

ARTIFICIAL INTELLIGENCE DRIVEN OPTIMIZATION OF PV STATCOM PI CONTROLLERS FOR REGULATORY COMPLIANT POWER QUALITY IN MOROCCAN DISTRIBUTION NETWORK CONTEXT

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ABSTRACT

The present paper leverages artificial intelligence algorithms to optimize and tune the parameters of PI controllers to enhance the performance of a PV STATCOM in terms of both dynamic and static responses. The proposed approach's effectiveness has been validated using a distribution grid model feeding capacitive and inductive loads at the point of common coupling (PCC) and controlled by three PI regulators. Comparative analysis between the traditional PI controllers and the refined parameters through Particle Swarm Optimization (PSO) and genetic algorithm (GA) reveals that this method substantially enhances both the static and dynamic performance characteristics of the whole system and allows providing dynamic grid support in faulty conditions. In addition, it ensures power factor correction while injecting active power. The study is performed and tested under technical Moroccan regulations. The STATCOM is implemented between a PV array module and the PCC to the distribution network, which is typical of a standard structure in the presence of renewable generators. The PV STATCOM is not yet used in current Moroccan electrical network context and the proposed system effectively manages network variability and grid disturbances, notably enhancing power quality at the (PCC). It dynamically adjusts to supply or absorb reactive power as needed, all within an acceptable reversing time, ensuring stability and resilience in the network. MATLAB Simulink software is used to conduct simulation, which provides the best outcomes while complying to the technical constraints set by local regulations.

Keywords: Moroccan regulations, PSO, GA, PCC, PV-STATCOM, Power Factor correction, Reactive power compensation.

1. INTRODUCTION

Within a few decades, electricity has taken on increasing importance as a cornerstone of society, serving as the focal point of contemporary life and economic activity by supplying energy essential to improving living standards and driving businesses. Actual power systems, however, are highly sophisticated and must cross growing power demands while preserving acceptable quality and affordability standards. The increasing integration rate of renewable production into distribution networks, combined with their growing complexity, has created a need for advanced technologies to enhance grid stability and power

quality. In this context, the Photovoltaic Static Synchronous Compensator (PV-STATCOM) emerges as a crucial solution, combining renewable energy provision and Flexible AC Transmission Systems (FACTS) functions within a single power electronic device [1] to enhance power quality in distribution system operating in low and medium voltages. This solution offers lower integration costs and grid resilience while dynamically compensating for reactive power imbalances, voltage sags, and faulty conditions.

The reorganization of power utilities, coupled with regulatory constraints on distribution network expansion, has increased uncertainty in system operation, reducing stability margins and raising the risk of outages and blackouts. High-power electronic controllers, such as FACTS devices like

STATCOM's and D-STATCOM's, are recommended to regulate power losses and voltage disturbances, ensuring flexible operation. These devices, capable of dynamic voltage restoration and reactive power compensation (Varma et Al. 2018), are essential in addressing voltage fluctuations, reactive power demands, and harmonic reduction in the face of increasing renewable energy penetration [2]. The introduction of PV-STATCOM in the Moroccan distribution network is a significant step toward meeting the new, stricter grid code requirements for renewable energy supply [3]. It also presents an opportunity for the optimization of dynamic behavior in electrical distribution networks, particularly during faults or heavy load connections. Additionally, devices like the distribution STATCOM (D-STATCOM), when connected to a PV power supply, can help improve voltage stability, reduce power losses, enhance Total Harmonic Distortion [4], and manage reactive power, resulting in greater efficiency and reliability in power distribution systems.

This work explores the integration of PV-STATCOM capabilities within the Moroccan distribution network, demonstrating its potential to mitigate power quality issues through MATLAB/Simulink simulations [5]. These solutions promise to enhance voltage stability, regulate voltage sags, and provide a better electricity supply to customers, meeting the evolving demands of modern power grids and ensuring a sustainable and resilient electrical distribution system.

1.1. RESEARCH QUESTIONS

RQ1: Can evolutionary optimization techniques such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) significantly improve the performance of PI-controlled PV-STATCOM systems compared to conventional tuning methods?

RQ2: Is the exploitation of PV inverter capacity during non-generating periods (e.g., nighttime) technically effective and economically viable for reactive power support in distribution grids?

RQ3: To what extent does the proposed approach comply with Moroccan grid codes in terms of voltage regulation, power factor correction, and fault ride-through capability?

1.2. HYPOTHESIS

From the previous questions, the study formulates the following hypotheses:

H1: AI-based optimization of PI controller parameters leads to superior static and dynamic responses, including reduced overshoot, faster settling time, and improved voltage support at the PCC.

H2: The proposed PV-STATCOM configuration offers a viable alternative to conventional D-STATCOM systems, enabling effective reactive power compensation even in the absence of active power generation.

H3: The integration of the AI-optimized controller allows compliance with local technical constraints, facilitating grid code alignment while enhancing renewable integration potential and overall grid resilience.

2. LOCAL REGULATIONS

In many updated grid codes worldwide, photovoltaic power plants connected to medium voltage networks must maintain their connection during short circuits and rapid transient voltage variations, ensuring fault-ride-through (FRT) capability as required. Renewable production units are required to keep connected if the voltage of the phase with the lowest voltage remains above a specific threshold. Similarly, the Moroccan regulations include technical requirements for generators to provide reactive power support, specifying minimum and maximum reactive power levels, as well as the response time and ramp rate for adjusting reactive power output.

Voltage sags and swells are common disturbances in power systems, often caused by faults, large load changes, or the connection/disconnection of energy sources. To tackle these issues, grid codes worldwide define acceptable voltage ranges and specify equipment responses during such events. In the European Union, the EN 50160 standard sets limits for voltage variations and interruptions, requiring utilities to ensure continuity within specific thresholds, often using technologies like STATCOMs and Dynamic Voltage Restorers (DVRs) for compensation. The U.S. IEEE 1159 standard regulates voltage sags and swells, focusing on their impact on end-use equipment, and utilities deploy DVRs and Voltage Regulators to mitigate disruptions. China's GB/T 12325-2008 emphasizes rapid recovery from voltage fluctuations, particularly in high industrial areas,

with compliance supported by Static Var Compensators (SVCs) and STATCOMs. In India, the Central Electricity Authority (CEA) mandates voltage maintenance within $\pm 10\%$ of nominal values for medium- and high-voltage systems, with investments in Voltage Stabilizers, SVCs, and compensation devices ensuring regulatory compliance.

On the other hand, reactive power is crucial for voltage control and overall system stability, particularly during grid faults, and grid codes worldwide enforce its management to ensure fault ride-through (FRT) capability and voltage recovery. In the EU, Regulation (EU) 2016/631 mandates that power plants, especially renewables like wind and solar, remain connected during voltage dips and provide reactive power to maintain voltage stability, with Transmission System Operators (TSOs) requiring reactive power-voltage (Q-U) control. In North America, FERC Order 661-A requires wind power plants to inject reactive power during faults for voltage stabilization, using devices like STATCOMs and D-STATCOMs [6]. India's Central Electricity Authority (CEA) similarly mandates reactive power support from both traditional and renewable generators under low-voltage conditions, while Australia's National Electricity Rules (NER), enforced by the Australian Energy Market Operator (AEMO), require generators to dynamically adjust reactive power during grid faults to maintain voltage stability [7].

The Moroccan technical requirements concerning LVRT profile is presented in fig.1, which describes the evolution of the minimum voltage permitted at the point of connection. It is noted that asymmetric faults follow the same profile.

The following figure shows the FRT in local Grid code.

