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Enhanced Renewable Energy Integration in EV Charging Stations using Adaptive Backstepping Control with Giza Pyramid Construction-Based MPPT for Improved Power Quality

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Abstract: - The increasing addition of Electric Vehicles (EVs) into the power grid necessitates advanced control strategies for renewable energy-based charging stations to efficient energy utilization. The proposed system aims to optimize energy extraction from renewable sources using a novel Maximum Power Point Tracking (MPPT) algorithm inspired by the Giza Pyramid construction methodology, termed Giza Pyramid Construction (GPC) based MPPT. The GPC-based MPPT algorithm is designed to dynamically adjust the operational point of the PV system to reach maximum power under varying environmental conditions. Its performance is rigorously evaluated and compared against the conventional Incremental Conductance (INC) MPPT algorithm through extensive simulation studies conducted using MATLAB/Simulink. The Key parameters considered include response time to changes in irradiance, power stability, and ripple in the generated power. The simulation results exhibit that the GPC-based MPPT process significantly surpasses the INC-MPPT, achieving faster stabilization times and reduced power ripples. Specifically, the GPC-MPPT achieves stability within 0.018 seconds under changing irradiance conditions, compared to 0.2 seconds for the INC algorithm, with power ripples reduced to 1.7% from 8.57%. The proposed system effectively manages the integration of PV and wind energy and maintains consistent power supply to EV charging stations. This study underscores the potential of advanced control strategies and novel MPPT algorithms in improving the performance and dependability of renewable energy-based EV charging stations. The findings highlight the GPC-MPPT as a promising alternative to conventional methods, offering improved efficiency and power quality in renewable energy applications.

Keywords: Electric Vehicles, Power, Giza Pyramid Construction MPPT, Incremental Conductance MPPT, Renewable Energy, Photovoltaic System, Wind Generation System, Grid-Interactive Charging Station, MATLAB/Simulink.

1. Introduction

Electric vehicle (EV) charging stations in a microgrid are often integrated with renewable energy sources like solar panels and wind turbines. This integration ensures that the energy used for charging EVs is clean and sustainable, reducing the overall carbon footprint. To manage the intermittent nature of renewable energy, EV charging stations in a microgrid may utilize energy storage systems, such as batteries. These systems store surplus energy generated during peak times and supply it when renewable generation is low, ensuring a regular and consistent power supply for EV charging [1]. Advanced control systems and smart grid technology are employed to optimize the energy flow within the microgrid. This includes demand response strategies, where charging schedules for EVs are adjusted based on real-time availability of renewable energy, grid conditions, and pricing signals. EV charging stations in a renewable energy microgrid can operate independently of the main grid, enhancing energy security and resilience. In the event of a grid outage, the microgrid can continue to function using locally generated renewable energy, ensuring uninterrupted charging services for EVs [2]. Utilizing renewable energy sources for EV charging stations in a microgrid reduces reliance on fossil fuels, leading to significant environmental benefits by lowering greenhouse gas emissions. Additionally, the usage of locally generated renewable energy can reduce energy costs and provide economic advantages to both the microgrid operators and the EV users [3].

MPPT guarantees that solar panels and other renewable energy sources operate at their highest efficiency, extracting the maximum possible power [4]. This is crucial for EV charging stations in a microgrid to make the most out of the available renewable energy, reducing the reliance on the grid and fossil fuels. MPPT improves the overall energy efficiency of the microgrid by continuously adjusting the operating point of renewable energy sources. This optimization leads to better performance and higher energy yields, which is essential for meeting the high energy demands of EV charging stations [5]. By optimizing the power output from renewable sources, MPPT helps in stabilizing the power supply within the microgrid. This stability is critical for the consistent and

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reliable operation of EV charging stations, ensuring that vehicles can be charged efficiently without fluctuations in power availability. Efficient utilization of renewable energy through MPPT can significantly lower energy costs. By maximizing the power harvested from renewable sources, the microgrid can reduce the need to purchase additional power from the main grid, leading to cost savings for both microgrid operators and EV users. MPPT contributes to the independence of the microgrid by ensuring that the renewable energy sources are used to their fullest potential [6]. This independence is vital for EV charging stations, especially in remote areas or during grid outages, as it allows for continuous operation using locally generated renewable energy [7].

