods to secure data transmissions effectively. Each approach strengthens the overall security framework of IoT networks.

6. Discussion and Results

This section outlines the setup of a real-time simulation (RTS) with Hardware-in-the-Loop (HIL) system used to determine the behavior of the proposed system. OPAL-RT technologies are employed for real-time simulation.

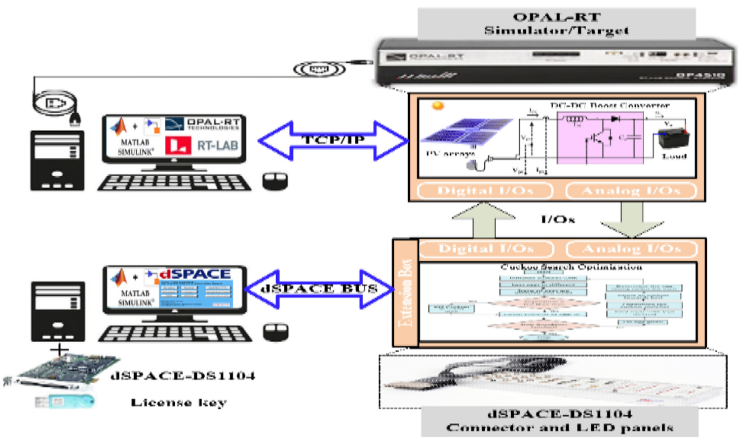

Figure 4

OPAL-RT sections in the HIL laboratory

The Hardware-in-the-Loop (HIL) system is implemented by combined with two OPAL-RT devices in a back-to-back configuration. The first unit (Unit-1), as represented in Figure 1, comprises a photovoltaic (PV) system, a converter, and a load. The second unit, depicted in Figures 3 and 4, incorporates the proposed control strategy, which manages the operation of the system. A generalized HIL configuration with OPAL-RT modules is illustrated in Figure 4, where data transfer between the two units is enabled via both digital and analog signals, allowing real-time dynamics of the system to be closely monitored and managed.

The proposed system's detailed block diagram elaborates on the interconnection and functional roles of the two OPAL-RT units. This configuration enables the precise simulation of real-world conditions in real-time, providing an accurate test environment for validating the control strategy. The behavior of the proposed controller is thoroughly evaluated by analyzing the results obtained from various case studies, which confirm its effectiveness in controlling the PV system and related components in a dynamic and real-time setting.

Case study-1: SMC's response regarding PI

To determine the performance of the PI and SMC controllers, the irradiance is reduced from 800 W/m^2 to 700 W/m^2 at $t = 4.0$ seconds. The behavior of the proposed control method is assessed using both controllers. The PI controller, with fixed gains optimized for 1000 W/m^2, performs well under these conditions. However, at 750 W/m^2, the same fixed gains fail to deliver satisfactory results. In contrast, the SMC (Sliding Mode Controller), which dynamically adjusts its gains, continues to perform effectively despite the changes in irradiance. The reference and actual power of the PV section using both the PI and SMC controllers are shown in Fig. 5. The use of SMC significantly improves MPPT performance compared to the PI controller, as demonstrated in Fig. 5. Additionally, oscillations at 750 W/m^2 cause greater voltage fluctuations at the dc-link when using the PI controller, due to its fixed gains. These oscillations can negatively impact the MPPT tracking performance of the PV system. As shown in the results, SMC provides superior performance under varying irradiance conditions.

Case study-2: Contrasting several optimization methods:

When operating under various partial shading conditions (PSCs), it is important to consider the response time required to trace the Maximum

Peak Point (MPP), or the global maximum (GM), to ensure maximum electrical energy is harvested from solar radiation. We compared the proposed hybrid MO-PO algorithm with other techniques such as traditional methods. A bar comparison of the MO-PO, traditional methods is demonstrated in Fig. 5(i). Similarly, Fig. 5(ii) shows the MPP tracking performance of the PV array. From Fig. 6, it is evident that the proposed hybrid MOPO algorithm outperforms the traditional methods, demonstrating superior efficiency in tracking the MPP under varying conditions.

