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Coordinated Distributed Generation and UPQC Optimal Placement for Voltage Profile Improvement and Loss Reduction



Abstract: - The high ratio of resistance to reactance in the distribution network and the growing penetration of nonlinear and distributed loads are prone to high power losses and voltage instability in distribution networks. Thus, traditional methods of voltage regulation have limited performance due to discrete control, slow response, and relatively poor reactive power support provided by series voltage regulators and shunt capacitors. The emergence of D-FACTS devices seems to be a strong solution to enhance the power quality and operation efficiency of the system. This paper studies the problem of optimal placement of DG and UPQC to minimize real and reactive power losses while enhancing the voltage profiles in radial distribution systems. The UPQC can provide simultaneous series and shunt compensations to mitigate voltage disturbances, suppress current harmonics, and regulate reactive power. The backward–forward sweep algorithm is performed for load flow study. The genetic algorithm provides sub-optimal locations to commence the particle swarm optimization to find the optimal placement of DG and UPQC. The efficacy of the proposed method is tested on a 30-bus distribution system implemented in MATLAB. The improvement in voltage profile, power quality, and overall system efficiency is confirmed.

Keywords: Unified power quality conditioner; Distributed generation; Distribution networks; Power quality improvement; Optimization techniques; Voltage regulation

1. Introduction

Due to the fast depletion of fossil fuel resources, growing concerns over the environment, and the need for greater reliability, the trend is witnessing a paradigm shift in conventional main generating stations in the direction of distributed energy resources (DERs), commonly known as microgrids, that function in the distribution voltage level. Technology developments in the sector of renewable energy sources, coupled with the advancements in the realm of power electronics, have encouraged the emergence of microgrids, active distribution networks, in which small-scale resources like solar photovoltaic, wind, and biomass plants have been placed close to the load points. Despite these benefits, DG mass integration poses new operational problems within the distribution networks. While optimally locating DG sources can effectively minimize the active power losses within the network, they contribute less to reactive power compensation, thereby causing voltage problems at some bus connections. The difficulty is worsened by the high resistance to reactors in the distribution system, which augments power loss along with the degradation of the existing voltage stability margins. Various studies have indicated that a substantial portion of the total power generation is lost within the distribution network, making it an important area for the application of sophisticated methods of voltage and reactive compensation.

However, to mitigate these problems, power electronic-based compensation systems have increasingly started focusing on compensation devices based on power electronic technology. Among different FACTS devices, Unified Power Quality Conditioners (UPQC) are being developed as multifaceted devices that perform both series and shunt compensations simultaneously. The UPQC efficiently compensates voltage disturbances, eliminates current harmonics, and provides reactive support, thereby reducing voltages and increasing power quality. Contrary to different energy storage systems, including batteries, flywheels, fuel cells, and ultra-capacitors, which are characterized by large costs, a shorter life span, their hazardous effects on human life, and difficulties in recycling, UPQC devices are very effective and do not use energy storage on a large scale. There have been many studies related to the optimal position and placement of DG, DSTATCOM, and other FACTS devices in the distribution system. Iqbal et al.[1] showed that placing DG units based on loss sensitivity factor

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LSF can minimize system loss, although, due to requirements of the system's voltage regulation, reactive compensation from DSTATCOM is required. Gupta and Kumar[2] have demonstrated a new method based on system sensitivities for optimal placement and sizing of DSTATCOM in mesh type distribution systems, which provides improved system stability margins and lower energy losses. Balamurugan et al. [3] have implemented a new strategy based on indices of voltage stability along with a whale optimization algorithm for focusing DSTATCOM, which provides improved system voltages and reduced system loss. Likewise, Salkuti [4] has carried out research related to the coordinated placement and sizing of DG and DSTATCOM based on artificial fish swarm optimization strategy, which provides considerable loss reduction in a regular radially meshed system.

A number of studies have also pointed out that inadequate placement of DG can adversely impact system performance due to voltage violations, increased losses, and reduced reliability. Suitable locations and sizes of DGs are hence determined with the help of sensitivity-based analytical techniques and metaheuristic optimization approaches. Comprehensive surveys have also demonstrated that all multifunctional FACTS devices such as UPQC, STATCOM, DVR, and UPFC work effectively in enhancing power quality, voltage stability, and system efficiency with coordinated deployment offering superior performance compared to its single compensator deployment. Although much research is focused on DG and DSTATCOM placement, coordinated optimal placement of DG and UPQC in active distribution networks has received relatively little attention [5]. In this paper, the research gap is addressed with a unified optimization framework to simultaneously place DG and UPQC for loss minimization of real and reactive power, voltage profile improvement, and enhancement in power quality. The load flow analysis is done using the backward–forward sweep method, suboptimal locations are identified using a genetic algorithm (GA), and particle swarm optimization (PSO) identifies the optimal placement. The proposed approach is tested on a standard 30-bus distribution system implemented in MATLAB.

2. Problem formulation and objectives

Problem Formulation and Objectives: This section defines the problem formulation and objectives that involve the optimal integration of Flexible AC Transmission System devices and distributed energy resources in a distribution network. In this regard, the paper focuses on the determination of the optimal locations of DGs and UPQC units, considering the minimization of real power losses, improvement of voltage profile, and mitigation of harmonic current penetration into the utility grid. A hybrid optimization framework using both GA and PSO is considered in order to take advantage of the global search capability of GA and fast convergence characteristics of PSO. Such approaches reduce the required computational effort and increase the solution's accuracy. The optimal placement is implemented in an iterative manner, aiming at an overall enhancement of the distribution system efficiency and ensuring reliable, secure, and sustainable power delivery. First, the load flow analysis of the uncompensated network is conducted using the backward-forward sweep method, which is re-conducted upon DG and UPQC integration in order to quantify improvement in loss reduction and voltage regulation. The proposed methodology offers a scalable solution that can be extended to future active distribution networks, microgrids, and emerging applications like electric vehicle charging infrastructure.

