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Improvement Of Hosting Capacity Of A Pv Solar System Using Optimization Techniques

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Abstract
The rapid expansion of solar photovoltaic systems within Low-Voltage (LV) distribution networks has introduced significant challenges, particularly concerning the Hosting Capacity (HC) due to voltage regulation issues. This study investigates strategies to enhance HC, focusing on advanced control methods. The deployment of Particle Swarm Optimization (PSO) in enhancing the Hosting Capacity (HC) of photovoltaic systems within (LV) distribution networks has demonstrated significant efficiency. This study evaluates PSO's performance against Model Predictive Controller (MPC) and Genetic Algorithm (GA) under both linear and non-linear load conditions, focusing on its impact on harmonic currents. The PSO-based control strategy effectively maintains stable active power at 95.5 kW prior to full PV penetration, subsequently accommodating an increase to 249.6 kW, reflecting a 161.36% improvement in HC. Additionally, PSO optimizes reactive power usage, achieving a 18.73% reduction in reactive power compared to Genetic Algorithm. These findings underscore PSO's superior adaptability and responsiveness, highlighting its potential as an effective solution for optimizing PV system performance in LV distribution grids.
Keywords: *Hosting Capacity (HC), Particle Swarm Optimization (PSO), Solar Photovoltaic system, Low-Voltage distribution networks.*

1. INTRODUCTION

The increased global energy demand has mounted the search for clean and renewable energy sources that are ample and long-term. The alternatives not only address increasing energy demands but also help ensure environmental sustainability by reducing carbon emissions. Forecasts indicate that renewable power will account for 86% of the world's power generation by the year 2050, providing about two-thirds of the world's energy supply [2], [3]. The use of distributed generation facilities, especially photovoltaic (PV) systems, is picking up speed as a sustainable solution for renewable energy. Solar power plants, such as large photovoltaic panel arrays, have been successfully incorporated into many distribution systems. In addition, solar plants can be incorporated into high-voltage systems with different power transformers. With conventional fossil fuel-based power generators being gradually replaced, comparable power generation is shifting toward renewable sources [4].

The incorporation of PV panels into Low-Voltage (LV) distribution networks may lead to voltage rise issues at feeder links and within the LV infrastructure, thereby imposing operational constraints and affecting overall system reliability [5]. Establishing and adhering to specific voltage violation thresholds is essential to prevent surpassing the feeder's capacity to accommodate additional solar panels [6], [7]. The Hosting Capacity (HC) of a PV system refers to the largest amount of solar power that may be integrated into a given electrical grid or distribution network without compromising its stability and reliability. In short, it is the ability of the grid to accommodate additional solar generation without threatening its operational integrity [8]. This capability is defined by various factors, including voltage spikes that can reverse power flows, thermal overloads in conductors and transformers, and voltage unbalances. Assessing the influence of a PV system on a real network requires consideration of several factors like network topology, feeder properties, load conditions, and individual PV installation points [9]. The primary challenges limiting the maximum capacity of connected PV arrays often involve voltage escalation in practical LV distribution networks, leading to violations of regulatory constraints [10].

Improving the Photovoltaic Hosting Capacity (PVHC) of low-voltage distribution networks can be done efficiently by using passive harmonic filters. The filters address optimization issues of overvoltage and under voltage conditions, transmission line losses, harmonic distortion due to nonlinear loads (such as six-pulse rectifiers), and the line capabilities available. The application of a passive harmonic filter has also been demonstrated to improve PVHC and improve the system's power factor through the damping of Total Harmonic Distortion (THD) and Total Demand Distortion (TDD) [12]. In, a new approach for filtering harmonics is presented, namely employing a passive C-type filter in achieving maximum hosting capacity in low-voltage electrical distribution networks. The primary objective of this method is minimizing voltage and current distortions in the terminal connected with renewable sources in order to utilize maximum hosting capacity with a novel optimization process.