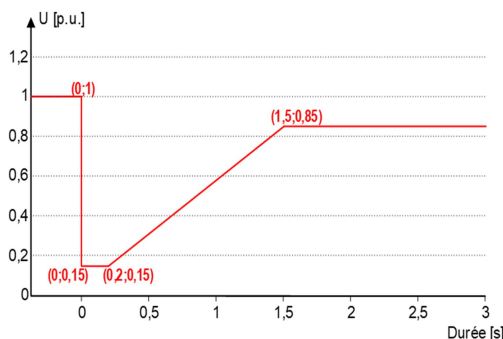


Fig. 1: FRT in Moroccan Grid Code.

The voltage dip withstand parameters are presented in relation to the nominal voltage (between phases) at the connection point.

In this work the LVRT capability of the grid is examined regarding technical requirements for the Moroccan code and the PV-STATCOM is used for reactive power compensation to achieve LVRT and improve dynamic performance of the distribution network and thus accelerate power system recovery undergoing faults or system perturbation. Likewise, to international grid codes, the Moroccan document includes technical requirements for generators to provide reactive power support, including the minimum and maximum levels of reactive power that must be provided, as well as the response time and ramp rate for changing reactive power output. It is noted that many recent research papers focused on the grid code compliant use of PV STATCOM and STATCOM in general since it improves the power quality at the connection point to the grid [8] [9].

The operating principle is proposed in fig. 2 given below.

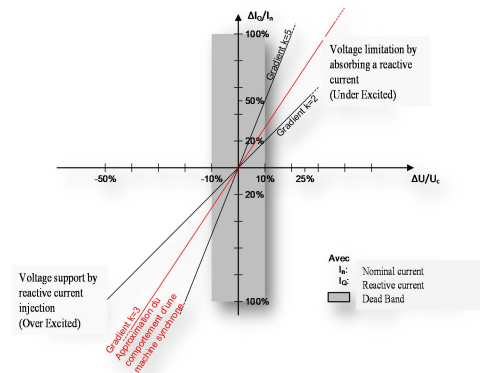


Fig. 2: Voltage support requirement during short circuit and voltage jumps.

It is observed that when the terminal bus voltage U of the DER unit deviates beyond the limits of the defined dead band (given in grey color), the generating unit is required to either inject or absorb reactive current. This action aims to regulate the voltage magnitude and bring it back within the acceptable range, as indicated by the shaded gray area in the accompanying figure.

3. STATIC SYNCHRONOUS COMPENSATOR

Reactive power can be supplied and absorbed by STATCOM, a power electronic based

reactive power compensation device that is connected in shunt to transmission and distribution networks. Instead of the controllable inductors and switched capacitors used in the static SVC compensator, the basic construction of the STATCOM device is built on a solid-state switching converter capable of generating or absorbing independently controllable active and reactive power at its output terminals. The world's first STATCOM was commissioned in Japan in 1991, and it was an 80 MVA device using 4.5KV – 3000A GTO devices [10].

The main goal of the first prototypes installations was to regulate the high voltage bus during load variations so that the duty on the tap changes on the transformer banks is reduced.

The advantages of STATCOM over SVC include its shorter response time, the fact that STATCOM installations require less space due to the elimination of bulky passive elements like inductors (which are necessary in SVC installations), and its ability to interface with various power sources such as capacitor banks, fuel cells, superconducting magnetic energy storage (SMES), or photovoltaic (PV) modules. Additionally, STATCOM offers higher overall performance compared to SVC.

STATCOM can be modelled as a voltage source with variable amplitude. As a result, it injects reactive power at the point where it is connected to the electrical network if its voltage amplitude is greater than the network voltage; This operating mode is called “Overexcited mode” where the STATCOM behaves like a variable capacitor. On the other hand, when the STATCOM voltage amplitude is less than the mains voltage amplitude, the STATCOM absorbs reactive power; this operating mode is called ‘under excited mode’ where the STATCOM behaves like a variable inductor [11].

It is mainly used for reactive energy compensation, voltage regulation and voltage stability improvement. It can also be adopted to improve the transient and dynamic stability of the receiving network and to increase the capacity of power transmission lines.

In the studied case of an electrical distribution network, D-STATCOMs have the benefits of limiting voltage swells caused by capacitor switching, reducing voltage sags due to feeder faults and customers load variation, and finally it contributes to increase the maximum load-ability of the whole electrical system.

A single phase STATCOM general schematic is given in fig. 3.

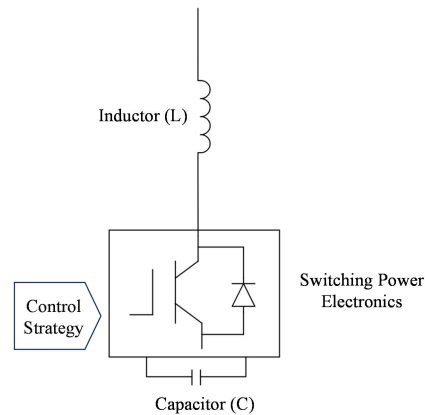


Fig. 3: Standard scheme of a grid connected STATCOM.

The voltage to current characteristics of the STATCOM function is given in fig. 4 presented below.

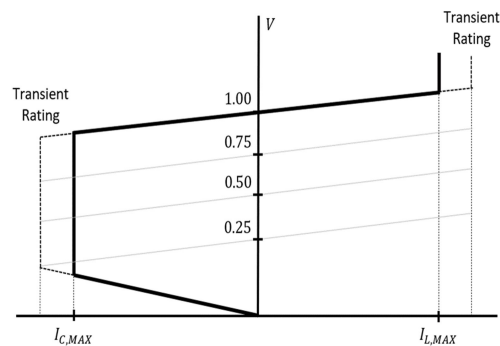


Fig. 4: STATCOM capacitive and inductive operation modes and maximum operating limits.

It is noted that STATCOM is functioning in voltage control mode in the slopped region between its maximums, where it either uses inductive vars to lower the voltage or supplies capacitive vars to raise it.

When operating at its maximums, the STATCOM is functioning in a VAR control mode, where it's supplying or consuming its maximum reactive output. It can supply its maximum capacitive rating at different voltage values at the connection point. Usually, a STATCOM is set to ride through voltage drops of around 0.3 p.u. or lower, so it can perform low voltage ride through requirement dictated by local grid requirements.

Additionally, a STATCOM may have a transient rating, which enables it to support the system more

effectively in the event of more faults by temporarily exceeding its maximum current. This rating depends on the specific design but can be as high as 3.0 p.u. in specific configurations and with appropriate electronic protection.

The injected current to the Line is given by the equation Eq. 1.

$$I_s = \frac{V_s - V_L}{jX_L} \quad (1)$$

The injected power to the PCC (Line L) is given by the equation (2).

$$S = \frac{V_L(V_s - V_L)}{-jX_L} = \frac{V_L V_s - V_L^2}{-jX_L} \quad (2)$$

And the injected active and reactive powers by the STATCOM are given below (3, 4).

$$P_s = -V_L V_s \frac{\sin(\theta_L + \theta_s)}{X_L} \quad (3)$$

$$Q_s = V_L \frac{V_s \cos(\theta_L - \theta_s) - V_L}{X_L} \quad (4)$$

Where:

V_L : Line voltage

V_s : STATCOM voltage

Q_s : Injected reactive power

P_s : Injected active power

The figure below (fig. 5) presents the capacitive and inductive mode of the STATCOM operation.