The Perturb and Observe (P&O) algorithm is one of the widely employed tracking techniques in commercial MPPT controllers [8]. The module's characteristics are used to extract the maximum power point of the module's output power [9-10]. In the enhanced P&O, the duty cycle of the boost converter is used as the perturbed signal instead of the module voltage. In [11] developed a unique algorithm based on P&O, that can extract 10% maximum power with 0.2 seconds of settling time. The Hill Climbing (HC) method concerns regulating the duty cycle of the converter to perform MPPT [12]. Although it operates on a similar principle to P&O, it is not identical. While P&O involves perturbation of the PV voltage, the HC method relies on perturbing the duty cycle [13].

INC is another traditional approach for extracting maximum power from PV systems which utilizes the current and voltage of PV arrays to identify the Maximum Power Point (MPP) and can adjust to altering climate conditions [14]. Artificial Neural Networks (ANNs) are a soft calculating approach inspired by the human brain. NNs are adjusted throughout the training procedure till the network accurately predicts the required voltage relating to the Maximum Power Point (MPP) [15]. Extracting the MPP through the total search region can increase optimization time and pose challenges for data storage. The FSB (Fast Search-Based) technique addresses this issue by significantly reducing search time by narrowing the operational range. The GNT [16], that uses a root-finding process, offers the increased extracting speed compared to other methods. The primary concept of Particle Swarm Optimization (PSO) is inspired by the actions of flocks of birds or schools of fish [17]. In PSO, particles move through the search region like a swarm of wandering insects to find the optimal solution [18]. PSO is utilized to identify the Global Maximum Power Point (MPP) of a PV system by optimizing the duty cycle of the converter, with the cost function being the output power [19].

The Cuckoo Search (CS) method is inspired by the parasitic reproduction of cuckoo birds [20]. The Artificial Bee Colony (ABC) method is a bio-inspired technique that is simple, involves only a few well-regulated parameters, and operates independently of the system's preliminary conditions. In the ABC algorithm, the MPP serves as the food source, and the duty cycle represents the food position [21]. Ant Colony Optimization (ACO) is a probabilistic approach inspired by the food-seeking behavior of ants. It is employed in both unified and dispersed MPPTs to minimize the number of local MPPs on the V-I curve [22]. In [23], Genetic Algorithm (GA) is used to train ANNs to predict the current and voltage at the MPP of a PV array. Additionally, GA helps in the efficient design of PV arrays with various inverters. The Wolf Optimization Algorithm (WOA) is adopted by the attacking strategies of grey wolves including searching for prey, encircling it, and then attacking [24].

This paper presents an innovative ABC strategy for a grid-interactive EV charging station powered PV and WGS. Objectives of the paper are outlined as

- Introduce the innovative GPC MPPT algorithm, assess its efficiency in real-time maximum power point tracking, and compare its performance with the conventional INC MPPT algorithm under various conditions.
- Achieve rapid stabilization of power generation from renewable sources with minimal ripples, thereby improving the reliability and efficiency of the EV charging station's operation in fluctuating environmental conditions.
- Maintain harmonic levels and power quality standards as per IEEE 519 through the implementation of the proposed control and MPPT strategies, ensuring the grid-connected EV charging stations operate within acceptable limits.

2. System Configuration

The EV charging station shown in Fig. 1 connects the PV, WGS and grid through a Voltage Source Converter (VSC). This structure enables both EV charging and power supply to domestic loads, operating in both Islanded

Mode (IM) and Grid-Connected Mode (GCM). The PV array is connected to the direct current (DC) link of the charging station. In contrast, the WGS, which is based on a Permanent Magnet Brushless DC (PMBLDC) generator, is linked to the DC bus via an uncontrolled rectifier and a DC/DC converter [25].