A thorough review in [14] addresses all parameters under Hosting Capacity (HC), such as its different definitions, references, constraints in the investigated systems, place categories, and methods used for their identification. Furthermore, the review offers a brief overview of the parameters affecting hosting capability in various systems and explains the structures used for improving it. Furthermore, [15] evaluates the optimal configuration of a distribution system concerning its ability to integrate solar power generation. This paper introduces a feeder-based approach formulated for the evaluation of solar PV hosting capacity, especially with respect to overvoltage-related limitations in low-voltage systems. Implementation of PV systems in Low-Voltage (LV) distribution networks is challenging, especially in the increase of Hosting Capacity (HC). Particle Swarm Optimization (PSO) is a promising method to overcome these challenges.

There is a notable lack of comprehensive studies comparing the performance of PSO with established control techniques such as reactive power control. This gap hinders the ability to assess the relative advantages and limitations of PSO in enhancing HC within LV distribution networks. Addressing this requires systematic investigations that evaluate PSO's effectiveness against traditional methods, focusing on metrics like voltage regulation, power factor improvement, and harmonic distortion reduction. Such comparative analyses are essential for determining the suitability of PSO in specific grid scenarios.

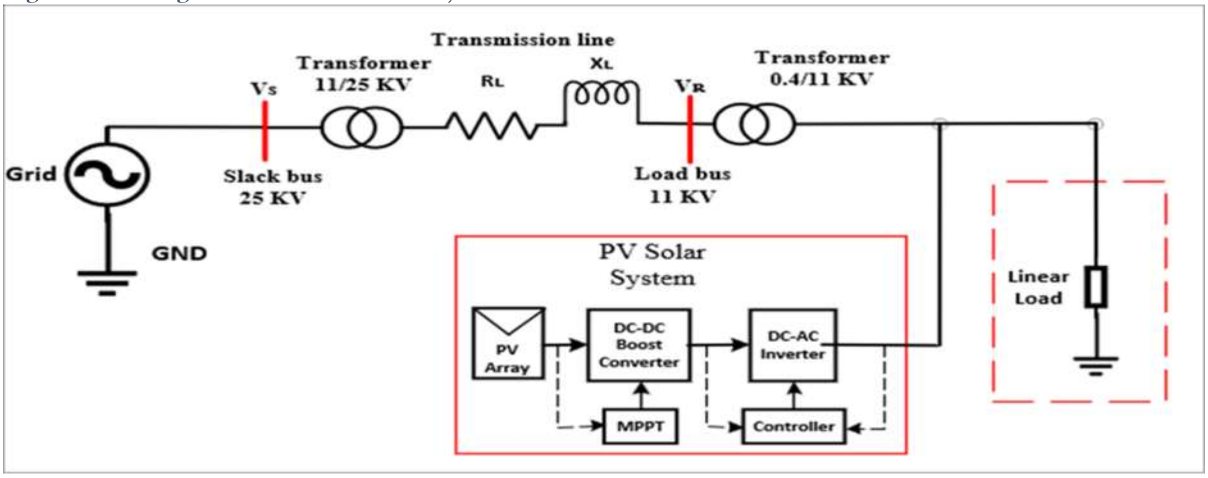
As PV penetration increases, selecting the most appropriate control strategy becomes critical for maintaining grid stability and maximizing HC. Currently, there is a deficiency in frameworks that guide stakeholders in choosing optimal control methods, such as PSO, based on varying grid conditions and PV integration levels. Developing decision-making criteria that consider factors like load variability, network topology, and existing infrastructure is imperative for informed strategy selection.

To bridge these gaps, focused research is necessary to conduct detailed comparative studies between PSO and traditional control methods under various operating conditions, and to develop comprehensive frameworks that assist in selecting optimal control strategies tailored to specific grid configurations and PV penetration levels. Resolving these issues will play an imperative role in orderly integration of PV systems into LV distribution networks, paving the way towards improved HC and grid reliability.

