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An Application of Ant Colony-Fuzzy Logic Controller for Shunt Active Filter in PV-UPQC

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Abstract: This paper presents an intelligent, optimized control approach designed to enhance the quality of power in power grids. It achieves this by integrating a Shunt Active Filter (SAF) with a UPQC with a renewable energy source (photovoltaic). The Shunt Active Power Filter (SAPF) is controlled using Ant Colony Optimization (ACO), a warm-based algorithm that draws inspiration from how ants forage for food. This ACO algorithm dynamically tunes the control parameters of the current reference generation mechanism, resulting in improved harmonic compensation. The effectiveness of this ACO-based controller is measured against conventional Proportional Integral (PI) and Fuzzy Logic Controllers (FLC). The simulation results clearly demonstrate the outstanding performance of the proposed ACO-SAPF. This is evident through a considerable reduction in Harmonic Distortion (THD), a more rapid dynamic behavior, and improved quality of voltage and quality of current, even when load and generation conditions fluctuate.

Keywords: Shunt Active Power Filter (SAPF), Ant Colony Optimization (ACO), UPQC integrated with renewable energy, Harmonics, Fuzzy Logic Controller (FLC).

1. Introduction

Modern electrical power systems are currently undergoing a major shift due to the rising adoption of renewables, with a focus on sustainable energy sources, particularly solar power systems [1]. While these distributed generation sources offer clean and sustainable energy, their unpredictable and intermittent nature introduces several challenges in ensuring quality power. These include issues like unstable voltage, waveform distortions, flickers, and load imbalances [2].

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Such problems can negatively affect the performance of sensitive electronic equipment and compromise the system's consistent and uninterrupted power delivery. To tackle these challenges effectively, Comprehensive solutions in the form of Unified Power Quality Conditioners (UPQCs) have risen to prominence. These devices integrate both series and shunt compensating elements to address a wide range of disturbances and variations in power quality [3]. A critical element of a UPQC is the Shunt Active Power Filter (SAPF). It is tasked with eliminating current harmonics, adjusting for reactive power, and ensuring a balanced load profile. Traditionally, PI controllers and Fuzzy Logic Controllers (FLC) are utilized for managing SAPF functionality [4]. However, these methods often struggle in dynamic, non-linear environments because of their fixed parameter settings or limitations with rule-based systems. This is where artificial intelligence and evolutionary algorithms have become increasingly important for optimizing control parameters. This paper introduces a new approach that uses Ant Colony Optimization (ACO). This is a heuristic optimization algorithm drawing from natural phenomena efficiently discovers optimal paths in intricate scenarios by simulating the foraging behaviour of ants. This paper introduces an innovative

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approach: integrating an Ant Colony Optimization (ACO) based control strategy for tuning fuzzy controller into the shunt compensator of a UPQC integrated with renewable energy, especially PV [5-9]. This integration aims to significantly boost system performance in key areas like harmonic suppression, dynamic adaptability, and voltage regulation.

The following sections of this paper will explore the system's architecture, the specific control strategy employed, the detailed design of the ACO algorithm, the simulation results, and a comprehensive comparison of its performance against traditional control methods [10-12]. The growing incorporation of sustainable energy, with a focus on PV systems, into power distribution networks brought forth several challenges in the quality of electrical power, including voltage dips and surges, harmonics. UPQCs, a hybrid of Series and Shunt compensators, are a strong contender for resolving these power quality concerns. While traditional controllers such as PI and Fuzzy controller (FLC) have been widely applied for SAPFs, their effectiveness often diminishes in the presence of variable and distorted load characteristics. To resolve these constraints, this paper introduces a novel bio-inspired control method that uses ACO for finely tuning the SAPF within a UPQC, which is integrated with renewable energy, mainly PV. ACO, which models the foraging pattern of ants, efficiently explores the solution space to optimize controller parameters, leading to superior harmonic mitigation and overall power quality enhancement.

The remaining paper is sectioned as follows, Section 2 presents the system configuration, Section 3 presents about the PV-UPQC modelling, Section 4 discusses about the control strategy, Section 5 about the results and conclusions are drawn in Section 6.