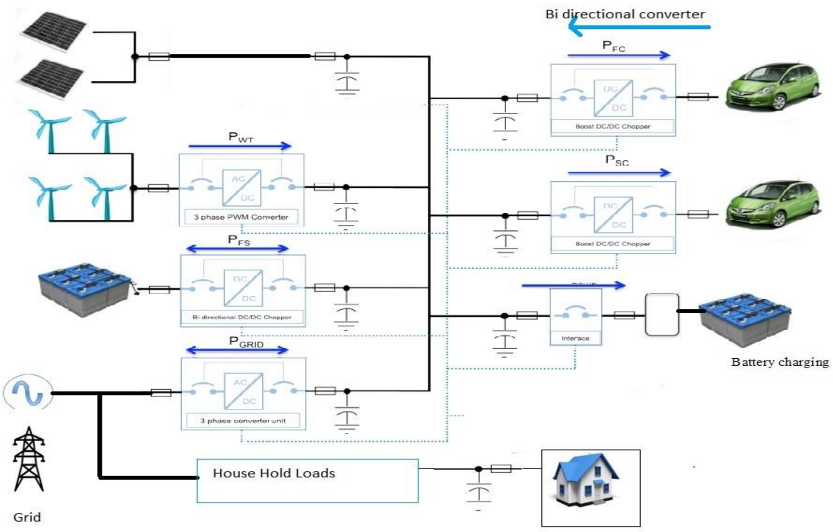


Figure 1: Charging Station with EV Chargers and renewable energy sources

The boost converter plays a vital role in the integrated charging station by capturing and optimizing the peak power generated by the WGS. In this coordinated setup, the EV efficiently draws power from both sources. The EV draws power from both the point of common coupling (PCC) and the dc bus of the charging station. This bidirectional power flow is managed by a bidirectional dc–dc converter (BiDC). At the same time, household loads are seamlessly integrated at the PCC of the entire system. To provide an effective interface between the charging station, the grid, and the PCC, a bidirectional static switch and interfacing inductors are strategically incorporated. These components manage the power flow between the PCC of the grid and the charging station. To ensure power supply integrity and minimize interference, RC filters are employed to effectively eliminate switching harmonics. The primary objectives of the charging station are to ensure continuous charging services for EVs under various operating conditions and to act as a dependable backup power source for household loads during emergencies.

3. Giza Pyramid Construction

The core concept of the GPC is optimizing the worker's control over transporting stone blocks up the ramp to the pyramid. For each stone block, the initial position and associated cost are predefined. The subsequent position or displacement of a stone block depends on the worker's energy. Various factors such as the ramp's slope and friction level significantly influenced the physical effort required to move the blocks. Given the variability in workers' physical abilities, replacing workers as needed was essential to maintain optimal power levels for transporting the blocks. As a result, some workers were replaced by others, leading to better stone block displacement and improved power balance. During optimization, it should be assumed that only one straight ramp with a horizontal angle of less than 15° is used. Workers with lower energy levels should be replaced with new ones, and friction during block displacement must be considered when calculating workers' positions [26].

Pseudo-code of GPC algorithm

1. Set maximum number of iterations, number of workers, number of solutions in the problem, size of the population and maximum and minimum ranges of output
2. Create an array with random elements for stone blocks or workers with population size.
3. Compute the fitness function of every initialized element of worker, obtain the minimum value and assign that worker as Pharaoh’s agent
4. **While** ite< Maximum iterations **do**

5.	**For** i=1 to the number of stone blocks or workers **do**
1.	Calculate movement of the stone block (Eq. 60)
2.	Calculate distance moved by the worker (Eq. 61)
3.	Evaluate the next position (Eq. 62)
4.	Calculate the possibility of replacing the workers (Eq. 60)
5.	Calculate the updated position and fitness function
6.	**If** new fitness function is less than Pharaoh's agent cost, **then**
1.	Set worker of new fitness function is Pharaoh's agent
7.	**End-if**
6.	**End-For**
7.	**End-While**
8.	Solution=c

When a worker operates a random force to a stone block on the ramp, the block is displaced **d** with an initial velocity v_o. As the block moves up the ramp, friction between the block and the ramp will eventually cause it to stop. The worker must then apply additional force to continue moving the block further. The stone block starts moving with an initial velocity v_o. In each iteration, an array of uniformly distributed random numbers can be selected to determine v_o, as the force applied by the workers to the stone block varies based on the energy each worker exerts.

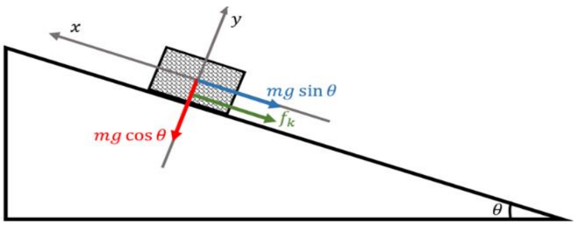


Figure 5. Forces on stone blocks while displacing.