2. PV SOLAR SYSTEM

The process of creating a grid-connected Photovoltaic system entails combining various important components for effective and safe conversion and distribution of energy. These are the main components that involve photovoltaic modules (solar panels) used to absorb solar energy, mounting structures used to position the panels at a secure position for receiving sunlight, inverter used to convert the generated DC into AC compatible with the utility grid, and electrical wiring and components that allow the electricity to flow. Further, the system includes grid connection systems, monitoring and control systems to monitor performance, safety systems to meet regulation, and optionally, battery storage systems for energy storage. The building process can differ based on the size of the PV system whether residential, commercial, or utility-scale and respective project needs. Professional installers, electricians, and engineers are generally involved to guarantee the system's regulatory compliance, efficiency, and safety [11].The Figure 1 shows the PV Solar System configuration.

Figure 1 Configuration of PV Solar System



To verify the proposed control method, a test system is employed that includes an elementary Low-Voltage (LV) distribution network supplying energy to a 100 kVA PV network and a 100 kVA load 5 km away from the feeder. The PV network is at maximum capacity, with parameters specified in Table 1[1]. The PV array is constructed with an appropriate series and parallel photovoltaic panels number in order to get the required capacity level. Operation conditions are set for 1000 W/m^2 of irradiation and 25°C of temperature, which are maintained constant in accordance with a deterministic approach.

In a grid-connected PhotoVoltaic (PV) system, the key interface devices that link the PV panels to the power grid are a DC/DC converter and a DC/AC inverter. DC/DC converter is regulated using a Maximum Power Point Tracking (MPPT) algorithm, i.e., the perturb and observe method, to harvest maximum power from the PV source. The algorithm controls the duty cycle of the converter to make the PV panels operate at the maximum power point, adjusting for variations in irradiance and temperature. The generated electricity is then channeled to the AC side using an inverter. Inverter control involves some key functions: synchronizing with the grid, ensuring DC link voltage stability, and controlling active and reactive power outputs. An efficient method is to modulate the current of the inverter to simultaneously regulate real and reactive power, providing efficient energy supply and meeting the grid demand [16].

Table 1 Parameters of photovoltaic (PV) solar systems

Characteristic	Magnitude
PV capacity	b100 KW
PV Power panel	305 W of solar energy
Current of panel at controller	5.58A
Voltage of panel at controller	54.7V
Limitations on brightness	1000W/m2
Quantity of series modules	5
Quantity of parallel strings	66
Weather	25 deg C
Transformer for distribution	100 KVA(0.4/11) kV
Supply distance	5km
Step-up transformer	47 MVA(25/125)kV
Line resistance	0.754Ω/km
Line inductance	0.25 mH/km
Static load	10 kVA

3. TYPES OF COTROL METHODS

Several control methods have been introduced to improve the HC of solar energy in Low-Voltage (LV) networks. This section introduces the use of Model Predictive Control (MPC), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) as reliable methods to enhance hosting capacity.

A. MODEL PREDICTIVE CONTROLLER (MPC)

Model Predictive Control (MPC) is a popular method for solving constrained control problems with multiple parameters. The MPC controller is in this approach a supervisory controller that computes a series of decision variables to maximize a given cost function over a fixed interval in the future called the control horizon. Once the best control sequence is calculated, the control actions are implemented for the current step, and the decision window moves forward. A new system measurement is then added, enabling the controller to update and improve the control strategy for the next control horizon.

B. GENETIC ALGORITHM (GA)

GA is an evolutionary optimization technique inspired by the principles of natural selection. It begins with a population of randomly generated solutions, each representing a unique set of control parameters. These parameters could include inverter switching angles, reactive power set points, or filter configurations. Each solution is evaluated based on a predefined cost function that measures network performance. This cost function typically includes terms for voltage deviation, power losses, and Total Harmonic Distortion (THD). The solutions with better performance are selected and combined through crossover and mutation to create a new population. Over successive generations, GA evolves toward the most optimal control configuration. This allows the system to adapt to changing conditions such as load variations and solar irradiance.