3. Methodology

The proposed method is applied on a conventional 33-node radial distribution system to optimize the placement of DG units with the goal of minimizing the power loss by installing a DG unit in the best location along with the conceptual design of UPQC. The initial stage involves the optimization of the OP of the uncorrected system with the goal of optimizing the power within the system through the use of the Newton-Lagrange method or Newton gradient method with the objective of quick convergence of the method during steady-state operation. The OP of the system is defined as a constrained minimization problem where the goal or the function to minimize is the total system cost or total power losses of the system. During the optimization process, the equality constraint of the power physics of the system along with the bus voltage limits of the direct or positive sequence is considered.

3.1 Problem statement: A general minimization problem can be written in the following form,

$$\text{Minimize } f(x) \text{ (objective function)} \tag{1}$$

$$\text{Subject to } h_i(x) = 0 ; i = 1,2 , \dots m \text{ (equality constraint)} \tag{2}$$

$$g_j(x) \leq 0 ; j= 1,2 \dots n \text{ (inequality constraint)} \tag{3}$$

There are m equality constraints and n inequality constraints and the number of variables is equal to the dimension of the vector x.

3.2 Development of Lagrangian: The solution of this problem by Newton’s method requires the creation of the Lagrangian as shown below,

$$L(z) = f(x) + \mu^T h(x) + \lambda^T g(x) \text{ (the lagrangian)} \tag{4}$$

where $z = [x, \mu, \lambda]^T$, μ and λ are vectors of lagrange multiplier and $g(x)$ only includes the binding inequality constraints .

A gradient and Hessian of the Lagrangian may then be defined as

$$\text{Gradient } \Delta L(z) = \left[\frac{dL(z)}{dZ} \right] = \text{a vector of the first partial derivative of Langragian} \tag{5}$$

$$\text{Hessian } \Delta^2 L(z) = H = \left[\frac{d^2 L(z)}{dZi dzj} \right] = [\] \tag{6}$$

a matrix of the second partial derivative of the Lagrangian

3.3 Objective Function: The objective function for the OPF reflects the costs associated with generating power in the system. The quadratic cost model for generation of power will be utilized

$$C_{PGi} = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \tag{7}$$

where P_{Gi} is the amount of generation in megawatts at generator i. The objective function for the entire power system can then be written as the sum of the quadratic cost model at each generator.

$$f(x) = \sum_i (a_i + b_i P_{Gi} + c_i P_{Gi}^2) \tag{8}$$

This objective function will minimize the total system costs, and does not necessarily minimize the costs for a particular area within the power system.

3.4 Equality and Inequality Constraints: The physics of the power system are enforced through the power flow equations which require that the net injection of real and reactive power at each bus sum to zero. Generators have maximum and minimum output powers and reactive powers which add inequality constraints

$$P_{Gimin} \leq P_{Gi} \leq P_{Gimax} \tag{9}$$

$$Q_{Gimin} \leq Q_{Gi} \leq Q_{Gimax} \tag{10}$$

To maintain the quality of electrical service and system security, bus voltages usually have maximum and minimum magnitudes. These limits again require the addition of inequality constraints.

$$V_{imin} \leq V_i \leq V_{imax} \tag{11}$$

3.5 Optimization Techniques: The genetic algorithm is a metaheuristic inspired by the process of natural selection that belongs to the larger class of evolutionary algorithms (EA). Genetic algorithms are commonly used to generate high-quality solutions to optimization and search problems by relying on biologically inspired operators such as mutation, crossover and selection.

3.6 Genetic Algorithm: In GA algorithm ,the population has n chromosomes that represent candidate solution; each chromosome is an m dimensional real value vector where m is the number of optimized parameters. Therefore each optimized parameter represents a dimension of the problem space.

Evolution usually starts from a population of randomly generated individuals, and is an iterative process , with the population in each iteration called a generation. In each generation, the fitness of every individual in the

population is evaluated; fitness is usually the value of the objective function in the optimization problem being solved. The more fit individuals are selected from the current population, and each individual's genome is modified (recombined and possibly randomly mutated) to form a new generation. The new generation of candidate solutions is then used in the next iteration of the algorithm. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population as shown in figure 1.

There are major six steps in genetic algorithm namely initialization , fitness , time updating , new population & replacement.

1. Initialization - set the timer counter $t = 0$ and generate n chromosomes .

$[x_j(0), j = 1, \dots, n]$, where $x_j(0) = [x_{j,1}(0), x_{j,2}(0), \dots, x_{j,m}(0)]$. $x_{j,k}(0)$ is generated in the search space $[x_k^{\min}, x_k^{\max}]$ randomly.

2. Fitness - Evaluate each chromosome in the initial population using the objective function , J. Search for the best value of the objective function J_{best} . Set the chromosome associated with J_{best} as global best .

3. Time updating - Update the time counter $t = t + 1$

4. New population - Create a new population by repeating the following steps until the new population is completed ,

- Selection - select two parent chromosomes from a population according to their fitness
- Crossover - with a crossover probability , crossover the parent to form a new child.
- Mutation - with a mutation probability method mutates a new child at each chromosome.
- Acceptance - place a new child in a new population.

5. Replacement - use generated population for a further run of algorithm.

If one of the stopping criteria is satisfied then stop, else go to step 2.