The stone block, with a mass mm, on a ramp with an angle, experiences a frictional force f_k that the worker must overcome, as described in Eq. 1.

$$f_k = \mu_k mg\ \cos\theta \quad (1)$$

Here, g represents the acceleration due to gravity, and $\mu_k$denotes the coefficient of kinetic friction. The total force FFF exerted by the workers to move the stone block is given by Eq. 2

$$F = ma = -mg\sin\theta - f_k \quad (2)$$

Then acceleration a is given in Eq. 3

$$a = -g\mu_k\cos\theta - g\sin\theta \quad (3)$$

Then the movement of the stone block on the ramp d is determined as shown in Eq. 4

$$d = \frac{v_o^2}{2(g\mu_k\cos\theta + g\sin\theta)} \quad (4)$$

In each iteration, the initial velocity v_o can be set to a random value between 0 and 1. The coefficient of kinetic friction $\mu_k$for the stone blocks is chosen as a evenly distributed random number within the range of μ_{k_min} and μ_{k_max}. This accounts for variations in the ramp's unevenness and surface texture. When pushing the stone block, the worker also moves along with it, and this movement can be calculated using Eq.5.

$$x = \frac{v_o^2}{2g\sin\theta} \quad (5)$$

In this equation, friction affecting the worker's movement is neglected due to their continuous motion. Based on the displacements of both the stone block and the worker, new positions for the solution are determined using Eq. 6.

$$\vec{p} = (\vec{p}_i + d) \times x\vec{\epsilon}_i \tag{6}$$

$\vec{p}$ is the next position, $\vec{p}_i$ is the current position and $\vec{\epsilon}_i$ is a random vector which develops levy distribution.

If a worker loses energy while moving the stone block up the ramp, a substitution can be made. Assuming a 50% probability, new positions are generated using the equation and can replace the initial solutions from the previous iteration.

If $\vec{p} = (\vec{p}_1, \vec{p}_2, \vec{p}_3, \dots, \vec{p}_k)$ and $\vec{p}_i = (\vec{p}_{i1}, \vec{p}_{i2}, \vec{p}_{i3}, \dots, \vec{p}_{ik})$ then $\vec{p}_{inew} = (\vec{p}_{inew1}, \vec{p}_{inew2}, \vec{p}_{inew3}, \dots, \vec{p}_{inewk})$

$$\vec{p}_{inewk} = \begin{cases} \vec{p}_{ik}, if\ rand(0,1) \leq 0,5 \\ \vec{p}_k, else \end{cases} \tag{7}$$

4. Simulation Results

The implementation of the proposed GPC-MPPT for EV charging stations utilizing solar PV and WGS has been developed and validated through simulations conducted in MATLAB/Simulink. Detailed parameters of the adopted system presented in table 1. For simulation, a 2.5kW, 460V, and 9.5A solar PV array is utilized, and wind generation system rating is 2kW. The battery is rated at 240 V and 35 Ah. Three cases are considered in simulation. In case 1, the simulation considers changes in solar irradiance to calculate the working of the GPC-MPPT under varying sunlight conditions. In case 2, simulates a temporary outage in the PV generation to evaluate the system's response and the efficacy of the GPC-MPPT in maintaining power supply to the EV charging stations. Third case involves real-time changes in irradiance, simulating the dynamic and unpredictable nature of sunlight exposure throughout the day.

Table1. Parameters of the system

Parameter	Values/Ratings
PV array	
Open circuit voltage Voc (V)	52V
Short-circuit current Isc (A)	5.15A
Voltage at maximum power point Vmp (V)	46V
Current at maximum power point Imp (A)	4.75A
Parallel strings	2
Series-connected modules per string	10
Battery rating	240V, 35Ah
Grid	230V, 50Hz
PMSG rating	2kW
DC Link Capacitor	1000µF
Load	20Ω, 10mH

CASE1: In this analysis, the consequence of irradiance changes on the PV system is simulated. The efficacy is compared among the proposed GPC based MPPT method and the conventional INC-MPPT method. Figure 6 illustrates the variation of irradiance over time, showing how sunlight intensity fluctuates, which directly impacts the power generation of the PV. Figure 7(a) presents the generated power, voltage, and output current

from the PV system for both the GPC-MPPT and the INC-MPPT methods. The power produced by the PV stabilizes much faster using GPC-MPPT, reaching stability within 0.018 seconds. In contrast, the INC-MPPT method takes 0.2 seconds to stabilize. The ripples in the generated power are significantly lower with the GPC-MPPT. The power fluctuation is only 1.7% with GPC-MPPT compared to 8.57% with INC-MPPT. This indicates that the GPC-MPPT provides a smoother and more stable power output from the PV system, leading to better overall performance and efficiency.