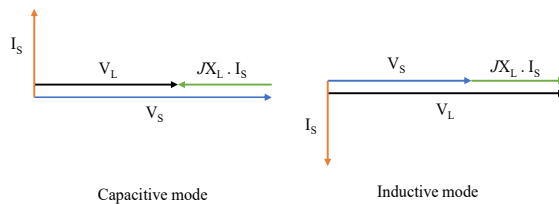


Fig. 5: voltage to current characteristic of the STATCOM function.

4. CASE STUDY OF THE PV-STATCOM

The integration of PV technology with a STATCOM involves combining the solar power generation capabilities with the voltage control and compensation features of the STATCOM.

This integration allows the device not only to contribute clean energy but also to actively support

the stability and quality of the electrical grid. It offers the benefits of both renewable energy generation and grid support. It can contribute to the reduction of greenhouse gas emissions, enhance grid reliability, and improve the overall efficiency of the power system [12]. It is noted that fault tolerant aspects of integrating PV-STATCOMs to the distribution networks manifests essentially in dynamic reactive power support, reduction of post fault voltage dip [13], grid support during fault recovery and preventing islanding by remaining synchronized to the grid [14].

The PV-STATCOM is mainly used in the distribution network to supply reactive power during distribution grid faults and when the solar production is not available to maintain acceptable power quality and is intended to supply or absorb reactive power at the point of common coupling to the network PCC if necessary, in this case the PV-STATCOM performs dynamic reactive power support as FRT behavior and support the grid voltage during fault occurrence [15]. It also helps control transient over voltages caused by asymmetrical faults [16].

The considered grid integration schematic of the PV-STATCOM is shown below in fig. 6:

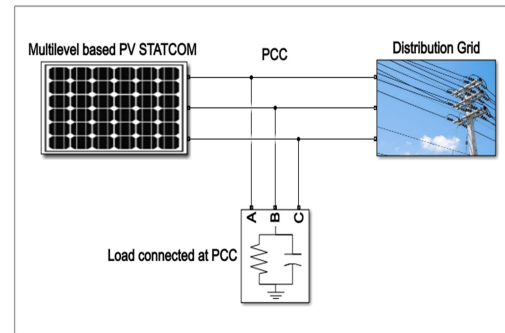


Fig. 6: The general use case of the PV-STATCOM in electrical networks.

We notice that the interface between the solar plant and the distribution network is exposed to numerous disturbances in the quality of the energy delivered to the network due to the presence of power electronics components that allow power injection or even Load connection and disconnection which imposes to guarantee regulatory requirements such as the Fault Ride Through, the frequency and voltage withstand, and the injection of reactive power when needed.

The PV power plant design is described in the section below.

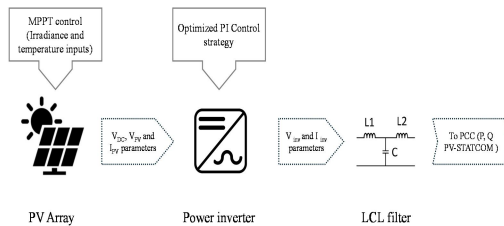


Fig. 7: Schematic of the PV power plant connected to PCC.

As shown in fig. 7, an LCL filter is integrated between the inverter and the PCC, the capacitor value is determined by the maximum absorbed reactive power of 5% of the rated power and the inductance value is designed regarding the maximum value of the voltage drop across it limited to 20% of the grid supplied voltage.

5. CONTROLLER TUNING METHODS AND CONSTRAINTS

The tuning of PI and PID controllers is carried out via a multitude of optimization methods for the parameters K_i , K_d , K_p , whether they are the classic methods used for some time which are Ziegler-Nichols Method, Cohen-Coon Method, Manual Tuning, Åström-Hägglund (Relay) Method, Tyreus-Luyben Method, Internal Model Control (IMC) Tuning. These techniques are based on process models and conventional control theory. Usually, they adjust controller parameters like the proportional and integral gains using mathematical formulas that are derived from system reactions such as oscillations or time constants [17]. These are simple, rule-based, and frequently made for specified system configurations such as dead-time or first-order processes.

A relatively recent approaches of controller tuning that makes use of data-driven strategies is artificial intelligence or machine learning. AI techniques, which are generally categorized under several classifications like Genetic Algorithms (GA), Neural Networks (NN) [18], Fuzzy Logic Controllers (FLC), Grey Wolf Optimization (GWO) [19] and Reinforcement Learning (RL), can automatically perform better tuning parameters through experience or simulations. They are usually applied to more complicated systems where real-time flexibility is necessary or when traditional techniques may not be sufficient. While

AI approaches are data-driven, adaptable, and able to learn and improve over time, classical approaches are rule-based and deterministic [20].

In literature we found that Particle Swarm Optimization (PSO) [21] and Genetic Algorithm (GA) are usually considered as the best choices for a Power Electronics application such as PV-STATCOM system, which involves nonlinearity, time-variability, and numerous objectives (such as reactive power supply, voltage stability).

Many research articles have concentrated on these two approaches since GA is more robust for complex and nonlinear systems, making it a good option for systems that may encounter high levels of disturbances or uncertainties, and PSO provides faster convergence and is computationally efficient, making it perfect for real-time applications like STATCOMs, where the controller must react swiftly to grid changes [22]. The basic PI controller design is described by the fig. 8 shown below.

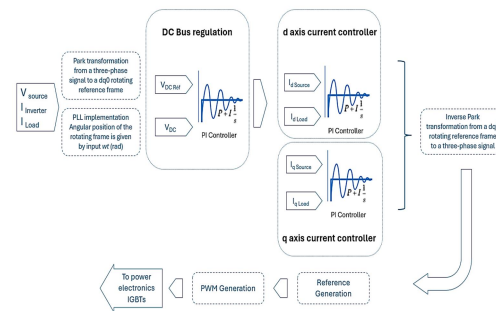


Fig. 8: Schematic of the PV power plant connected to PCC.

The PV-STATCOM controller is designed by using two bus systems to generate reactive power. The three-phase inverter's PWM (pulse width modulation) pulses are generated via an adaptation of parameters based on Pq theory. The PI-controller is used to regulate the DC-bus voltage as well as the direct and quadratic axis current.

The source voltage is transformed to its (α, β) components and then synchronized to the grid frequency, a phase locked loop is applied on (α, β) components of grid voltages to generate (ωt) parameter, and the reference for the PWM module is generated by the combined $(d$ and $q)$ axis current controllers and DC bus controller based on a given voltage reference ($V_{dc} = 800$ V).

Genetic algorithm and Particle swarm optimization PI tuning methods

The optimal tuning of PI controller parameters, specifically the proportional gain and the integral gain K_p, K_i remains a challenge for engineers, as inadequate tuning can lead to suboptimal performance, oscillations, or even system instability [23]. In this context, advanced optimization methods, such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), present viable ways to automatically and methodically determine the ideal settings.

Inspired by the concept of natural evolution, the Genetic Algorithm explores the search space and converges towards an ideal solution through the mechanisms of crossover, mutation, and selection. In complex, nonlinear search contexts, where it would be challenging to find the ideal response using conventional, heuristic-based tuning techniques, this algorithm performs very well.

Particle Swarm Optimization, on the other hand, was developed by Kennedy and Eberhart, is a population-based stochastic optimization technique [24] that has been widely and successfully applied across various research domains due to its versatility. It is based on cooperation between particles to explore and exploit the search space by continuously modifying particle positions and velocities towards the best collective solution found. It derives inspiration from animal social behavior, including flocking birds or swarms of fish. PSO is known for its minimal computational cost and quick arrival of solutions close to the global optimum.