Case study-3: Output voltage at the DC-link

To generate peak power during partial shading conditions (PSCs), it is essential to track the voltage equivalent to the global maximum power point. The power output generated by the PV system, as obtained using both traditional methods and the hybrid Multi-Objective Particle Optimization (MO-PO) algorithms, is illustrated in Fig. 6.

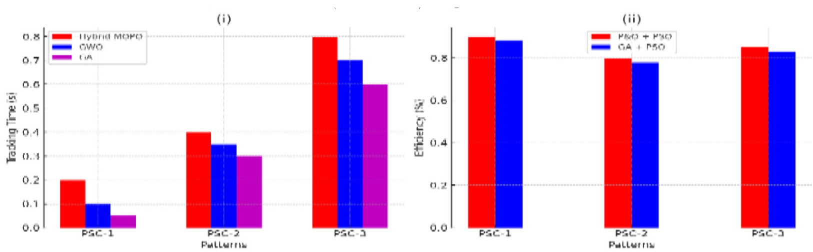

Figure 5

Chat presentation for MO-PO, GA, GWO, and PSO

The P_{SC}-1, exhibits constant radiation for time 3sec to 5sec, P_{SC}-2, for time 5sec to 7sec and P_{SC}-3 for time 7sec to 9sec.

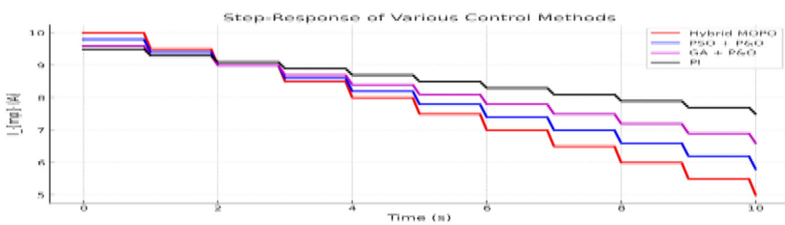

Figure 6

Various PSCs, power was harvested from the PV system using MO-PO, GA, PSO, and GWO.

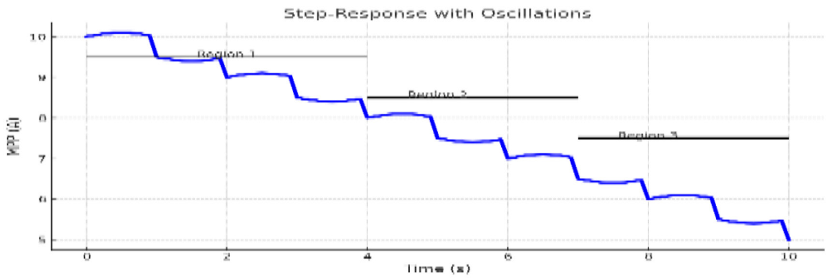

Figure 7

DC-link voltage using the MO-PO algorithm.

This figure compares the effectiveness of each approach in maximizing power output under varying operational conditions. In addition, Fig. 7 shows the voltage tracking behavior at the DC-link when utilizing the traditional methods and the hybrid MO-PO algorithms, under Partial Shading Conditions (PSC) as outlined in Table 2. These figures provide a clear comparison of the behavior of each method in terms of their ability to track the global maximum peak point (GMPP), particularly in challenging shading scenarios. The output highlights the superiority of the hybrid MO-PO methodology in maintaining higher power output and more stable voltage tracking compared to traditional methods, especially when confronted with complex shading patterns.

7. Conclusion

The proposed system utilizes a hybrid MO-PO method to demonstrate the performance of various PV parameters under different partial shading conditions (PSCs). Additionally, comparisons with GWO, GA, and PSO algorithms for tracking MPPT performance are presented. The results indicate that OPAL-RT technology in a Hardware-in-the-Loop (HIL) setup can effectively generate a range of findings. The boost converter leverages the Sliding Mode Controller (SMC) to deliver the necessary control pulses. Compared to a conventional PI controller, a PV system equipped with an SMC exhibits faster response times, highlighting the superior efficiency of the SMC in managing the PV system under varying conditions.

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