Figure 7(b) illustrates the power transferred to the grid. This includes the power from the PV system and potentially other sources within the microgrid. The smoother and quicker stabilization of power generation with GPC-MPPT make certain that the power transferred to the grid is more stable and reliable. The reduced ripples in PV power output with GPC-MPPT translate to fewer fluctuations in the grid power, improving the power quality and stability of the microgrid. The GPC-MPPT method demonstrates better performance in tracking the maximum power point quickly and with minimal oscillations. The rapid stabilization and reduced power ripples contribute to a more efficient and stable power supply, both for direct use and for feeding into the grid. This improved performance is particularly beneficial for applications in microgrids with EV charging stations, where consistent and reliable power is crucial.

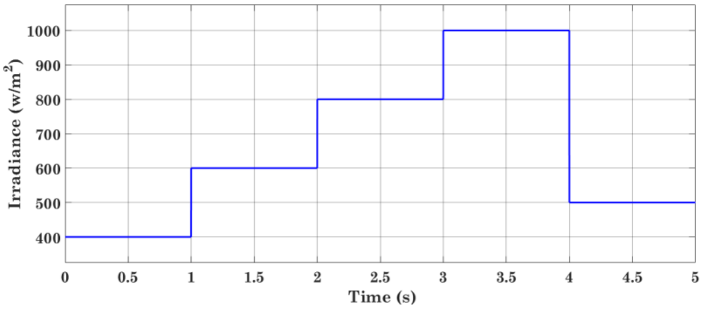
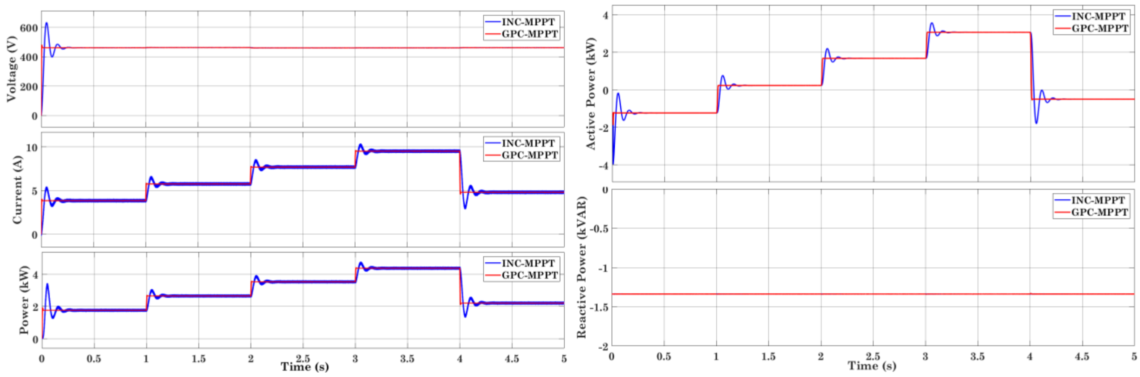