2. System configuration

The proposed PV-UPQC system integrates a PV array as its distributed energy source, converting solar radiation into electricity via photovoltaic cells. This energy then feeds into the grid or local loads through a power conditioning unit, which handles voltage regulation and frequency regulation. Given the non-consistent and fluctuating nature of solar energy, an efficient interface with power quality devices like the UPQC is essential for steady and robust power delivery [13-14]. A series active filter is integrated into the system to mitigate voltage sags and swells, common disturbances often caused by load changes or faults. This filter, positioned in series with the power line, introduces a corrective voltage to ensure stable voltage at the PCC, protecting delicate equipment from voltage irregularities.

ASAPF is also included for addressing current-related harmonic distortions and reactive power. Connected in parallel with the load, the SAPF monitors and feeds corrective currents that neutralize unwanted harmonic components and reactive power from non-linear loads. It achieves this by generating a reference current signal and using a Voltage Source Inverter (VSI) to inject an equal but opposite waveform into the system, resulting in a nearly sinusoidal source current. This improves the power factor, reduces losses, and ensures compliance with IEEE 519 harmonic standards. Both the shunt compensator and the series active filter share a DC link, with VSI connecting two converters [15-18]. The VSI acts as the core switching unit, converting DC voltage from the shared DC link into a controlled AC output used by both filters for compensation. Operating with a high-frequency PWM approach, the VSI assures a rapid reaction to dynamic variations in load and power supply circumstances. Its dual role in providing both series and shunt compensation significantly boosts the total efficiency and compactness of the PV-UPQC, underscoring its importance for successful power quality refinement.

3. Modelling of PV-UPQC

The solar powered UPQC setup combines a PV source with both series compensator and shunt filters to effectively reduce power network disruptions. The PV array is modeled as a current source, with its output influenced by solar irradiance and temperature. For regulating voltage of DC, this output is sent to a DC-DC boost converter, which in turn supplies the shared DC link of the UPQC as shown in Fig. 1.