In this work, we propose a comparison of PI parameter optimization performance using GA and PSO for the PV STATCOM controller, assessing their respective performance in terms of tracking accuracy, response time, and system stability [25]. This analysis highlights the strengths and limitations of each approach and provides practical suggestions for their effective implementation in various control systems [26]. The obtained results demonstrate that these optimization techniques can significantly improve PI controller performance, offering a reliable and automated approach to control parameter tuning and allow even an online fine tuning in case of disturbances and dynamic behavior of the loads connected to the distribution grid.

The fig. 9 gives the general flow chart of GA method.

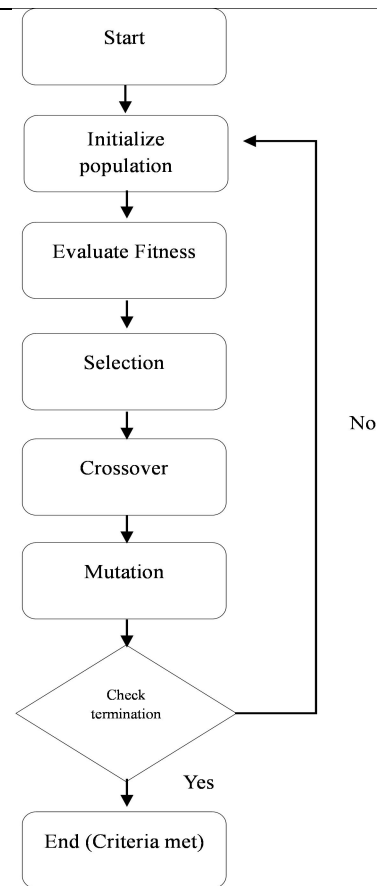


Fig. 9: Flow chart of GA optimization.

The genetic algorithm is an optimization approach used for solving both constrained and unconstrained problems by mimicking the process of natural selection observed in biological evolution. This method iteratively adjusts the population of possible solutions. In each iteration, the algorithm selects individuals from the existing population to act as parents, generating offspring to form the next generation. Through multiple generations, the population gradually advances toward an optimal solution. We can apply the genetic algorithm to solve a variety of optimization problems including cases in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear [27].

The main algorithmic steps are depicted in the figure below.

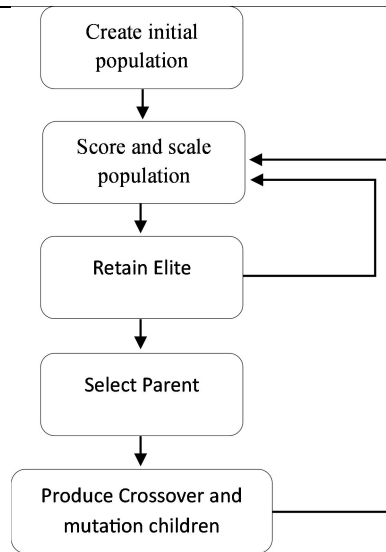


Fig. 10: Main GA steps.

The main basis is that each individual (solution) in the GA population represents a candidate set of controller parameters:

$$\text{Chromosome} = [K_p \quad K_i] \quad (5)$$

For each individual, fitness is computed using a performance criterion defined as Integral of Time-weighted Absolute Error (ITAE) as:

$$\text{Fitness} = \frac{1}{J(K_p, K_i)} \quad (6)$$

Where $J(K_p, K_i)$ is a cost function that measures the system's performance, such as:

Integral of Absolute Error (IAE):

$$J = \int_0^T |e(t)| dt \quad (7)$$

ITAE :

$$J = \int_0^T t |e(t)| dt \quad (8)$$

Integral of Squared Error (ISE):

$$J = \int_0^T e^2(t) dt \quad (9)$$

Here, $e(t)$ is the error between the desired setpoint and the system output.

Individuals are then selected based on their fitness values, often using random selection or tournament selection:

$$P_i = \frac{\text{Fitness}(i)}{\sum_{i=1}^N \text{Fitness}(j)} \quad (10)$$

Next the crossover step combines the K_p and K_i of two parent solutions to generate offspring.

In the mutation phase, random small changes are applied to K_p or K_i with a probability p_m :

$$K_p^{\text{new}} = K_p^{\text{old}} + \Delta K_p \text{ and } K_i^{\text{new}} = K_i^{\text{old}} + \Delta K_i \quad (11)$$

Where ΔK_p and ΔK_i are small random perturbations within predefined bounds.

The next population combines elite individuals and offspring as:

$$\text{Population}_{\text{next}} = \text{Elite}_{\text{current}} \cup \text{Offspring} \quad (12)$$

Where:

$$\text{Offspring}_1 = [K_{p_1}, K_{i_2}] \quad (13)$$

$$\text{Offspring}_2 = [K_{p_2}, K_{i_1}] \quad (14)$$

And:

$$\text{Offspring}_i[j] = \begin{cases} \text{Parent}_1[j] & \text{if random } r < 0.5 \\ \text{Parent}_2[j] & \text{otherwise} \end{cases} \quad (15)$$

Is the uniform crossover.

Finally, the algorithm stops after a fixed number of generations or when the fitness converges to the desired objective. It allows defining the optimal values of proportional and integral Pi parameters to perform the desired performance.

The GA parameters used in the present work are given in table 1.

Table 1: system parameters

Population size	50
Maximum generations	100
Number of variables	4
Lower bound	0
Upper bound	100
Constraint tolerance	1e-03
Function tolerance	1e-06

PSO general principle:

The simple principle is that several particles spread over the search region at their starting locations during the initialization phase. Every

particle's starting position automatically becomes its starting best position. The global best position of the swarm is determined by selecting the most advantageous of the best places that each particle retains. Every iteration begins with the calculation of a velocity vector for each particle, after which the current particle positions are modified in accordance with the velocity vectors. Furthermore, the objective function value is compared to the modified positions. These iterations are carried out repeatedly until the stopping requirement is met or until a predefined maximum number of iterations has been reached [28]. This method is widely used in PID controllers tuning for VSC use in renewable energy combination [29].

The general flow chart of PSO method is given below.

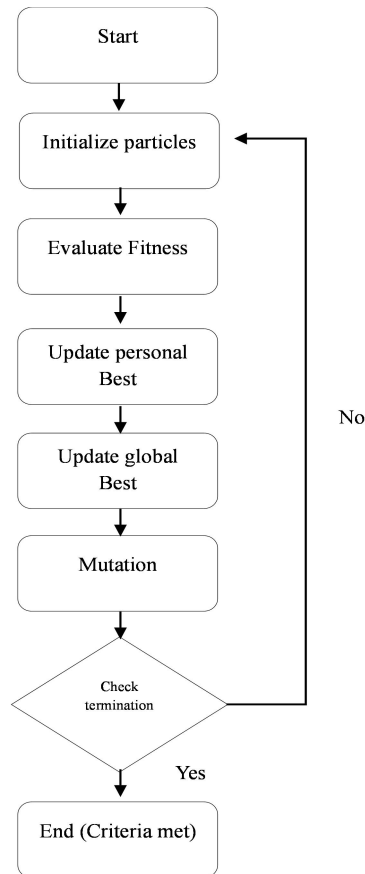


Fig. 11: Flow chart of the PSO method.

The iterations are carried out recurrently until the stopping requirement is met or until a predefined maximum number of iterations has been reached. The locations of local particles in the exploration field are updated as:

$$X_{k+1}^i = X_k^i + V_{k+1}^i \quad (16)$$

where the velocity of the particles V_{k+1}^i is calculated as:

$$V_{k+1}^i = V_k^i + C_1 r_1 (P_k^i - X_k^i) + C_2 r_2 (P_k^g - X_k^i) \quad (17)$$

Where:

X_k^i is the particle location,

V_k^i : particle velocity,

P_k^i : optimal position of the specified particle,

P_k^g : optimal location of the swarm,

C_1, C_2 : cognitive (personal best) and social (global best) parameters

r_1, r_2 random numbers between 0 and 1.