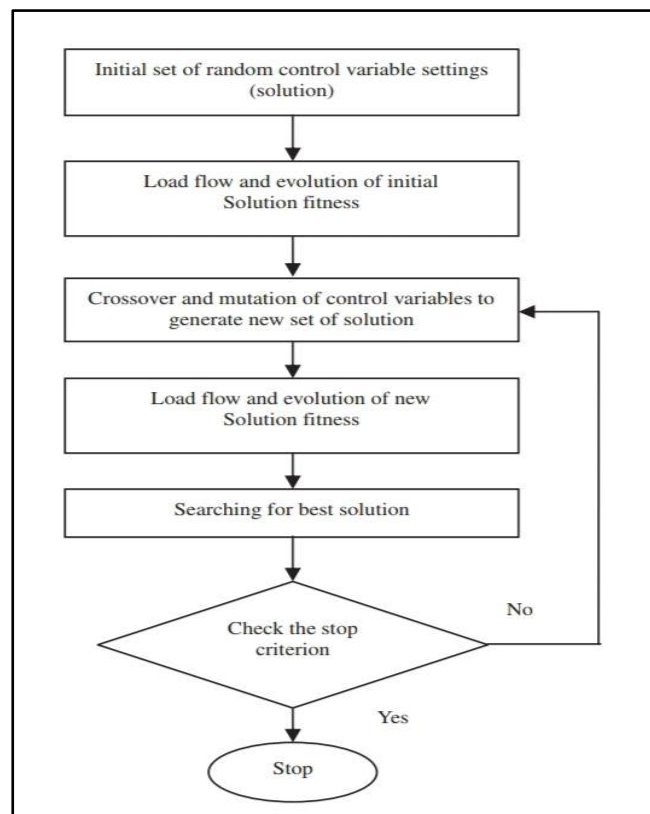


Fig 1: Flow chart for Genetic Algorithm

3.7 Particle swarm optimisation: In the PSO algorithm, the population has n particles that represent the candidate solutions. Each particle is an m dimensional real valued vector where m represents the number of optimized parameters. Each particle was initialized at a random position in search space. The position of particle i is given by the vector $x_i = (x_{i1}, x_{i2}, \dots, x_{iD})$ where D is the dimensionality of the problem. Its velocity is given by the $v_i = (v_{i1}, v_{i2}, \dots, v_{iD})$. Two kinds of memory were implemented that influence the movement of the particles. In cognitive memory $p_i = (p_{i1}, p_{i2}, \dots, p_{iD})$ and the vector $p_{best} = (p_{best1}, p_{best2}, \dots, p_{bestD})$, also called "social memory", contains the position of the best point in the search space visited by all swarm particles so far. The inertia weight w can either be implemented as constant or in a way so that its value is changed linearly with time.

A start and end value is set and for each epoch a new value of w is calculated as

$$w = w_{start} - \dots \quad (12)$$

Therefore each optimized parameter represents a dimension of the problem space.

The PSO technique can be described in the following steps :

1. Initialization - set the time counter $t = 0$ and randomly generate n chromosomes, $[x_j(0), j = 1, \dots, n]$, where $x_j(0) = [x_{j,1}(0), x_{j,2}(0), \dots, x_{j,m}(0)]$. $x_{j,k}(0)$ is generated in the search space $[x_k^{min}, x_k^{max}]$ randomly. $v_j(0)$ is randomly generated for evaluation of the objective function. For each particle, set $x_j^*(0) = x_j(0)$ and $j^* = j, j = 1, \dots, n$. Search for the best value of the objective function J_{best} . Set the particle associated with J_{best} as the global best,

$x^{**}(0)$ with the objective function of j^{**} . Set the initial value of $w(0) = 0.98$

2. Time updating - update the time counter $t = t + 1$

3. Weight updating - update the inertia weight

4. Velocity updating - using the global best and the individual best to change the particle velocity in the following equation.

$$V_{j,k}(t) = \omega(t) v_{j,k}(t-1) + c_1 r_1 (x_{j,k}^*(t-1) - x_{j,k}(t-1)) + c_2 r_2 (x_{best}^{**} - x_{j,k}(t-1)) \quad (13)$$

5. Position updating - Based on the updated velocity, each particle changes its position according to the following equation

$$X_{j,k}(t) = X_{j,k}(t-1) + V_{j,k}(t) \quad (14)$$

If a particle violates its position limit in any dimension, set its position at the proper limit.

6. Each particle is evaluated according to the updated position. If $j_{min} < j^*$ then updates individual best as

$$x_j^*(t) = x_j(t), j_i = j_i^* \quad (15)$$

7. Now search for the minimum value, if $j_{min} < j^{**}$ then updates global best as $j^{**} = j_{min}$ and $x^{**} = x_{min}(t)$

Now if one of the stopping criteria is satisfied then stop else goto step 2 as shown in figure 2.

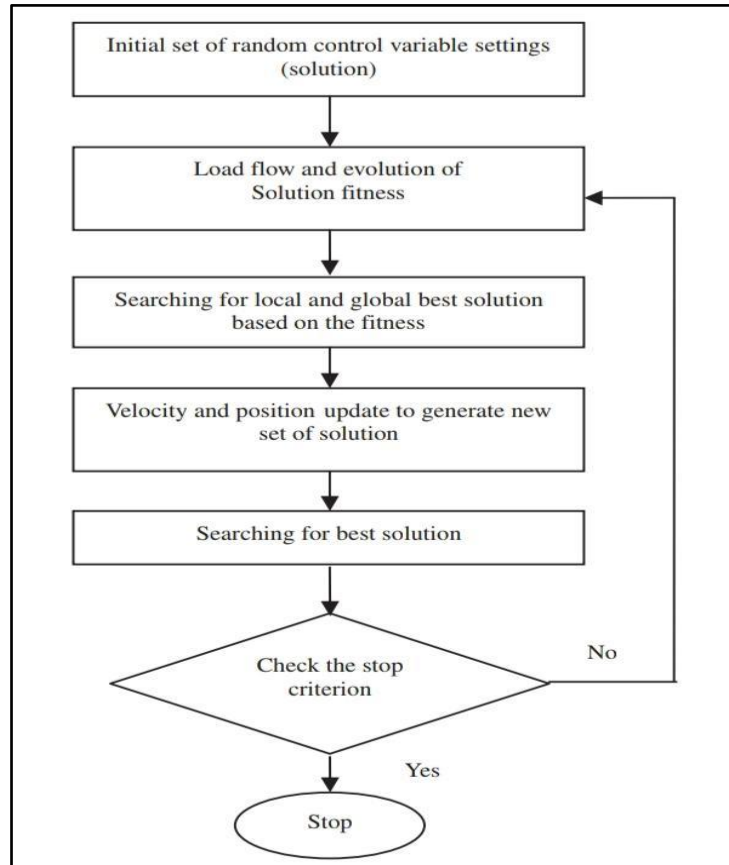


Fig 2: Flowchart for Particle Swarm Optimization

3.8 Hybrid GAPSO: Hybrid GAPSO algorithm includes the use of both genetic algorithm and particle swarm optimization. Hybrid GA-PSO algorithm is proposed to schedule the workflow tasks over the available resources. The proposed algorithm aims to achieve three objectives: reducing the makespan, reducing the cost, and balancing the load of the workflow tasks on heterogeneous VMs in the selected cloud DC.