Figure 6. Irradiance

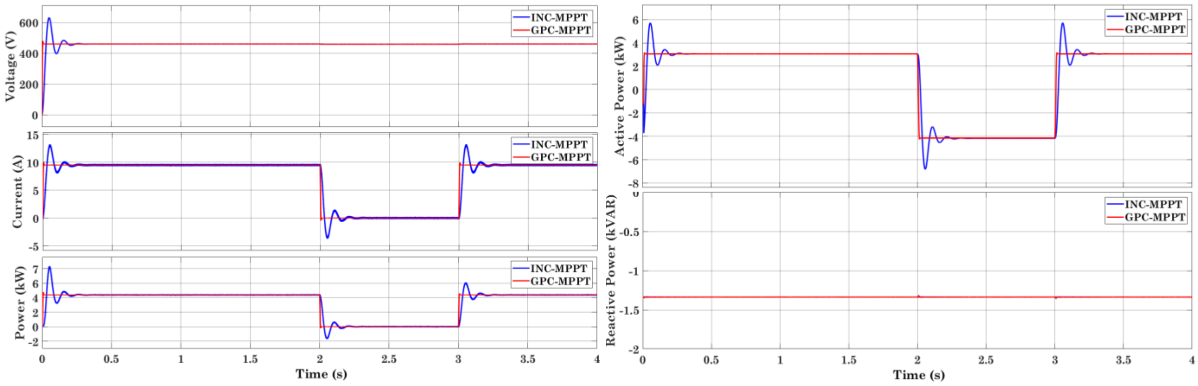


(a) (b)

Figure 7. (a) PV voltage, current and generated power (b) Grid Active power and reactive power

CASE2: This analysis investigates the effectiveness of the proposed GPC based MPPT algorithm during an outage of the PV system. The focus is on how the system manages power supply to the EV charging stations in the absence of PV-generated power. Between 2 to 3 seconds, the PV system is intentionally disconnected to simulate an outage scenario. Due to this disconnection, the power produced by the PV system drops to zero. This is depicted in Figure 8(a), which displays the PV system's power output before, during, and after the outage period. During the PV system outage, the responsibility of supplying power to the EV charging stations shifts entirely to the grid. Figure 8(b) illustrates this transition, highlighting how the grid compensates for the loss of PV power by increasing its power output to meet the demand of the EV charging stations. The grid seamlessly takes over the load, ensuring that the EV charging stations receive a continuous and stable power supply despite the absence of PV-generated power. The proposed GPC-MPPT algorithm demonstrates its robustness and adaptability in managing power supply transitions. By ensuring that the EV charging stations remain powered during the PV system outage, the GPC-MPPT algorithm proves its capability to maintain system stability and reliability. The swift and smooth transition of power supply from the PV system to the grid minimizes disruptions and ensures continuous operation of the EV charging stations.

The performance of the GPC-MPPT algorithm during the PV system outage confirms its efficacy in maintaining a reliable power supply to the EV charging stations. The algorithm's ability to handle sudden changes in power generation and ensure a stable power supply from the grid highlights its effectiveness in real-world scenarios where PV outages may occur. This robustness is crucial for microgrid applications, particularly those involving EV charging stations, where consistent power availability is essential for operational reliability.



(a) (b)

Figure 8. (a) PV voltage, current and generated power (b) Grid Active power and reactive power

CASE3. This case examines the proposed GPC based MPPT algorithm's performance under real-time variations in irradiance. Data for this analysis is sourced from the National Solar Radiation Database (NSRDB) data viewer, which provides irradiance data on an hourly basis. For the purposes of this simulation, the data is scaled to represent per-second variations. Figure 9 illustrates the real-time variation in irradiance. This variation is essential to simulate as it directly impacts output power from the PV. Figure 10(a) presents the PV system's response to the fluctuating irradiance levels. This includes the voltage, current, and generated power from the PV. The PV system, controlled by the GPC-MPPT algorithm, adjusts its operating point continuously to extract the maximum power effectively despite the variations in irradiance. Figure 10(b) displays the grid's real and reactive power during the varying irradiance conditions. The grid's power dynamics are crucial in understanding how the microgrid balances the power supply to the EV charging stations under different irradiance conditions. With maximum irradiance, the PV system generates its peak power output. This is clearly depicted in Figure 10(a), where the voltage and current are optimized to achieve maximum power. The GPC-MPPT algorithm make certain that the PV system functions at its MPP, maximizing the energy harvested from the solar panels. Figure 10(b) shows that during times of maximum PV power generation, the grid's active power is positive, indicating that excess power is being fed into the grid or used for other loads. Conversely, while the PV power is inadequate to meet the demands of the EV charging stations (such as during periods of low irradiance or nighttime), the grid power turns negative. This indicates that the grid is delivering additional power to compensate for the deficit. The grid's ability to provide or absorb power as needed ensures a stable power supply to the EV charging stations. The reactive power management by the grid also plays a significant role in providing voltage stability and power quality. The GPC-MPPT algorithm effectively tracks the quick variations in irradiance, to always get maximum power extraction from the PV system. The algorithm's quick response to irradiance changes minimizes power losses and maximizes the efficiency of the PV system.