Table 2 presented below shows the selected parameters of PSO method.

Table 2: system parameters

Number of particles	30
Iterations	25
Number of variables	4
Lower bound	0
Upper bound	1000
Inertia weight (w)	0.8
Personal best	1.5
Social best	1.5

The PSO tuning method was verified according to the global best value of the objective function which is represented by the following profile.

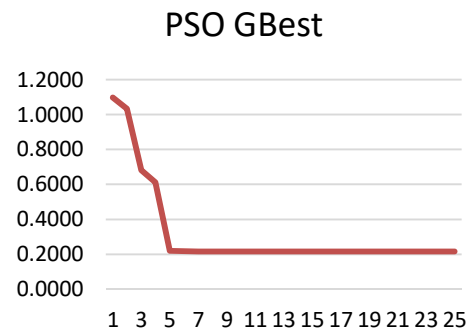


Fig. 12: PSO GBest profile.

The Convergence is achieved quickly (after approximately 8 iterations), demonstrating the algorithm's effectiveness in optimizing the PI controller parameters. The stabilization of values

indicates a thorough exploration of the search space by the algorithm. This shows that the optimized parameters obtained are robust.

In final, classical tuning algorithms generate a single point per iteration, advancing deterministically toward an optimal solution [31]. Genetic algorithms, on the other hand, generate a population of points per iteration and use random number generators to evolve the population so the best point gradually approaches an optimal solution. In contrast, Particle Swarm Optimization maintains a swarm of particles (potential solutions) that move through the search space, updating their positions based on their own experience and that of their neighbors, converging toward an optimal solution through collaboration and adaptive exploration.

The intelligent tuning parameters for both GA and PSO methods are kept minimal as much as possible to prevent increasing the calculation time needed to perform the operation.

6. STUDY DESIGN AND RESEARCH PROTOCOL

The research protocol involves the construction of a detailed model of a medium-voltage distribution feeder incorporating photovoltaic (PV) generation interfaced through a voltage source inverter. The inverter is configured to operate in both active and reactive power control modes, with the capability to inject or absorb reactive power during daytime and nighttime periods. Capacitive and inductive loads are connected at the point of common coupling (PCC) to represent realistic consumption scenarios and stress test the voltage regulation capacity of the system. Fault scenarios and load variation conditions are also introduced to simulate typical disturbances encountered in distribution networks.

Controller design is central to the study. Three PI regulators are implemented: one for DC-link voltage control, one for reactive power control, and one for current regulation. The initial gains are selected using classical tuning methods and then optimized using two distinct algorithms which are GA and PSO. The optimization objectives include minimizing voltage deviation at the PCC, reducing overshoot during disturbances, and ensuring fast settling time without oscillations. Each algorithm is executed with its specific population size, iteration limits, and convergence criteria. Performance metrics such as total harmonic distortion (THD), voltage profile, reactive power

injection capacity, and dynamic response time are computed to benchmark the different control strategies.

All simulations are conducted using MATLAB/Simulink, where grid voltage, PV generation profile, and load dynamics are parameterized to reflect realistic conditions consistent with Moroccan grid code specifications. The simulation environment also includes blocks simulating faults, grid impedance, and switching behavior of the inverter. The experimental design ensures reproducibility and allows direct comparison between the three controller variants (PI-classical, PI-GA, PI-PSO), highlighting the contribution of AI-based optimization in enhancing PV-STATCOM performance under regulatory and operational constraints.

7. SIMULATION RESULTS AND DISCUSSION

In this simulation, we are considering inductive and capacitive loads connected to the injection point of the PV power plant and powered by both the grid and the PV unit. It consists of a PVSTATCOM power inverter connected to PCC of distribution network over an LCL filter, an RL load is connected to the PCC and an RC active load is added at $t = 0.35$ s. This configuration is adopted to test the system response under tense conditions.

The simulation concerns full STATCOM mode, PV STATCOM mode and power factor correction using standard MATLAB tuned PI parameters and artificial intelligence tuning methods.

STATCOM Mode

In the present section, the PV STATCOM is used in full STATCOM mode (illustrated by night-time mode or daytime faulty condition). The power plant provides reactive power through the inverter to the PCC and the grid continues to feed the active power demand of the connected loads. The simulation is performed using MATLAB Simulink environment.

At $t=0.02$ s the STATCOM mode is active, an inductive load is connected to PCC and no active power is provided by it whereas the full active power demand is fulfilled by the grid and the reactive power is delivered by the STATCOM.

At $t=0.35$ s a capacitive load is connected to the system and the STATCOM responds by absorbing

reactive power as illustrated in Fig. 14 and 15 presented below.

The general topology of the simulated system is given in fig. 13.

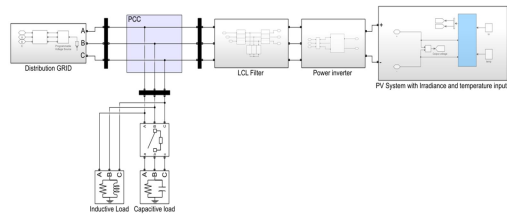


Fig. 13: STATCOM mode system topology.

In this section, the simulation is performed using classic iterative tuning method for direct axis and quadratic axis current PI controllers, the loads connected at PCC are 150 kW, 15 kVAR inductive load and 300 kW, 60 kVAR capacitive load respectively.

The PCC voltage is shown in Fig 14. The voltage remains regulated after the connection of the second load at 0.35s at the point of common coupling PCC.

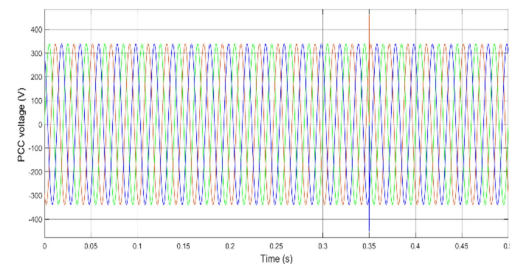


Fig. 14: PCC voltage during simulation.

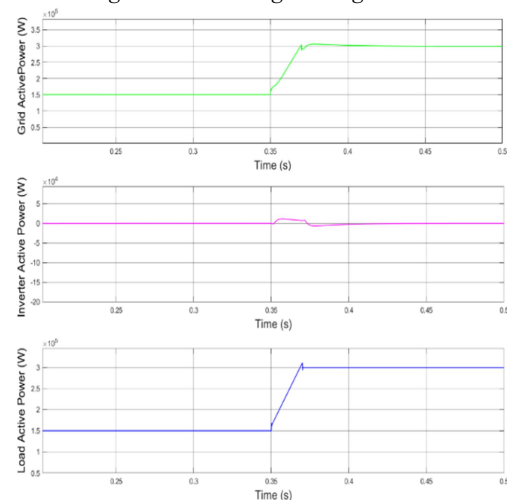


Fig. 15: Active power of the grid, inverter, and load.

The device acts in STATCOM mode and provides necessary reactive power in both inductive and capacitive configurations. We note that the PI controller's parameters are tuned using classic iterative method for this section.