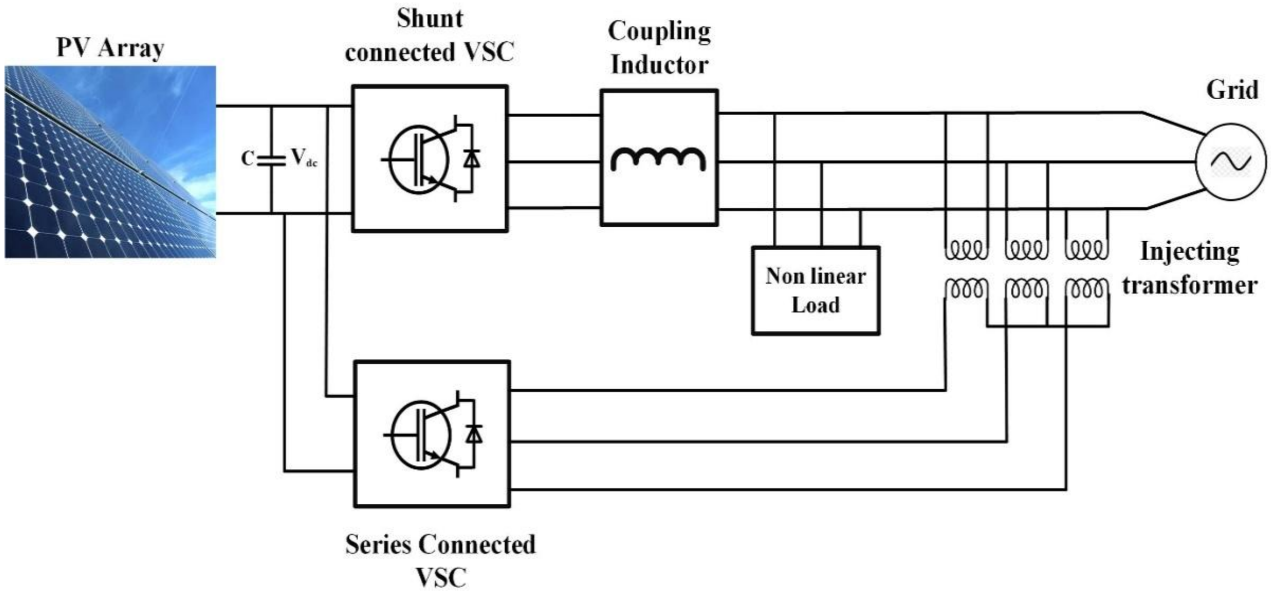

Fig. 1: Schematic diagram of PV-UPQC

This DC link connects to both the series and shunt inverters, which are modelled using ideal switching devices controlled by pulse width modulation (PWM) signals. The entire system's operation, including the interplay between renewable generation and power quality control mechanisms, is simulated using MATLAB/Simulink**.**

3.1 Series Active Filter Controlled by PI Controller

The Series active compensator is managed by a Proportional Integral controller to achieve a stable voltage at the point of common coupling's output. The controller's mechanism involves a comparison between the reference voltage it aims for and the real-time load voltage. Any difference, or error, it is subsequently handled by the PI controller, resulting in a control manipulating signal (1). This signal, in turn, modulates the PWM pattern sent to the inverter as shown in Fig. 2. The VSI then feeds a balancing voltage into the line in series, effectively counteracting voltage surges and voltage dips and consequently. Boosting the quality of the voltage supplied to the load [19].

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = p \begin{bmatrix} \cos\alpha & \cos(\alpha-120) & \cos(\alpha+120) \\ \sin\alpha & \sin(\alpha-120) & \sin(\alpha+120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

Where p=2/3

To control the voltage injected by the Series Active Power Filter, a PI controller is employed**.** We achieve this regulation by altering the modulation index of the PWM-based Inverter (VSI). Proportional gain (K_p) and Integral gain (K_i), are typically obtained using established techniques.

3.2 Shunt Active Filter PI Controller

The Shunt Active compensator is modelled using the instantaneous *pq* theory. This involves transforming the load currents into $\alpha\beta$ reference frame (stationary) components. From these, the both instantaneous real power and reactive powers are calculated, from this, reference compensation currents can be derived to eliminate non-linear elements. These reference currents are transformed back into three-phase signals and compared against the actual SAPF currents. The resulting error is directed to a controller as shown in Fig. 3. This controller adjusts gating pulses sent to the Inverter (VSI) through a technique of PWM ensuring the SAPF injects the correct compensating currents (2). This process effectively maintains sinusoidal source currents and achieves a corrected power factor [20].

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = x \begin{bmatrix} 1 & 0.5 & 0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (2)$$

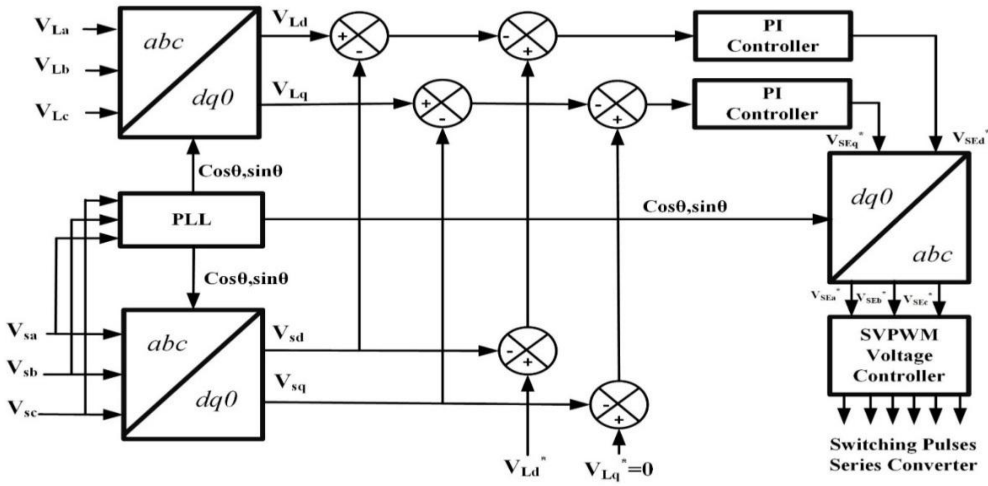

Fig. 2: Illustrates the series active power filter's control approach

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ V_0 \end{bmatrix} = x \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3)$$