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In the context of PV systems, GA can optimize inverter settings to control voltage profiles and reduce harmonics. By injecting or absorbing reactive power at the right locations, voltage limits can be maintained within regulatory boundaries. Simultaneously, THD is reduced by tuning filters or switching strategies, improving power quality. GA's global search capability makes it well-suited for complex, nonlinear problems. Once optimal settings are determined, they are applied to the PV inverters or control systems. These settings can be updated periodically as system conditions change. In real-time applications, GA can operate in supervisory control loops rather than fast dynamics. This ensures that computation time does not hinder system performance. The result is an improved hosting capacity, allowing more PV systems to be integrated without overloading the network. Additionally, the reduction in THD contributes to equipment protection and energy efficiency. GA does not require exact mathematical models, making it robust under uncertain conditions. Its flexibility and effectiveness make it a promising tool for modern smart grid control.

C. PARTICLE SWARM OPTIMIZATION (PSO)

Particle Swarm Optimization (PSO) is a fast, population-based optimisation algorithm modeled on the social behaviour of fish and birds. It has proved to be effective in optimizing the hosting capacity of solar PV systems and minimizing Total Harmonic Distortion (THD) of low-voltage distribution networks. To this end, PSO is utilized to calculate the optimal set of control parameters such as inverter operating points, levels of reactive power dispatch, or filter tuning coefficients that provide voltage stability and improve the power quality.

Every particle in the swarm is a candidate solution and varies its position in the solution space depending on the both its experience and also the neighbourhood's particles. This collective behaviour drives the swarm toward the best-known solution. The optimization process is guided by a cost function that typically includes objectives like minimizing voltage deviations, reducing THD, and maximizing PV hosting capacity.

Through iterative updates, PSO efficiently explores the search space and rapidly converges to optimal or near-optimal control strategies. These strategies enable greater incorporation of PV systems into the grid without violating technical constraints, while keeping harmonic levels compliant with standard limits. Due to its simplicity, fast convergence, and ability to handle nonlinear, multi-objective problems, PSO stands out as a robust method for both real-time and offline control of PV systems.

Figure 2 demonstrates the standard depiction of the PSO control scheme applied to the power converter. Figure 3 demonstrates the PSO based controlling.

Figure 2 Diagram demonstrates the integration of particle swarm optimization in a photovoltaic (PV) system

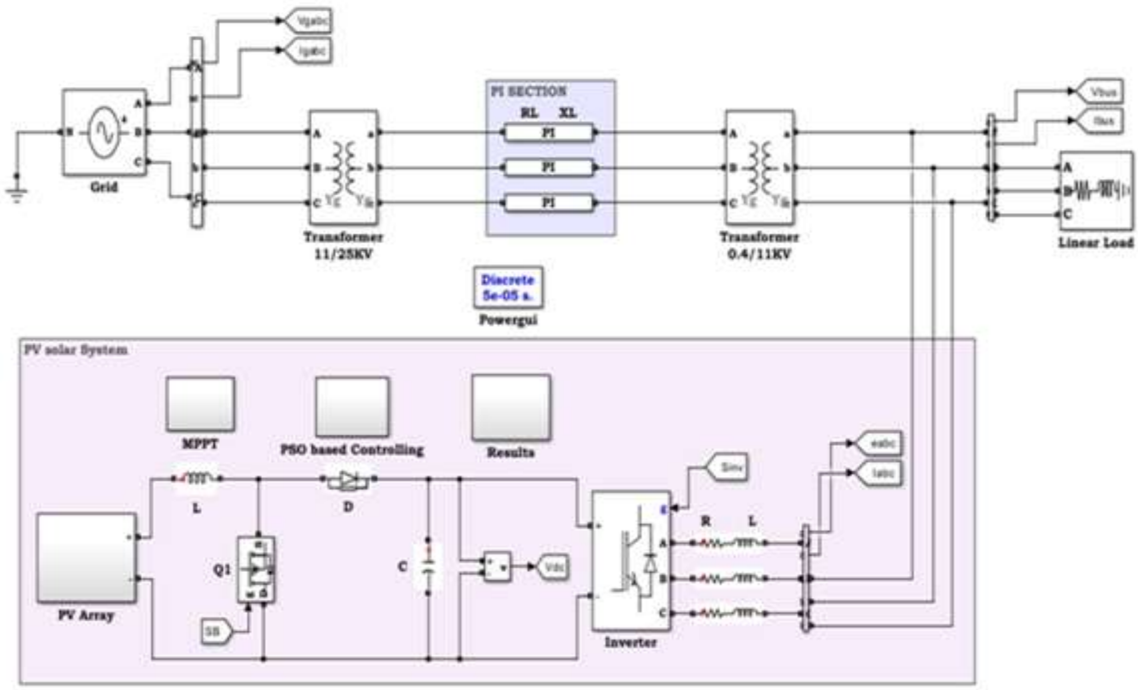
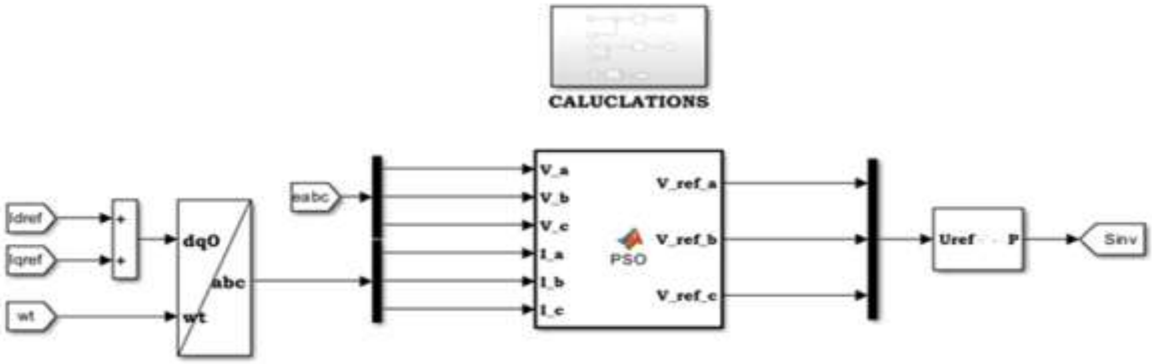