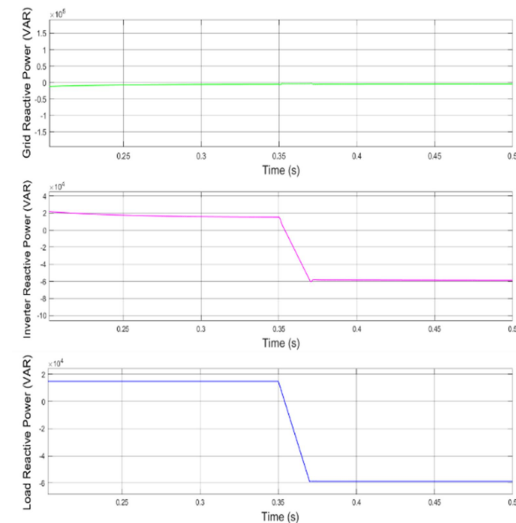


Fig. 16: Reactive power of the grid, inverter, and load.

The asynchronous phase between the phase A voltage and current is given by fig. 17.

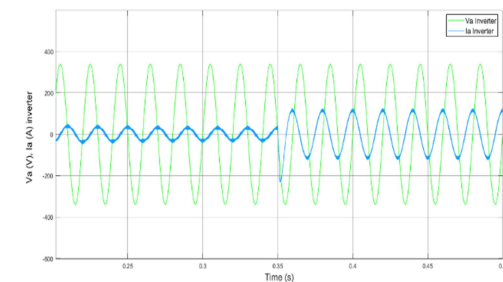


Fig. 17: Voltage and current of the STATCOM in inductive and capacitive modes.

The current injected by the STATCOM follow the PCC requirement for inductive and capacitive modes, the simulation was conducted while switching between the two modes to test the system response speed. The voltages at PCC are kept stable even after the reconnection of the large load and the inverter response is within 0.02 s which is enough to satisfy the requirements of the local grid code.

In the next section of simulation results, the Genetic algorithm (GA) and Particle swarm optimization (PSO) methods were applied to tune the d and q axis current PI controllers which allows improving the response of the system in

reactive power injection under different load configurations. The system response is given below.

The system parameters used in the simulation model are mentioned in table 3.

Table 3: system parameters

Inductive load active power	150 kW
Inductive load reactive power	15 kVAR
Capacitive load active power	300 kW
Capacitive load reactive power	60 kVAR
Frequency	50 Hz
d axis PI optimized parameters (current regulator) GA method	$K_i = 866.3605$ $K_p = 627.0492$
q axis PI optimized parameters for current regulators (GA method)	$K_i = 6.323592462254095e^{-02}$ $K_p = 1.6261173551946306e^{-02}$
d axis PI optimized parameters for current regulator (PSO method)	$K_i = 0.25$ $K_p = 0.4669$
q axis PI optimized parameters for current regulator (PSO method)	$K_i = 95.2415$ $K_p = 1.1902$
Voltage reference	800 V
LCL Filter inductance	$500e^{-06}$ H
LCL Filter capacitance	$100e^{-06}$ F
DC bus capacitance	$5600e^{-06}$ F

The system response as a STATCOM is depicted in Fig. 18 and 19.

The tuning method consists of using two intelligent methods to optimize the proportional and integral parameters of the current regulators for direct and quadratic components of the connected load and PCC. The methods used are Genetic Algorithm and Particle Swarm Optimization.

The legend of the fig. 17 presents the different tuning methods used for comparison.

The active power comparison is given on Fig. 18.

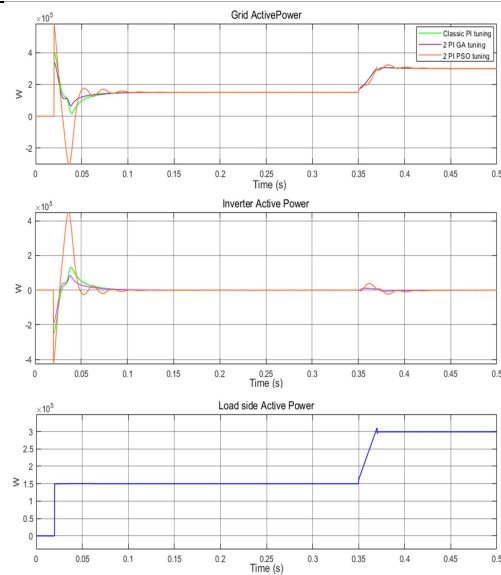


Fig. 18: Active power profiles for standard tuning, GA 2 PI tuning and PSO 2PI tuning.

A detailed view of the active power response of the system is given below in fig. 19 using GA tuning method showing the best results.

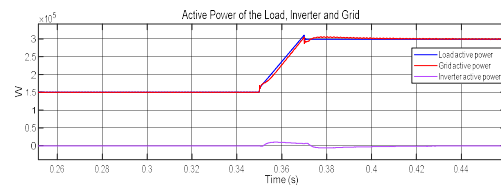


Fig. 19: Zoom on the active power response in STATCOM mode.

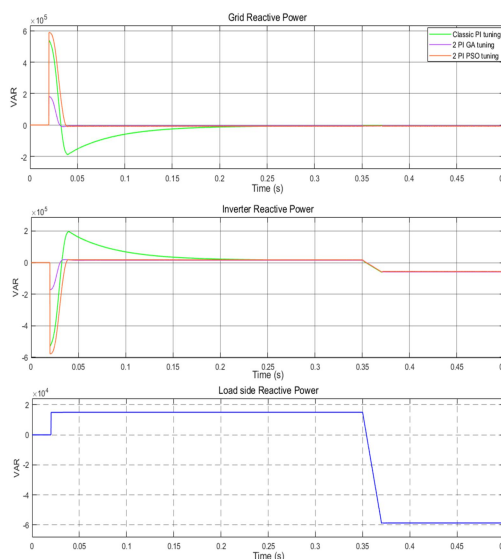


Fig. 20: Reactive power profiles for standard tuning, GA 2 PI tuning and PSO 2 PI tuning.

A detailed view of the active power response of the system is given below in fig. 21 using GA tuning method showing the best results.

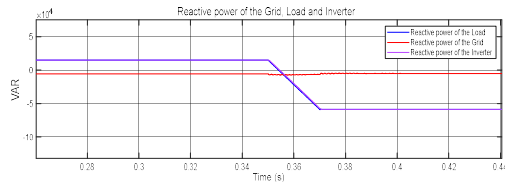


Fig. 21: Zoom on the reactive power response in STATCOM mode.

It is noted that the system performance is primarily affected by the PI controller's parameters. A transient simulation is used to assess the designed controller's performance. The two approaches are effective at finding the global optimum, have a faster convergence rate, use less computing time, with fewer function parameters. It is also found that GA performs better than PSO in the search for the optimized proportional and integral values especially for reactive power supply and absorption.

The full STATCOM mode allows us to partially achieve the low voltage ride through capability by supporting the distribution grid voltage when supplying full inverter capacity reactive power to the network.

The power factor (PF) value of the simulated system at PCC is maintained at an acceptable value regarding local requirements (minimum value: 0.8). The STATCOM mode is disabled at $t = 0.42$ s to present the effect of the system on the PCC power factor which drops to 0.98.

The figure below shows the power factor profile of the simulated system.

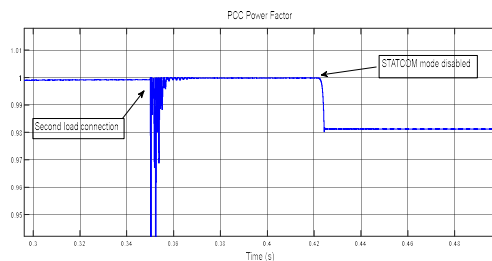


Fig. 22: Power factor profile of the system in STATCOM mode.

PV STATCOM mode

In this part of the work, the PV STATCOM is used in PV injection and partial STATCOM mode. It uses the available capacity of the inverter to

compensate for reactive power at PCC in parallel with injecting its rated active power. The power plant also provides reactive power through the inverter to control the power factor and to bring it to an acceptable value close to unity as much as possible.