In summary, the GA-based algorithms provide better results than other algorithms when the number of iterations is large. However, increasing the number of iterations means that the GA algorithm will consume more time to reach the optimal solution. On the other hand, the PSO-based algorithms provide better results than the other algorithms and in less time. However, the results may not be accurate due to the fast convergence of the PSO-based algorithms to the solution, which may cause being stuck in the local optimal solution.

Therefore, the proposed Hybrid GA-PSO algorithm is distinguished by the characteristics of the GA and the PSO algorithms. The Hybrid GA-PSO algorithm is expected to work faster with different sizes of workflow applications compared to other algorithms with the same objectives. Moreover, the Hybrid GA-PSO algorithm may not get trapped in the local optimal solution, because of the use of the GA mutation operator that enhances the accuracy of the solutions. The flowchart of GA-PSO is shown in figure 3.

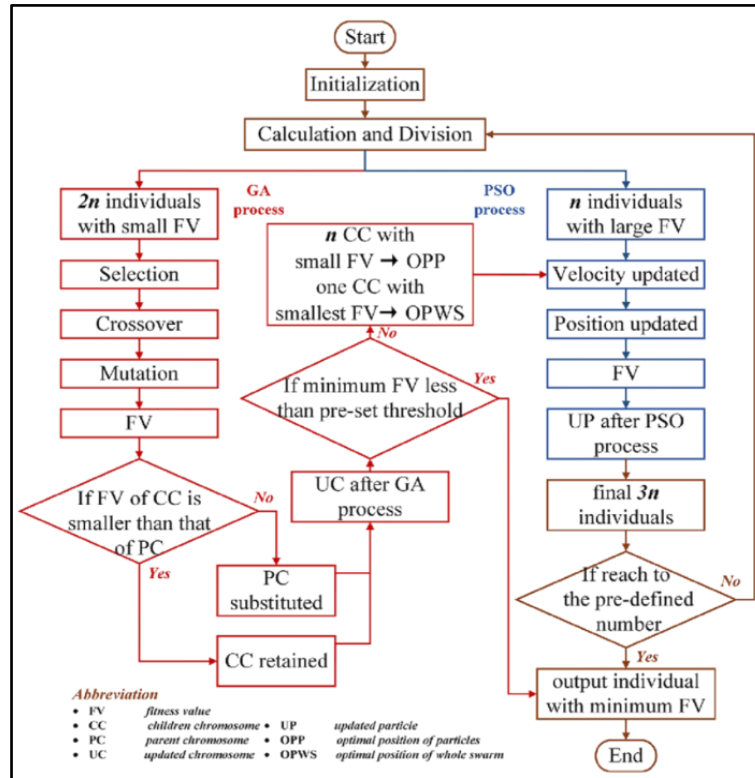


Fig 3: Flowchart of Hybrid GA PSO

3.9 optimal locations and sizes of DG and UPQC: A hybrid optimization technique of genetic algorithm and PSO is selected to identify the best location and size of DG & UPQC. Genetic Algorithm is initially used to obtain the sub-optimal solutions by applying the process of selection, crossover, and mutation operators (Fig. 2). The solutions obtained from the genetic algorithm are then refined by the PSO method by updating the velocity and positions of the particles on the basis of the best individual solution and global best solution (Fig. 3). The hybridization of GA & PSO method helps to overcome the premature convergence problem of the PSO method along with the optimization process taking less time to execute (Fig. 3). Finally, the OPF solution will again be optimized to measure the effectiveness of the optimized DG & UPQC on the reduction of power losses and voltage regulation of the distribution system.

4. Power Distribution System, Losses, and Power Quality Issues

4.1 Distribution Network Characteristics and Power Flow Analysis: The power distribution system is the last and most crucial stage of the electricity supply chain, having a direct impact on system efficiency, utility economics, and end-user service quality. The electrical network operates at voltage levels below 132 kV (66 kV, 33 kV, 22 kV, 11 kV, and 0.4 kV) and feeds residential, commercial, or industrial consumers. Because of the inherently high R/X ratio, there are significant technical problems in the distribution system, including high loss values, voltage instability, and low power quality. This situation may be aggravated by long feeders, dispersed loads in rural areas, inappropriate sizing of conductors, incorrect transformer allocations, and low power factor operating conditions. Unlike transmission systems, load flow methods such as the Newton–Raphson and Gauss–Seidel techniques are not effective for the distribution network; thus, for the distribution network, the BFS method is preferred because of its numerical robustness and suitability for radial topologies.

The load flow analysis forms the basis for many other system studies since it solves for bus voltages, phase angles, and power flows at the various points of interest in steady-state system performance. If bus voltages are outside acceptable limits, system security and reliability may be compromised. Distribution losses can be divided into two main categories: technical and non-technical losses. Technical losses include conductor resistance, transformer copper and core loss, and unbalanced loading, all of which account for the bulk of total losses. Non-technical losses are due to metering inaccuracies, inefficiency in billing procedures, administrative failure, and energy theft. Poor load balancing, poor workmanship, low power factors, and faults in transformer

ratings such as oversized or overloaded further exacerbate losses. Feeder phase balancing, strategic transformer placement, power factor correction, and turning lightly loaded transformers off during low-demand periods are some of the mitigation measures that help in reducing such losses considerably. However, these conventional approaches may fall short in modern active distribution networks with increasing nonlinear load penetration and proliferation of DERs. A consequent need towards advanced power electronic-based compensation techniques has emerged for the improvement of the system efficiency and operational performance.

4.2 Power Quality Challenges and FACTS-Based Compensation Using UPQC: Power quality can be defined as the capability of the power supply system to sustain a sinusoidal voltage and current waveform at its predetermined level and frequency, thus making it possible for the desired equipment to function properly. On the other hand, power quality degradation in a power supply system can be attributed to various effects in a distribution network, which include voltage sags, swells, interruptions, transients, harmonics, flicker, unbalance, frequency variation, and notching. The said effects can be attributed to events on the utility side, which include faults, switching, lightning, and transformer energization, and nonlinear loads on the consumer side, which include rectifiers, motor drives, arc furnaces, and welding machines. In turn, harmonics and voltage distortions can cause increased losses and overheating, as well as device failures in sensitive electronic devices, which can also be brought about by poor power quality.