Where $x = \sqrt{2}/3$

In the context of *p-q* theory**,** instantaneous real and reactive power are composed of average ($p-$ and $q-$) and oscillating ($p\sim$ and $q\sim$) components. A filter (low pass) is essential for extracting the active power from p; its design is critical to prevent errors during transient conditions (3). The oscillating components directly indicate the existence of harmonics. These harmonics can be compensated in real time by a shunt active compensator, ensuring the source currents remain sinusoidal [21-22]. Furthermore, a voltage regulator determines the power loss (P_{loss}) required to maintain the DC-link voltage **(**V_{dc}**)** at a reference value or near its reference value (V_{ref}) (4).

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p\sim \\ q\sim \end{bmatrix} \qquad (4)$$

Finally, compensating reference currents are obtained using the inverse Clark transformation (5) referred from [1].

$$\begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} = \sqrt{2}/3 \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \qquad (5)$$

Where i_{ra}, i_{rb}, i_{rc} are the reference currents

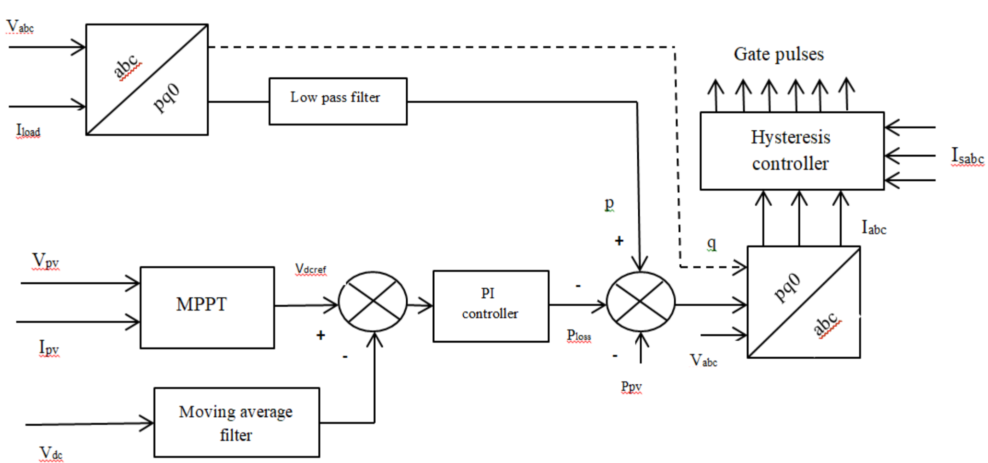

Fig. 3: Illustrates the control strategy of shunt active power filter

4. Control strategy for shunt active power filter

Control strategies are important in SAPF systems for effectively mitigating issues related to power quality. Within Unified Power Quality Conditioner (PV-UPQC) systems integrating PV, where both renewable energy generation and load conditions are highly dynamic, a robust control mechanism is essential to ensure stable and high-quality power delivery. These strategies are responsible for generating precise reference signals and modulation commands that direct the (VSI) to introduce the needed corrective currents or voltages**.** The objectives of SAPF control strategies include:

- Sustaining an almost unity power factor
- Improving the purity of the source current by reducing its THD.
- Ensuring a stable DC link.
- Adapting quickly to dynamic changes in demand and supply.

By utilizing effective control algorithms, SAPFs can successfully eliminate non-linear current components, which significantly boosts the overall performance of a UPQC system. The subsequent subsections will compare traditional control approaches with the intelligent, optimization-based method introduced in this study.

4.1 Conventional Control Methods

Traditional SAPF control strategies focus on maintaining high power quality. They do this by injecting compensating currents that effectively cancel out harmonics. The most common methods used for this purpose are PI controllers and FLC.