Figure 3 PSO based controlling



4. HOSTING CAPACITY CALCULATION

Hosting capacity is the maximum level of Decentralized energy systems like solar PV, wind, or batteries that can be reliably and safely added to the electricity distribution network at a given site without necessitating extensive grid upgrades or transgressing power quality standards[17],[18].

$$HC\ (\%) = \frac{P_{PV}}{S_{rated}} * 100 \qquad (1)$$

where, P_PV is the amount of solar PV output, and S_rated is the same as nominal apparent energy of the load connector[14].

The HC equation, either compared with two controls or to one control.

$$Hosting\ Capacity\ \% = \frac{HC\ (with) - HC\ (without)}{HC\ (without)} \qquad (2)$$

In the above equation, HC (with) is the value in watts under control, and HC (without) stands for the watt value without control.

Hosting capacity is constrained by various performance criteria such as voltage regulation at the interconnection point, tolerable limits of voltage and current Total Harmonic Distortion (THD), thermal capacity of distribution feeders, the maximum allowed PV penetration at the load bus, and adherence to power factor regulations. This can be briefly summarized as follows:

A.TOTAL HARMONIC DISTORTION (THD):

According to IEEE Std. 519, THD is a ratio of the harmonic voltage RMS to fundamental voltage RMS. The percentage of THD should not be more than 5%.

$$THD(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} |V_{s2}(h)|^2}}{V_{s2}(1)} \leq 5\% \qquad (3)$$

B.TOTAL DEMAND DISTORTION (TDD):

According to IEEE Std. 519, TDD is the ratio of the values of the harmonic current to the value of the fundamental current, both as RMS. The TDD percentage should not be greater than 8%.

$$TDD(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} |I_{s2}(h)|^2}}{I_{s2}(1)} \leq 8\% \qquad (4)$$

5. SIMULATION RESULTS

The investigation of hosting capacity in the PV system is divided into three distinct phases. The first phase examines the system performance when the PV array is integrated into the grid using Model Predictive Controller (MPC). The second phase examine the effect of using Genetic Algorithm (GA) to reduce issues like voltage rise, power factor problems, and harmonic distortion in particular Total Harmonic Distinction (THD) and Total Demand Distortion (TDD) at the Point of Common Coupling (PCC). The third phase deals with the use of Particle Swarm Optimization (PSO) to maximize and enhance the hosting capability of the network as a whole.