To meet these requirements, Flexible AC Transmission System (FACTS) devices have been found as efficacious solutions for reactive compensation, voltage regulation, loss reduction, and improving stability. FACTS devices work by using both series and/or shunt compensation techniques as shown in Figure 6. These devices are classified into series devices such as Thyristor Controlled Series Capacitors (TCSC) and Static Synchronous Series Compensators (SSSC) which provide control over the line reactance for power flow and stability control as shown in Figure 4. On the other hand, shunt devices such as Static VAR Compensators (SVC) and STATCOM provide reactive current injection for voltage and loss reduction as shown in Figure 5. These devices provide compensation for specified applications. Nevertheless, the present day distribution network requires solutions for overcoming both voltage and current-related disturbances at the same time.

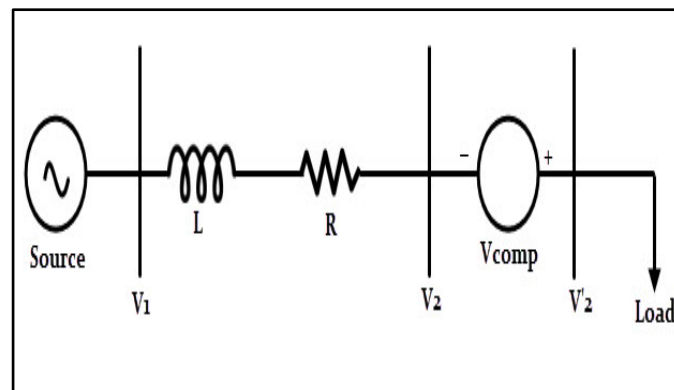


Fig 4: Series Compensation

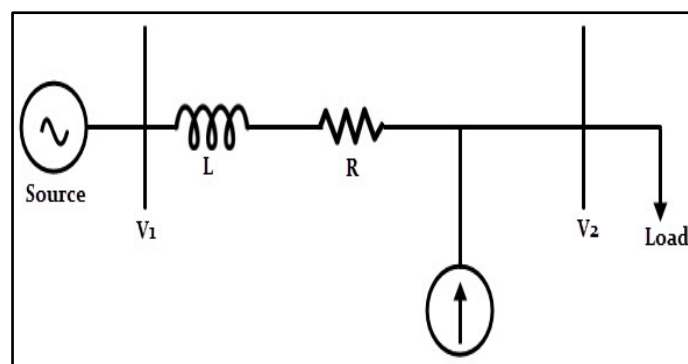


Fig 5: Shunt compensation



Fig 6: Function of FACTS Devices

The Unified Power Quality Conditioner (UPQC) serves this purpose by combining a series compensator (DVR) and a shunt compensator (STATCOM) via a dc link. The UPQC system successfully compensates supply-side problems of sag, swell, flicker, and harmonics, and load-side problems of current harmonics, reactive power, and neutral currents. Thus, by ensuring series and shunt compensation, the UPQC ensures balanced and sinusoidal load currents and volts, which enhances power quality and system reliability greatly. The traditional energy storage system has some disadvantages, such as high cost, short lifespan, safety problems, and recycling problems, and therefore requires a new and efficient alternative solution such as the UPQC in modern active distribution networks with high penetration of DERs.

4.3 Losses in Distribution Systems: The power distribution system is considered to be the weakest link in the entire electric power industry because of its large loss percentage. Though transmission system loss is approximately 17%, distribution system loss constitutes almost 50% of the total loss in the power system. The power system loss may be mainly categorized as a result of technical loss and non-technical loss, which occur due to different reasons.

4.3.1 Technical Losses: Technical losses are caused by the physical properties of power system elements and are mainly attributed to energy losses in conductors, transformers, and other related equipment. Technical losses also involve I²R losses in conductors, copper losses in transformers, and magnetic core losses. Technical losses on average form about 22.5% of total losses and are greatly influenced by the power system network configuration, loading, and operating methods. Technical losses also contribute a major share from the primary and secondary distribution networks, while the contribution from the transmission and sub-transmission networks is about 30% of total technical losses. Technical losses in power systems cannot be avoided, and their reduction and effective minimization can be accomplished by applying effective design and operating methods. Technical losses in power systems are also influenced by rapid loading, which may exceed defined limits.

4.3.2 Non-Technical Losses: Non-Technical Losses: This type of loss, averaging 16.6%, is not dependent on the technical parameters of the network, being caused by administrative or commercial factors. Such factors may include meter reading errors, faulty or manipulated meters, billing errors, unmetered consumption, administrative inefficiencies, revenue constraints, and power theft. As opposed to technical losses, the former type could be easily minimized with the aid of more sophisticated monitoring, automation, or enforcement.

4.3.3 Causes of Technical Losses: A major reason for the technical losses is the large length of the distribution lines, especially in the rural sector. Long 11 kV as well as low tension lines are always used for the supply of remote stations of larger loads, thereby increasing the line resistance as well as line I²R losses. Further, if the conductors in the radial supply are undersized, a large voltage drop occurs, increasing the losses. The displacement of distribution transformers from the load centers is a factor that contributes significantly to losses as well. Displacement of non-centralized transformers results in increased feeder lengths on the secondary

networks, hence increased losses and reduced voltage level at the consumer terminals. It is therefore important to reduce disparities in potential drops and resulting losses when near load centers.

Low power factor in the case of the primary as well as the secondary distribution networks also affects the power transfer significantly because, in the case of LT networks, the power factors vary from 0.65 to 0.75. Therefore, power factor correction through the use of shunt capacitor banks installed in the substations, feeders, or consumer terminals could greatly lower the line losses. It has been found that with proper capacitor bank installation, line losses could be reduced by 4-9%. Inadequate workmanship is a further cause of technological losses. This includes low or damaged joints, incorrect connections, as well as improper maintenance of switching gears and transformer terminals with resultant high currents due to increased contact resistance and associated power losses. Another source of losses that can be addressed quite easily is the load imbalance among feeder phases. Phase current imbalance causes unequal voltage drops and, in turn, develops increased losses. Maintaining phase current magnitudes within acceptable limits and redistribution of the loads between feeders can improve system efficiency significantly. Distribution losses are also affected by the load factor. Losses rise with the magnitude of the current; therefore, massive variations in demand over time, common in residential and commercial load, result in higher peak losses. An increase in load factor, which can be achieved by making demand profiles flatter, can reduce peak losses and energy losses. Transformer sizing and selection methods have a very important role in loss lowering. The transformers supplying the power in a distribution network have both load-dependent copper losses and no-load core or iron losses, which depend neither on the load current nor time.