The considered load for this part of the simulation is set to fixed values of resistance and inductance requiring 25 kW and 100 kVAR respectively, the power factor is initially set at 0.75 and the PV STATCOM mode is disabled at $t=0.25$ s to confirm the inverter contribution by injecting the reactive power at PCC.

The PV array V-I and P-V characteristics are given in fig. 23 below.

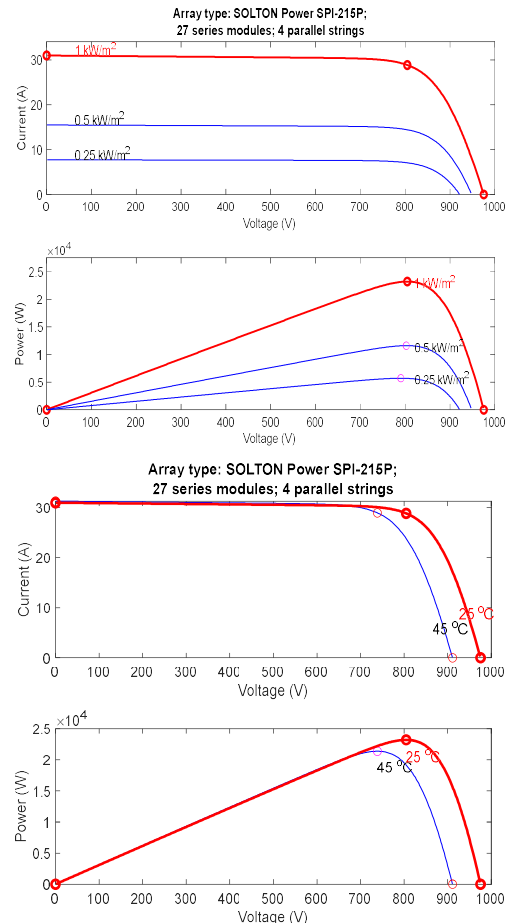


Fig. 23: I-V and P-V characteristics of the PV array for fixed temperature and irradiance.

The system response in active and reactive power of the Grid, Inverter and Load are given in fig. 24 and 25.

The PV STATCOM is connected to the system and supplies the full active power of the PV power

plant through the inverter and is sufficient to feed the connected load.

At time 0.25 s the partial STATCOM mode is disabled to check the inverter contribution of injected reactive power at PCC.

It is noticed that the device injects reactive power equal to the load requirement to compensate for it while satisfying the active power demand within its capacity limit.

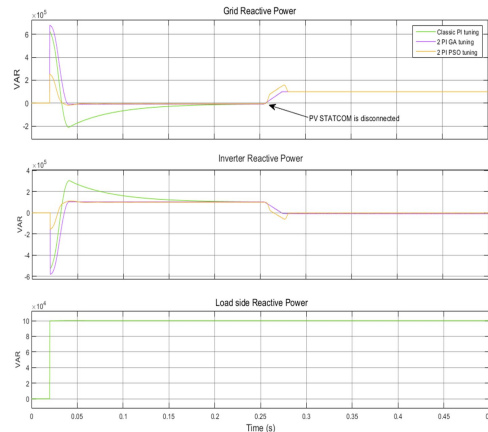


Fig. 24: Reactive power of the grid, inverter, and load in partial PV STATCOM mode.

Fig. 24 presents the grid, inverter and load reactive power profiles for different values of PI parameters as given in Table 3, the three simulation modes presented are: classic iterative method (Ziegler-Nichols), genetic algorithm method and particle swarm optimization method. The artificial intelligence methods parameters are given in table 1 and table 2 respectively.

The GA method presents better convergence time and offers a good dynamic response, while the PSO method shows a faster convergence than GA and classic iterative one, but less robust for dynamic changes in the system behavior.

To test the contribution of the PV STATCOM at the connection point, the inverter is deactivated at $t=0.25$ s and the fig. 25 shows that the network at the PCC supplies the necessary reactive energy instead of the it, which demonstrates the contribution of the device for the injection of the reactive energy requirement at the connection point.

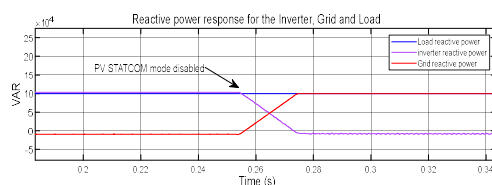


Fig. 25: Zoom on the reactive power response in partial PV STATCOM mode.

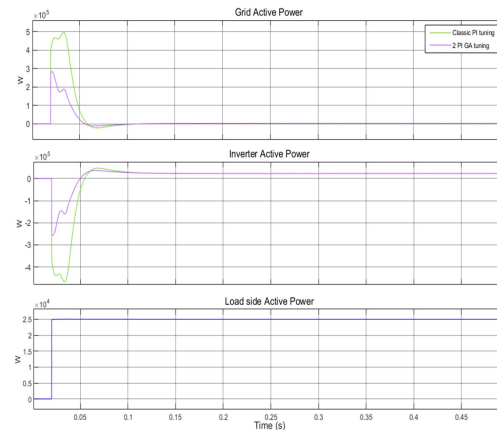


Fig. 26: Active power of the grid, inverter, and load in partial PV STATCOM mode.

The analysis of the system response confirms the conclusion about reactive power response.

A detailed view of the active power response of the system is given below in fig. 27 using GA tuning method.

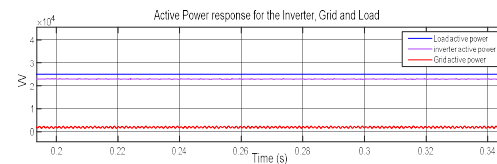


Fig. 27: Zoom on active power response in partial PV STATCOM mode.

The presented profiles confirm that the PV STATCOM continue supplying active power during daytime while providing the necessary reactive power when needed.

The phase A voltage and injected current are given in fig 28. It shows the system response to provide the necessary reactive current at the connection point of the PV system.

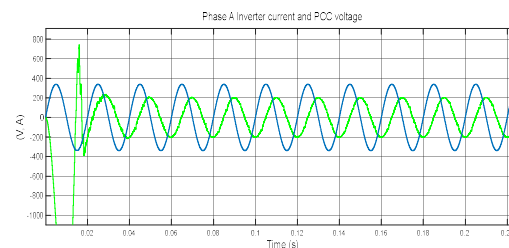


Fig. 28: PCC voltage and injected current by the PV STATCOM.

After the transient state (0.02s) the current stabilizes into a sinusoidal waveform and leads the voltage, which is characteristic of reactive power injection, it aligns with the voltage in terms of

frequency, indicating proper synchronization with the grid.

The current THD analysis of the proposed system is resented below based on fast Fourier transform (FFT) algorithm on MATLAB.

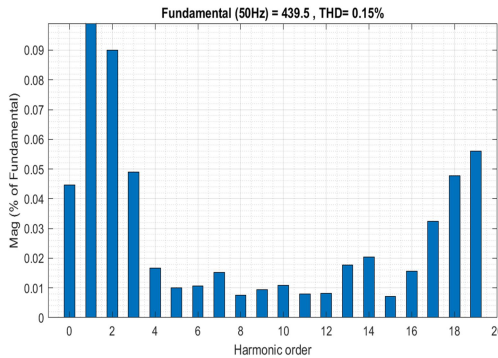


Fig. 29: Current THD response of the system in PV-STATCOM mode.