A. THE PV SOLAR SYSTEM INCORPORATING MPC CONTROL

Figure 4 depicts the dynamic performance of active power, reactive energy, and bus voltage in a PV system under MPC regulation. Initially supplying 95.5 kW of active power, the system experiences a 100% increase in PV penetration at 6 seconds, raising output to 191.6 kW and enhancing hosting capacity by 100.62%. MPC also decreases reactive power demand from 39 kVar [1] (in Volt-Var control mode) to 32.57 kVar, decreasing it by 16.48%. Bus voltage significantly improves, reducing from 1.2 pu to 0.98 pu (by 18.3%).

B. THE PV SYSTEM INCORPORATING GENETIC ALGORITHM

Figure 5 illustrates the dynamic performance of active power, reactive energy, and bus voltage in a GA-regulated PV system. The system starts by supplying 95.5 kW of real power and goes through a 100% augmentation in PV penetration and increasing output to 219.6 kW and increasing hosting capacity by 129.94%. The GA also reduces reactive power demand from 32.57 kVar (under MPC control) to 27.43 kVar, a 15.78% reduction. GA contributes bus voltage as 0.9877 pu.

C.THE PV SYSTEM WITH PSO TECHNIQUE

Figure 6 shows the dynamic active power, imaginary energy, and node voltage performance of a PV system controlled by PSO. The PV system provides 95.5 kW of active power initially. Following the 100% increase in PV penetration, the active power output has significantly increased to 249.6 kW, which causes a significant enhancement of the hosting capacity of the system by 161.36%. Under Particle Swarm Optimization method (PSO), the system also exhibits improved reactive power control, reducing the imaginary power demand from 27.43 kVar to 22.29 kVar which is an 18.73% reduction. PSO is attaining a bus voltage of 0.9937 pu.

Figure 4 Figure 4 Depicts the dynamic performance of active power, reactive energy, and bus voltage in a PV system under MPC regulation.

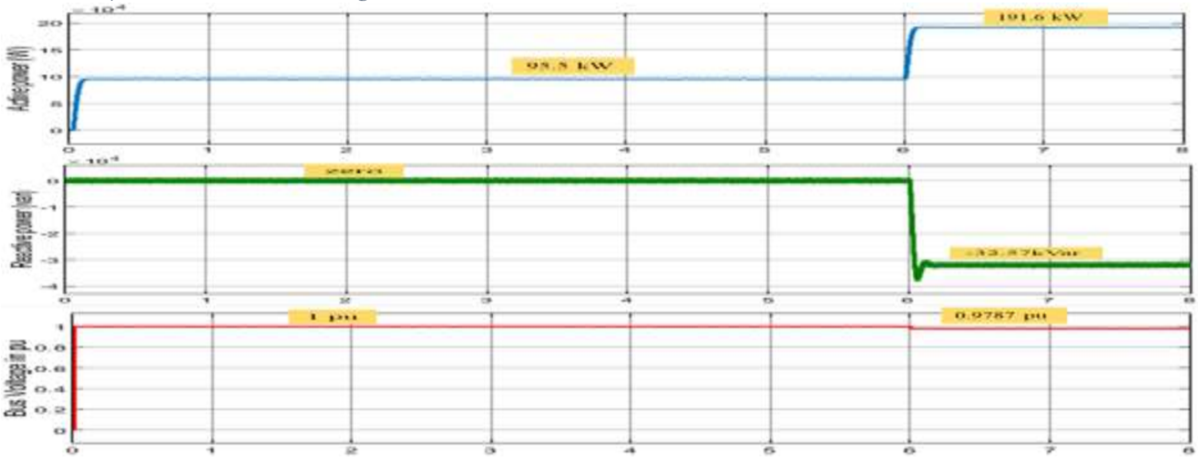


Figure 7 shows the actual power, quadrature power and voltage profile at the bus performance under three control strategies Model Predictive Control (MPC), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) under linear load conditions. From the results, it can be seen that PSO has a stable active power output but there is a significant drop in active power in both MPC and GA control schemes. This is a pointer to the higher ability of PSO in maintaining a firm and stable active power profile, an attribute that makes it more ideal for dynamic and distorted settings.