Even though loading transformers close to their capacity can minimize investment, it is not a good practice to overload transformers excessively, as it raises their core and copper losses. Hence, the transformers have to be carefully chosen based on the total cost, which includes the cost associated with peak loss. Periodic three-phase load equalization of transformers can help lower the losses. Switching off the transformers when they are lightly loaded during times of low demand has proved effective for the reduction of fixed core losses. But it has to be done carefully without impairing supply reliability or equipment integrity.

4.3.4 Energy Storage Systems: ESSs are considered a very effective solution in increasing the efficiency and performance of distribution networks. If optimally sized and appropriately located, ESSs may support peak demand, enable further integration of renewable and distributed energy resources, improve power quality, and delay network expansion. When properly operated, ESSs contribute significantly to loss reduction and overall system optimisation.

4.4 Power Quality: Power Quality PQ can be defined as the capability of an electric power delivery system to provide, at the receiving terminal, voltage and current of the required level and frequency, and waveform under controlled conditions. Power Quality Problems problems arise when there's a departure from standard voltage, frequency, and waveform, which can sometimes cause an electric device or system to malfunction or deteriorate at a faster rate.

4.4.1 Causes of Poor Power Quality: Disturbances in the PQ numbers come from the utility company side and the consumer side. On the generation side, there are fluctuations due to repairs, changes in the load, and power shortages. On the transmission level, the impact of voltage regulation problems, lightning strikes, and circuit switching affects the transmission systems. On the distribution systems, voltage sags, surges, interruptions, and transformer energization occur. On the consumption side, the presence of non-linear loads causes voltages to deviate due to the changes in impedance.

4.4.2 Common Power Quality Disturbances: Transients represent short-duration high-magnitude deviations due to switching operations, lightning, or faults, which could result in insulation failure or equipment damage. Voltage variations include sags ($V < 0.9V_{nom}$, $V < 0.9 V_{nom}$), swells ($V > 1.1V_{nom}$, $V > 1.1 V_{nom}$), under-voltages, and over-voltages, which arise from sudden changes in load or faults. Voltage unbalance in three-phase systems occurs when phase magnitudes or angles are different from 120° , resulting in heating and reduced equipment efficiency. Flicker is rapid voltage fluctuations affecting lighting and sensitive devices. Waveform distortion due to harmonics and DC offsets Harmonics are sinusoidal components at integer multiples of the fundamental frequency, typically generated by nonlinear loads. Total harmonic distortion specifies waveform distortion quantitatively:

$$THD_V(\%) = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100 \quad (16)$$

where V_1 is the fundamental voltage and V_n is the n th harmonic voltage. Higher THD corresponds to poorer PQ. Power factor (PF), defined as:

$$PF = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} \quad (17)$$

where P is active power, Q is reactive power, and S is apparent power, also reflects PQ. Values closer to unity indicate efficient energy utilisation and reduced losses.

Variation in frequency occurs due to the imbalance in the demand for power and the resulting deviation of the frequency from the standard frequency of 50-60 Hz. The introduction of high frequency harmonics in power by voltage notching caused by switching in power electronics poses a problem to sensitive and fragile electronics. The cause of interruptions in power may be faulty protective schemes, weather, and faulty systems. Therefore, in short, PQ is affected by generation, transmission, and distribution as well as the load side. Indices such as THD and PF values are necessary for evaluating and correcting the distortions in the contemporary distribution system.

5. Software and Hardware Requirements

All simulation and optimization tasks discussed within this research were conducted on a conventional personal computing platform with processing capability sufficient to support iterative load flow simulation studies as well as basic metaheuristic optimization processes. The personal computer platform consists of an HP 15-DA0388TU with 8 GB RAM along with conventional input devices that were satisfactory for performing simulation iterations associated with conventional radial distribution networks on a convergence basis.

MATLAB was utilized as the main simulation and analysis tool owing to its robust numerical calculation facility, matrix-based structure, and comprehensive set of optimisation tools, as well as its well-structured power system simulation tools. MATLAB, with its sophisticated environment, supports the efficient implementation of backward-forward sweep techniques for load flow studies, Genetic Algorithm (GA), Particle Swarm Optimisation (PSO), as well as the combination technique of GA-PSO. Drawbacks Associated with the Model-Based Approach: MATLAB analysis environment helps in the systematic assessment of voltage profile, power loss, and convergence. Its development toolboxes enable modular development, which is highly required in the case of distribution system analysis with iterative optimisation.

A feasibility study revealed that the proposed framework is both technically possible and economical since the project only uses commonly available hardware components and commercial software, making it free of any new implementation cost. From the user experience point of view, the simulation-based technique demands minimal interaction of the user, minimizing the need for any special training besides that of MATLAB. Validation of the system was done before the analysis was conducted to check for mathematical consistency, optimisation algorithm accuracy, and reproducibility of solutions for varying system conditions. Scaling up for maintenance and modifications for increased sizes of the system, new FACTS devices, or electric vehicles would be possible at the software level.

6. Results and Discussion

The proposed approach has been applied on a standard 30-bus radial distribution system and validated. First of all, under base conditions, i.e., without the integration of DG or UPQC, load flow analysis was executed by using the backward-forward sweep method. All quantities of the system were converted into a per-unit system on 100 MVA base. From this baseline analysis, large real power losses are identified and considerable voltage drops on several buses are observed. This confirms the poor voltage profile that is commonly observed in a high R/X ratio distribution network. Bus type 1 or 2 represents PV bus and bus type 3 represents PQ bus respectively. The value of tolerance is taken to be 1. The further Jacobian matrix four columns J_1 , J_2 , J_3 , and J_4 is calculated; in the given matrix on and off-diagonal elements are computed separately.