- The PI controller functions by evaluating the linear difference between a signal taken as reference and the actual measured one, then applying a control action derived from its proportional and integral terms. While it is simple to implement and commonly used in industrial settings, its performance can significantly worsen in non-linear or rapidly changing load conditions because of its fixed gain structure. PI controller is tuned using trial and error method or Ziegler Nicholas method and the K_p and K_i values obtained are to be 10 and 1 for shunt active compensator and using this, THD obtained is 19.03%.
- ***Fuzzy Logic Controller (FLC)****:* Unlike PI**,** an FLC operates guided by a set of heuristic guidelines, allowing it to manage system uncertainty and non-linearity more effectively. It doesn't need a precise mathematical system model, equipping it with greater robustness for complex environments. However, an FLC's performance heavily relies on how its rule base and membership functions are designed, and it lacks a systematic way to optimize itself. After using this FLC-based shunt compensator in PV-UPQC the THD obtained is 7.24%.

Traditional methods often struggle to adapt to dynamic power quality disturbances. Consequently, there's increasing interest in incorporating optimization algorithms to dynamically tune control parameters, aiming for enhanced SAPF performance.

4.2 Proposed ACO - Based control

FLCs are popular in power electronic applications like SAPFs because they can handle nonlinearities and uncertainties without needing a precise mathematical model. However, an FLC's performance is heavily reliant on correctly selecting its parameters, namely membership functions and the rule base**.** Incorrect tuning can result in a slow response, persistent steady-state errors, or even instability. Therefore, optimizing these FLC parameters is crucial to enhance overall system performance, improve dynamic response, and boost harmonic compensation in PV-UPQC systems.

Many optimization techniques have been used to fine tune (FLCs)**,** like Genetic Algorithms (GA), PSO and ACO. These meta heuristic methods efficiently explore the solution space to discover optimal or near-optimal parameter sets, thereby overcoming the limitations of manual tuning or trial-and-error approaches.

The foraging behaviour of real ants is the inspiration behind ACO, particularly, their knack for finding the quickest way from their nest to food sources via trails with pheromone level. This metaheuristic algorithm proves exceptionally good at solving combinatorial and nonlinear problems due to its inherent positive feedback mechanism, distributed computation, and robust search capabilities. When applied to tuning FLC parameters for SAPFs, ACO offers several advantages: it ensures fast convergence, helps avoid getting stuck in premature local optima, and maintains an excellent balance between exploration and exploitation**.** These attributes make it highly suitable for optimizing fuzzy controllers within complex power systems.

A nature inspired meta heuristic algorithm, ACO, replicates how ants in nature discover paths connecting their colony to food supplies. In ACO, "artificial ants" develop solutions through creating probabilistic choices, influenced by both the intensity of virtual pheromone pathways and guiding heuristic insights. With the algorithm's advancement through iterations, these pheromone trails are updated. This reinforcement mechanism strengthens promising solutions, effectively guiding the search towards the global optimum.

4.3 Ant colony optimisation algorithm

In a SAPF, the FLC is tasked with generating precise reference currents or voltage signals. These signals enable the SAPF to supply the system with corrective currents, thereby mitigating harmonics. and ensures consistent power quality despite varying load and photovoltaic (PV) conditions. An FLC's performance is highly dependent on meticulously tuning its various scaling factors and membership function parameters to achieve optimal results. Manual tuning proves inefficient and often leads to suboptimal outcomes, especially in complex, non-linear, and time-varying systems such as a PV-UPQC. Consequently, an optimization-based approach like ACO is used to address challenge, as shown in Fig. 4.

4.4 Parameters Tuned by ACO

Following parameters of FLC are calibrated using ACO code,

ke: Error gain (scaling factor for the input error)
kce: Change in error gain
ku: Output gain (scaling factor for the output)
X: Scaling factor used to define fuzzy membership function ranges
z_a: Amplitude for output membership functions (used for rule base tuning)
v_a: Amplitude for input membership functions

These parameters dictate how the FLC interprets incoming error signals and subsequently generates output control signals. Incorrect values can result in issues such as oscillations, a sluggish response, or inadequate compensation from the SAPF.

4.5 ACO Search Mechanism for Parameter Tuning

The ACO algorithm employs a stochastic search process, following the patterns of ant foraging, to find the optimal combination of these six parameters.

Initialization

- The optimization process begins by setting a predetermined number of ants and iterations.
- Each parameter is divided into a fixed number of nodes, *n*, within its defined lower and upper limits.
- A pheromone matrix, denoted as *T*, is initialized; this matrix is vital for directing the ant selection probabilities throughout the optimization process.