Figure 5 Figure 5 Depicts the dynamic performance of active power, reactive energy, and bus voltage in a PV system under GA regulation.

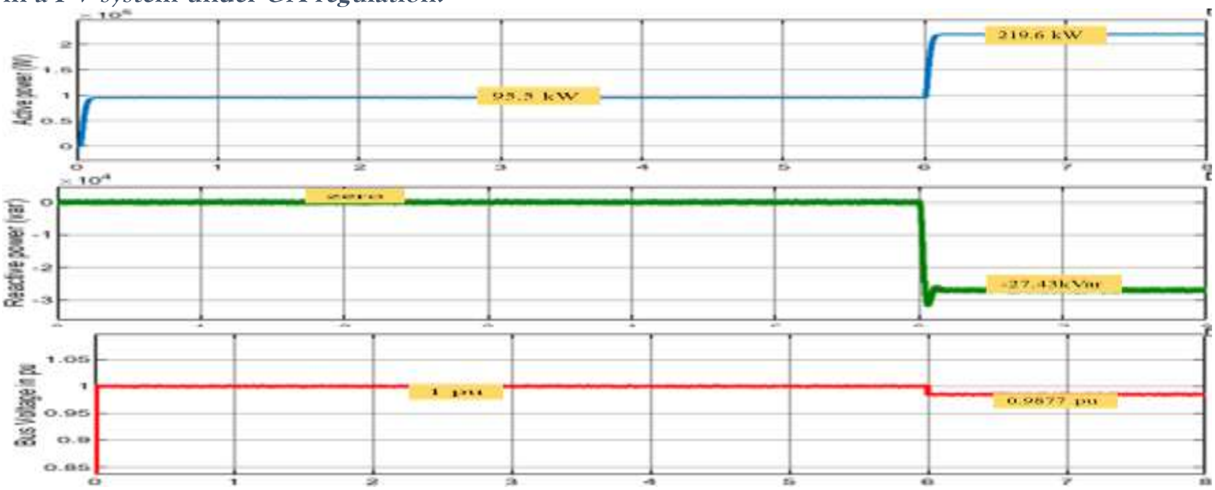


Figure 6 Figure 6 Depicts the dynamic performance of active power, reactive energy, and bus voltage in a PV system under PSO regulation.