Table 1: Bus data for 30 bus distribution system

Bus	Type	V	del	P _g	Q _g	P _l	Q _l	Q _{min}	Q _{max}
1	1	1.06	0	0	0	0	0	0	0
2	2	1.043	0	40	50.0	21.7	12.7	-40	50
3	3	1.0	0	0	0	2.4	1.2	0	0
4	3	1.06	0	0	0	7.6	1.6	0	0
5	2	1.01	0	0	37.0	94.2	19.0	-40	40
6	3	1.0	0	0	0	0.0	0.0	0	0
7	3	1.0	0	0	0	22.8	10.9	0	0
8	2	1.01	0	0	37.3	30.0	30.0	-10	40
9	3	1.0	0	0	0	0.0	0.0	0	0
10	3	1.0	0	0	19.0	5.8	2.0	0	0
11	2	1.082	0	0	16.2	0.0	0.0	-6	24
12	3	1.0	0	0	0	11.2	7.5	0	0
13	2	1.071	0	0	10.6	0.0	0.0	-6	24
14	3	1.0	0	0	0	6.2	1.6	0	0
15	3	1.0	0	0	0	8.2	2.5	0	0
16	3	1.0	0	0	0	3.5	1.8	0	0
17	3	1.0	0	0	0	9.0	5.8	0	0
18	3	1.0	0	0	0	3.2	0.9	0	0
19	3	1.0	0	0	0	9.5	3.4	0	0
20	3	1.0	0	0	0	2.2	0.7	0	0
21	3	1.0	0	0	0	17.5	11.2	0	0

22	3	1.0	0	0	0	0.0	0.0	0	0
23	3	1.0	0	0	0	3.2	1.6	0	0
24	3	1.0	0	0	4.3	8.7	6.7	0	0
25	3	1.0	0	0	0	0.0	0.0	0	0
26	3	1.0	0	0	0	3.5	2.3	0	0
27	3	1.0	0	0	0	0.0	0.0	0	0
28	3	1.0	0	0	0	0.0	0.0	0	0
29	3	1.0	0	0	0	2.4	0.9	0	0
30	3	1.0	0	0	0	10.6	1.9	0	0

Table 2: Line data for 30 bus distribution system

From Bus No.	To Bus No.	Resistance (R)	Reactance (X)	Ground Admittance (B/2)	Tap setting Value
1	2	0.0192	0.0575	0.0264	1
1	3	0.0452	0.1652	0.0204	1
2	4	0.0570	0.1737	0.0184	1
3	4	0.0132	0.0379	0.0042	1
2	5	0.0472	0.1983	0.0209	1
2	6	0.0581	0.1763	0.0187	1
4	6	0.0119	0.0414	0.0045	1
5	7	0.0460	0.0460	0.1160	1
6	7	0.0267	0.0820	0.0085	1
6	8	0.0120	0.0420	0.0045	1

6	9	0.0	0.2080	0.0	0.978
9	10	0.0	0.5560	0.0	0.969
9	11	0.0	0.2080	0.0	1
4	10	0.0	0.1100	0.0	1
12	12	0.0	0.2560	0.0	0.932
12	13	0.0	0.1400	0.0	1
12	14	0.1231	0.2559	0.0	1
12	15	0.0662	0.1304	0.0	1
12	16	0.0945	0.1987	0.0	1
14	15	0.2210	0.1997	0.0	1
16	17	0.0824	0.1923	0.0	1
15	18	0.1073	0.2185	0.0	1
18	19	0.0639	0.1292	0.0	1
19	20	0.0340	0.0680	0.0	1
10	20	0.0936	0.2090	0.0	1
10	17	0.0324	0.0845	0.0	1
10	21	0.0348	0.0749	0.0	1
10	22	0.0727	0.1499	0.0	1
21	23	0.0116	0.0236	0.0	1
15	23	0.1000	0.2020	0.0	1
22	24	0.1150	0.1790	0.0	1
23	24	0.1320	0.2700	0.0	1
24	25	0.1885	0.3292	0.0	1

25	26	0.2544	0.3800	0.0	1
25	27	0.1093	0.2087	0.0	1
28	27	0.0	0.3960	0.0	0.968
27	29	0.2198	0.4153	0.0	1
27	30	0.3202	0.6027	0.0	1
29	30	0.2399	0.4533	0.0	1
8	28	0.0636	0.2000	0.0214	1
6	28	0.0169	0.0599	0.065	1

Table 1 represents the Bus Data which includes the bus number , type of bus , bus voltage , phase angle , active power from sending end , reactive power from sending end , active power from sending end , reactive power from receiving end, Table 2 describes the line data of 30 bus radial distribution systems.

6.1 Load flow before optimisation : Load flow analysis before optimization is done using backward - forward sweep method by making the data table. Data table consists of line data and bus data given in table 1 and 2.