Solution Construction

A solution is developed by each ant via,

- Each ant constructs a solution by probabilistically selecting one value (node) for each of the six parameters using a roulette wheel method.
- The likelihood of choosing a particular node is determined by a combination of its pheromone intensity and its heuristic desirability (which is the inverse of the node's value).

4.6 Evaluation Using Cost Function

Each ant's chosen set of parameters is evaluated by executing the Simulink model with those specific settings. The cost function serves as a performance index, integrating:

$Cost = RMSE + IAE + ITAE + ISE$

Where *RMSE, IAE, ITAE, ISE* are root mean square, integral absolute, integral time absolute and integral square error. This cost reflects the quality of power compensation, with lower values indicating better performance.

4.7 Pheromone Update

Once all ants have been evaluated, the pheromones are updated.

- Nodes that were part of better-performing ants' solutions receive an increased amount of pheromone.
- Evaporation gradually reduces pheromone levels, aiding the algorithm in avoiding local minima.

4.8 Elitism

- If the current iteration's best cost is inferior to the overall best cost found so far, the worst-performing ant in the current generation is replaced by the best ant from the previous generation.

4.9 Integration with the FLC

- The optimal parameters identified by the best ant in the final iteration are then integrated into the FLC block of the Simulink model.
- The values *ke, kce*, and *ku* are used as input/output scaling factors in the fuzzy controller.
- The *X, z_a,* and *v_a* values define the shapeand range of fuzzy membership functions (e.g., *NB, NM, PM, PB*) used in inference.
- These affect how the error signal is mapped to control actions, tuning the sensitivity and responsiveness of the controller.

4.10 Benefits of This Tuning Approach

- Automatic tuning eliminates the need for trial and error, streamlining the optimization process
- Multi objective optimization allows for a balanced approach, effectively managing the trade offs between speed, accuracy, and smoothness.
- The adaptive design ensures that the FLC performs effectively, even when faced with the nonlinear and time varying conditions commonly found in a PV-UPQC system.
- The approach offers scalability, allowing it to be extended to optimize a greater number of parameters or integrate with hybrid controllers like Adaptive Neuro Fuzzy Inference System (ANFIS) or PI Fuzzy combinations.

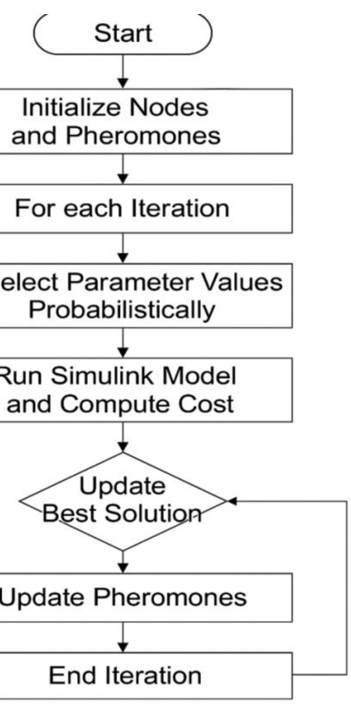

Fig. 4: Flowchart of ant colony optimisation technique

The steady state performance and dynamic performances of the PV UPQC are evaluated through simulations in Simulink (MATLAB). The system uses rectifier (Diode bridge - 3 phase) with RL load, and a solver size of 1e−6s for accurate result.

5. Simulation Results

The PV array has a V_{mpp} of 29 V and a I_{mpp} of 7.35 A, resulting in a maximum power output of 213.15 W. This PV module is employed with 19 modules in series and 23 parallel strings to achieve the desired output. Grid requirements are 400 V and 50 Hz, aligning with conditions of standard power grid. The results of the voltage swell and sag are shown in Fig. 5. THD using ACO tuned shunt compensator for UPQC integrated with PV are shown in Fig. 6.