The current THD at the load side is given in fig. 30 and is below the limited value of 2% required by the local grid code. The power factor is regulated above 0.8 value which proves that the system performance could be used to provide power factor correction in daytime while ensuring active power injection to the distribution grid.

Table 4: PV STATCOM simulation parameters

Parameter of the simulation	Value
Grid voltage	415 V
Inductive Load Active Power	25 kW
Inductive Load Reactive Power	100 kVAR
Frequency	50 Hz
Filter inductance	500 e-6 H
Filter capacitance	100 e-6 F
Vdc bus reference	800 V
Rated PV plant power	100 kW
Switching frequency	10 kHz
Resonant frequency	1 kHz
PV type	SOLTON Power SPI-215P
V PV nominal	800.1 V
I PV nominal	28.99 A

8. DISCUSSION

Several recent studies have explored the use of AI-based optimization for reactive power compensation and voltage regulation in power

systems. For instance, works involving GA- or PSO-optimized D-STATCOM or PV inverter systems have demonstrated improvements in dynamic voltage support and reduction in total harmonic distortion (THD). Compared to these existing studies, the present work extends the scope by integrating the PV-STATCOM into a realistic Moroccan distribution grid context, with detailed modeling of local load conditions, fault scenarios, and compliance with national grid code specifications. Moreover, it specifically leverages the idle capacity of PV inverters during nighttime, which remains underexplored in many published studies.

In terms of performance, the proposed method yields faster convergence and more stable voltage profiles at the PCC when compared to conventional PI controllers, aligning well with previously reported improvements in similar applications. However, unlike some works that incorporate complex neural or fuzzy logic systems, the present approach remains relatively simple and adaptable for field deployment, which increases its practical relevance. The comparative advantage lies in the balance between performance gain and implementation simplicity.

In response to the first research question (RQ1), simulation results confirm that both GA and PSO significantly improve the dynamic and steady-state performance of PI-controlled PV-STATCOM systems compared to conventional tuning. GA offers higher precision and robustness, while PSO ensures faster convergence, making it suitable for real-time control. Regarding RQ2, the proposed configuration demonstrates the effective use of PV inverters during non-generating periods for reactive power support, offering a cost-efficient alternative to standalone compensators by repurposing existing infrastructure. For RQ3, the results show compliance with Moroccan grid code requirements in terms of voltage regulation, fault ride-through, and power factor correction, validating the approach's regulatory relevance. Nonetheless, the current work remains limited to simulation and does not yet include experimental validation or harmonic distortion analysis, which should be addressed in future studies.

Nevertheless, the current work presents certain limitations that merit further investigation. Firstly, the analysis is based entirely on simulation, and real-time implementation using hardware-in-the-loop (HIL) or DSP platforms remains to be conducted. Secondly, while the study considers both capacitive and inductive loads, it does not cover all possible grid disturbances such as long-

duration voltage sags or harmonic-rich industrial scenarios. Finally, the focus is limited to two optimization techniques (GA and PSO) whereas hybrid and adaptive AI algorithms could further enhance controller tuning in future studies.

9. FUTURE RESEARCH DIRECTIONS AND OPEN ISSUES

Although the proposed PV-STATCOM configuration demonstrates strong potential in enhancing voltage support and power quality under various load and fault conditions, further research is necessary to generalize its applicability and improve its adaptability to evolving grid requirements. One of the primary avenues for exploration lies in the integration of adaptive and real-time control mechanisms. While the current approach based on offline tuning via GA and PSO yields impressive results, it lacks the responsiveness needed in dynamic environments. Future work could focus on the development of hybrid controllers that combine artificial intelligence with real-time optimization techniques, allowing the PV-STATCOM to self-adjust to changing network conditions without human intervention.

A second research direction involves expanding the optimization objectives beyond voltage regulation and power factor correction. In actual grid scenarios, several competing constraints must be simultaneously satisfied, such as minimizing harmonic distortion, managing inverter thermal limits, and optimizing operational costs. Developing multi-objective optimization frameworks that incorporate these constraints can enhance the overall reliability and economic viability of PV-STATCOM systems. Furthermore, incorporating predictive control strategies based on real-time forecasting of solar generation and load demand may help in anticipating disturbances and taking preventive actions before instability occurs, especially in networks with high renewable energy penetration.

Another important challenge is the integration of PV-STATCOM systems into the broader cyber-physical infrastructure of smart grids. This requires addressing critical issues such as communication delays, data loss, cyber vulnerabilities, and the need for coordinated control with other distributed energy resources. Research in this area should also consider the comparative merits of centralized versus decentralized control architectures, particularly in

terms of resilience and scalability in large-scale deployments. Such considerations are vital to ensure seamless operation of PV-STATCOM units in future distribution networks characterized by high levels of automation and data exchange.

Finally, there remains a need for experimental validation and economic assessment of the proposed solution. While simulation-based results are promising, testing the approach on real hardware platforms such as through hardware-in-the-loop setups or DSP-based control benches, would strengthen its credibility and facilitate industrial adoption. Simultaneously, a thorough economic analysis that evaluates capital investment, maintenance, and lifecycle benefits compared to conventional compensation methods is essential. Moreover, adapting and extending local regulatory frameworks to fully recognize the capabilities of PV-STATCOM systems, especially for nighttime voltage support and ancillary services, will be critical in promoting their deployment at scale. Together, these research directions form the basis for future work that can build on the current study to deliver smarter, more robust, and cost-effective solutions for grid-interactive renewable energy systems.

10. CONCLUSION

In the Moroccan context, the injection of energy produced by PV plants begins with the policy of opening up to the approach of the energy market in which the quality of the energy injected and its availability in different circumstances remains a priority for network managers, however, the premature use of converters equipped with controllers based on artificial intelligence will allow competitively approaching the market and will open the door to the integration of more power in the same network.

In the present work, the use of PV power plants as PV STATCOM was studied and the compliance of regulatory constraints was verified. The main advantage of the proposed configuration is the exploitation of the inverter capacity during nighttime when no power is generated or delivered to the distribution network. Additionally, we note that the use of PV-STATCOM in distribution grid is cost effective compared to standalone D-STATCOM devices and it is an affordable solution to dynamically support electrical network when faults and disturbances occur within the limit of the capacity of its inverter. Thus, it ensures consistent power supply to connected loads while

providing quick and effective control over reactive power helping to mitigate impact of sudden changes in load or fluctuation in renewable energy generation, it improves the general quality of the power delivered to the grid and the PCC connected loads and enables integration of more renewable generation without additional voltage regulation devices and hence offers good transient performance in line with the Moroccan grid code requirements.

The integration of artificial intelligence methods to tune the proportional integral controllers is found to be much more efficient to meet different technical requirements from the grid side using the classic controllers which are simple and not complex in comparison with fully AI based controllers. It allows reactive power supply for voltage support, power factor correction and low voltage ride through condition. The integration of the online controller tuning is possible since the proposed approach doesn't require complex parameters configuration and could be achieved to meet the local distribution requests.

For the studied system using the tuning of PI controllers, GA is most effective for scenarios where robustness and precision are dominant while PSO offers a practical solution for continuous systems but may be less robust in finding the global optimum but could be used in real-time application due to its faster convergence. Both methods significantly outperform classical techniques, demonstrating the potential of AI-driven optimization to enhance power quality at the point of common coupling (PCC), improve system stability, and comply with regulatory standards.

In final the PV STATCOM can supply necessary reactive power to the distribution grid in different conditions such as faulty conditions of connection of large loads at PCC, it is also capable of correcting the power factor within acceptable values. The reactive power injection allows the grid voltage at the connection point and allows the power plant to remain connected as long as possible to ensure the dynamic voltage support within the required limits imposed by local grid code.

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