This test case confirms the robustness and adaptability of the GPC-MPPT algorithm. The algorithm ensures that the PV continuously operates at its maximum efficiency, despite of the changing solar conditions. The grid dynamically compensates for any shortfall in PV power, to provide a reliable and stable power supply to the EV charging stations. This performance is critical for the sustainable operation of microgrids with renewable energy sources, especially in applications requiring consistent and reliable power, such as EV charging stations. By effectively managing the power dynamics among the grid and the PV, the proposed GPC-MPPT algorithm demonstrates its capability to improve the reliability and efficacy of renewable energy-based microgrids.

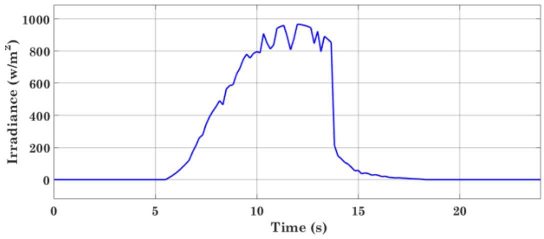
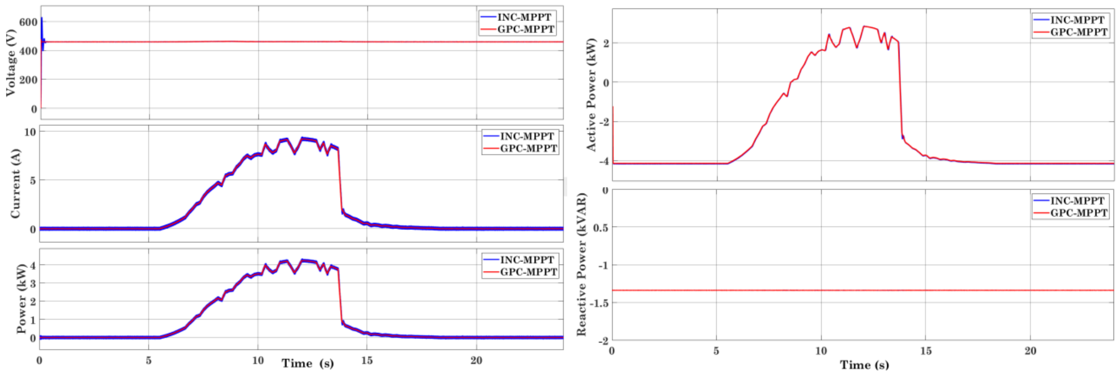


Figure9. Irradiance



(a) (b)

Figure 10. (a) PV voltage, current and generated power (b) Grid Active power and reactive power

5. Conclusion

The incorporation of renewable energy sources in EV charging stations presents both opportunities and challenges in achieving efficient and reliable energy management. This study introduces an ABC strategy combined with a novel GPC based MPPT algorithm to address these challenges. The primary objective is to maximize energy extraction from PV and WGS, ensuring optimal operation of grid-interactive EV charging stations. Through comprehensive simulation studies using MATLAB/Simulink, the execution of the proposed GPC-based MPPT algorithm was estimated against the conventional INC-MPPT algorithm. The results highlight the advantage of the GPC-MPPT in terms of response time and power stability. The GPC-MPPT achieved stability within 0.018 seconds under varying irradiance conditions, compared to 0.2 seconds for the INC algorithm. Additionally, the power ripples were significantly reduced to 1.7% with the GPC-MPPT, compared to 8.57% with the INC-MPPT. These improvements translate to more efficient and reliable energy management in renewable energy-based EV charging stations. It effectively balances active and reactive power flows, ensuring continuous power supply even during events such as voltage sags and outages. This study underscores the potential of advanced control strategies and innovative MPPT algorithms in optimizing the EV charging infrastructure. The GPC-based MPPT algorithm, inspired by the GPC methodology, offers a promising alternative to conventional MPPT methods, providing faster and more stable power output. The findings demonstrate that the proposed system can significantly increase the efficiency and reliability of renewable energy-based EV charging stations, contributing to sustainable energy management and grid stability. The integration of the ABC strategy with the GPC-based MPPT algorithm presents a significant advancement in the field of renewable energy and EV charging infrastructure. Future work will focus on further refining these control strategies and exploring their applicability in larger, more complex grid environments.

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