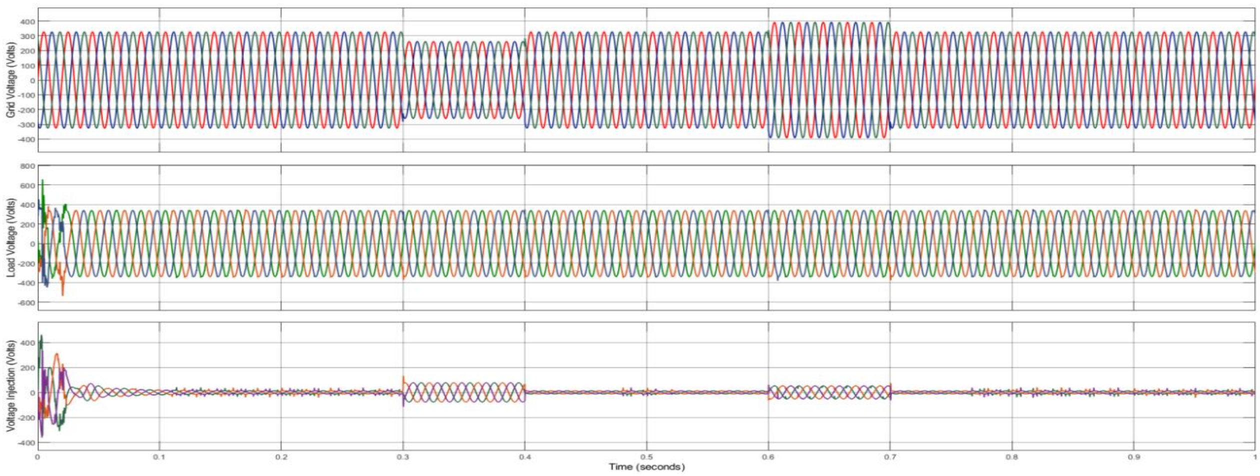

Fig. 5: Voltage surge and dip mitigation

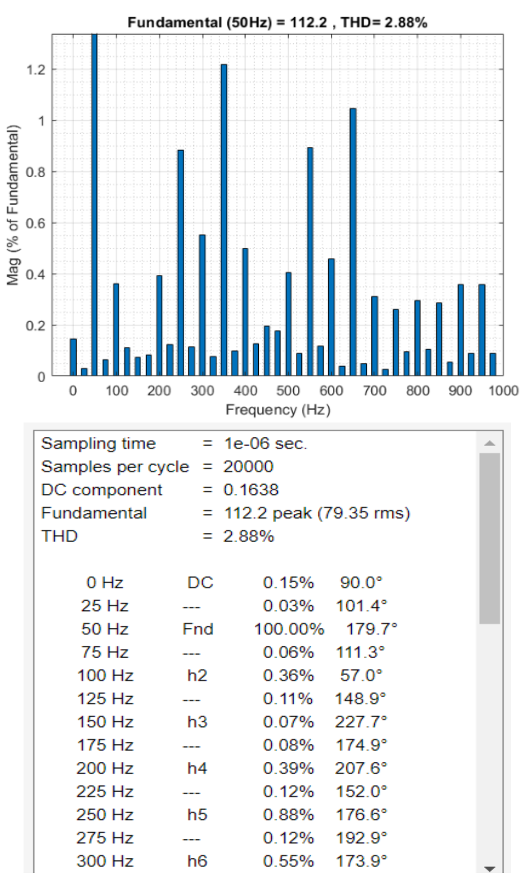

Fig. 6: THD using ACO tuned shunt compensator for UPQC integrated with PV

6. Conclusion

This paper details the creation of a SAPF for a PV-UPQC system, utilizing an ACO, FLC. Furthermore, the achieved Total Harmonic Distortion (THD) is 2.88%, within in IEEE limits as shown in Table. 1. Consequently, the ACO based SAPF for PV-UPQC is presented as an effective approach for modern distribution networks, skill fully integrating distributed generation and elevating power quality.

Table. 1: Comparison of the results

S. No	Controller used	THD (%)
1	PI controller based SAPF for PV-UPQC	19.03
2	Fuzzy logic controller based SAPF for PV-UPQC	7.24
3	Ant colony optimized fuzzy controller based SAPF for PV-UPQC	2.88

Conflict of Interest

The authors declared "No Conflict of Interest"

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