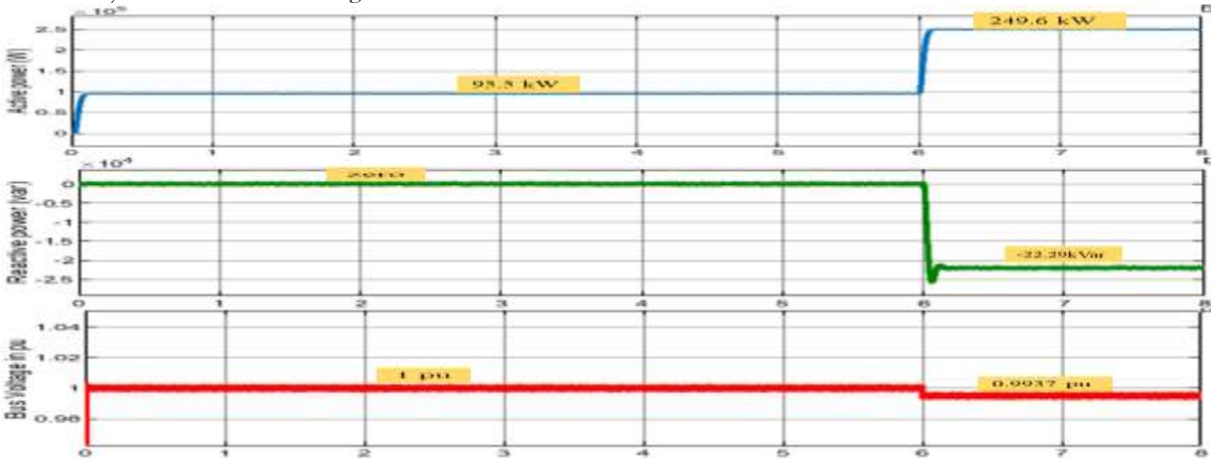
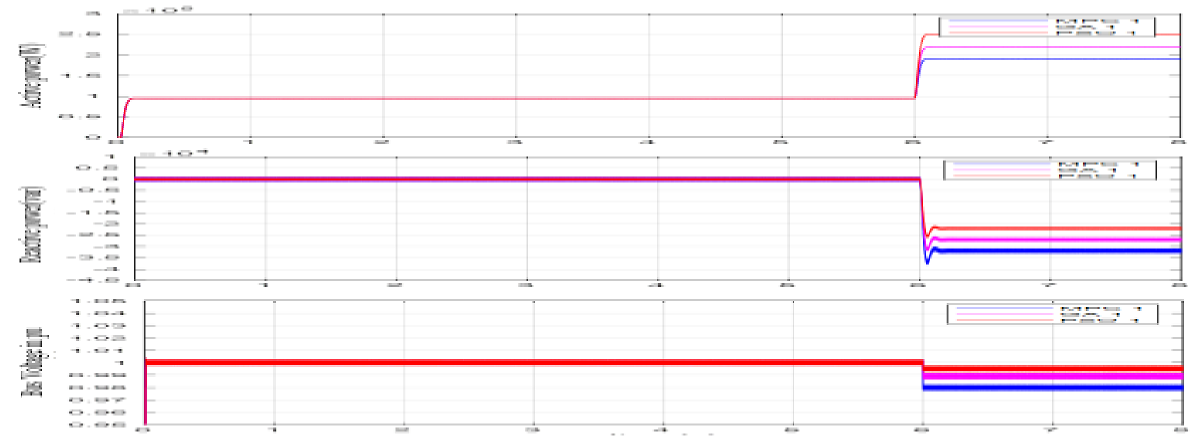


Figure 7 Figure 7 Demonstrates the differences in actual power, reactive power, and bus voltage under varied control situations when linear loads are used



PSO exhibits the lowest reactive power absorption from the grid, indicating improved reactive power compensation performance compared to other two controllers and control methods results demonstrate that voltage levels remain stable, highlighting the effectiveness of the controllers in maintaining voltage regulation.

Table 2 THD and TDD with different controls

	THD	TDD
Model Predictive Controller	7.25%	4.74%
Genetic Algorithm	5.65%	4.26%
Particle Swarm Optimization	3.26%	2.45%

Table 2 summarizes the THD and TDD performance across different control methods. The results show that under MPC and GA Total Harmonic Distortion (THD) exceed standard system limits, highlighting its limited effectiveness in harmonic mitigation. While PSO shows some improvement and the result is in the acceptable boundaries.

6. CONCLUSION

The study demonstrated that the Particle Swarm Optimization (PSO) strategy enhanced the hosting capacity (HC) of PV systems in Low-Voltage (LV) distribution networks. Comparative analysis against MPC and GA methods revealed that PSO significantly improved the critical performance indices, particularly under varying load conditions. Under linear load scenarios, the PSO strategy maintained a consistent active power output of 95.5 kW, which increased to 249.6 kW at full PV penetration (100%), thereby reflecting a 161.36% improvement in HC. This outcome underscores the PSO controller dynamic adaptability and superior tracking capability in accommodating higher levels of distributed PV generation without compromising system stability. In addition to real power performance, PSO yielded measurable improvements in reactive power control. The reactive power demand at the point of common coupling

(PCC) decreased from 27.43 kVar to 22.29 kVar corresponding to a 18.73% reduction, indicating enhanced efficiency in reactive power compensation. Furthermore, the bus voltage is 0.9937 p.u., enhancing power quality and system stability.

PSO demonstrated under distorted loading, effectively managing voltage and reactive power while minimizing harmonic impacts. Overall, PSO proves to be a scalable, reliable and intelligent control strategy for maximizing sustainable energy integration and securing the stable execution of LV distribution grids.

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