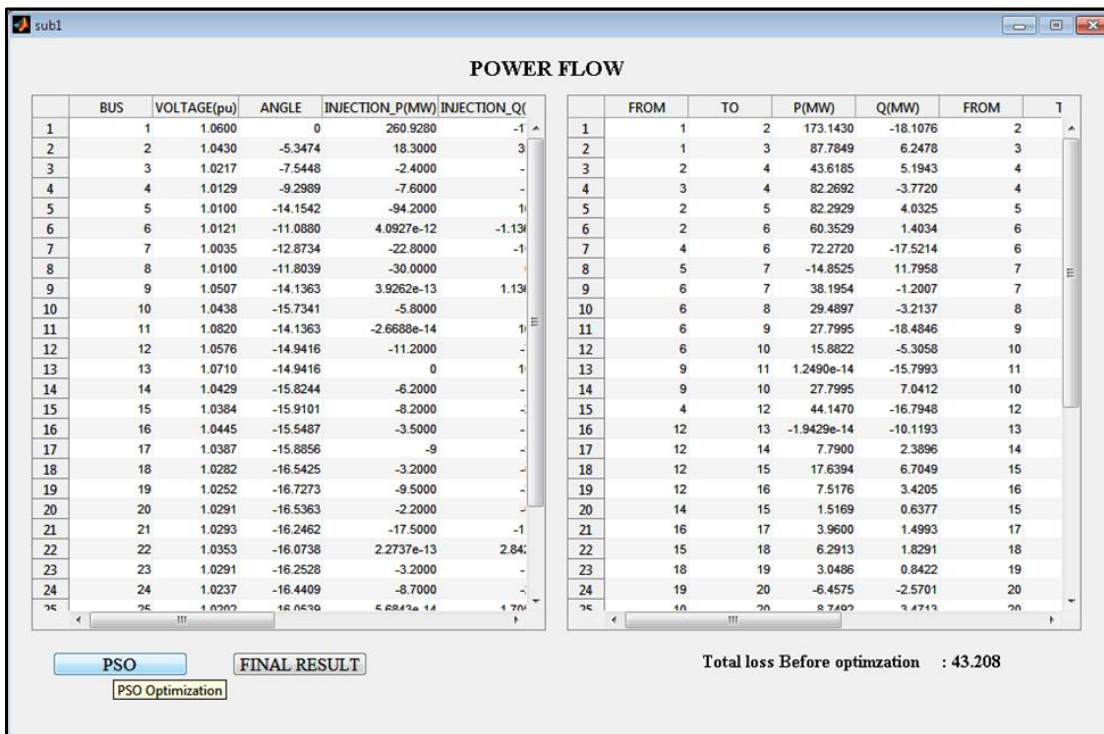


Fig 7: Total loss before optimization

6.2 Optimisation using hybrid GA PSO: The optimization of the 30 bus distribution system to find optimal location of UPQC and DG is done through hybrid genetic and particle swarm optimization technique. The PSO parameters are shown in table 3.

Table 3: Default PSO parameters

P(1)	df	Epoch between updating display , default =100
P(2)	me	Maximum number of iteration (epoch) to train , default = 2000
P(3)	ps	Population size , default = 24
P(4)	ac1	Acceleration constant 1(local best influence). , default =2
P(5)	ac2	Acceleration constant 2(global best influence) , default=2
P(6)	iw1	Initial inertial weight , default = 0.9
P(7)	iw2	Final inertia weight , default = 0.4
P(8)	iwe	Epoch when inertial weight at final value , default = 1500
P(9)	ergrd	Minimum global error gradient
P(10)	ergrdep	Epoch before error gradient criterion terminates
P(11)	errgoal	Error goal
P(12)	trelea	Type of pso used(trelea type, clerc constricted)
P(13)	PSOseed	PSOseed , initial particle position

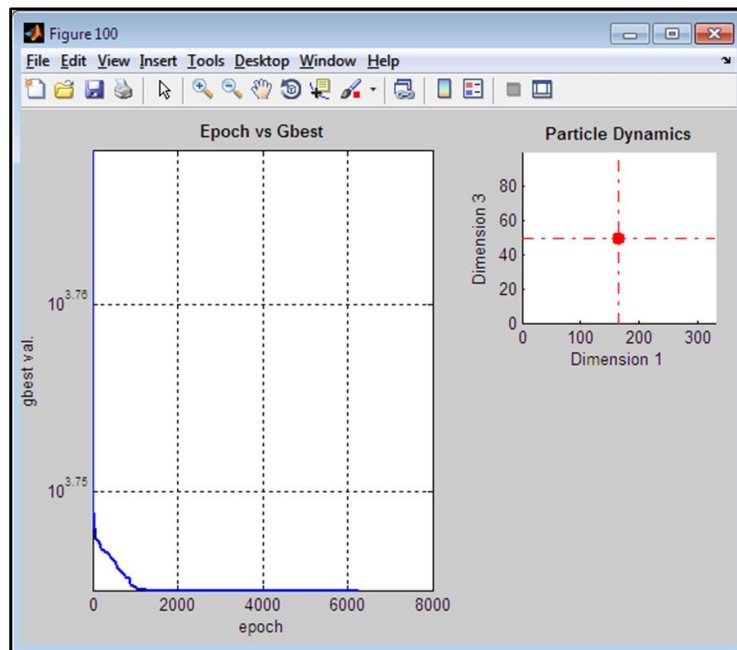


Fig 8: Gbest Vs epoch of particle in PSO.

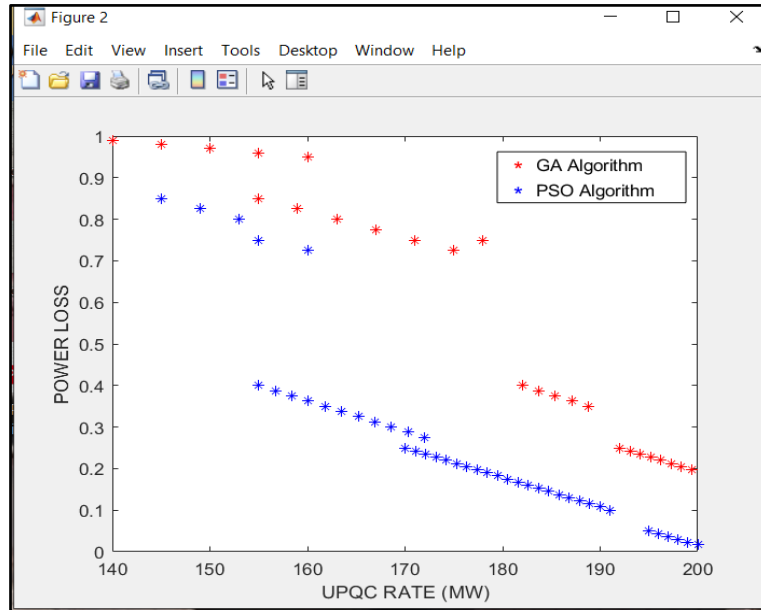


Fig 9 GA-PSO algorithm (Power loss vs UPQC rate)

6.3 Placement of UPQC and DG: Optimal location of UPQC and DG is derived through the hybrid PSO technique, Three types of control methods are used UPQC -P , UPQC - Q , UPQC -S .

	Selected BUS	Injection power	UPQC-Type
1	1	10	UPQC-P
2	2	10	UPQC-P
3	3	17.5000	UPQC-P
4	4	17.5000	UPQC-P
5	5	17.5000	UPQC-P
6	6	20	UPQC-S
7	7	20	UPQC-S
8	8	17.5000	UPQC-P
9	9	20	UPQC-S
10	10	10	UPQC-P
11	11	17.5000	UPQC-P

	Selected BUS	Injection power	UPQC-Type
1	2	10	UPQC-P
2	8	10	UPQC-P
3	9	17.5000	UPQC-P
4	19	20	UPQC-P
5	20	20	UPQC-P
6	21	17.5000	UPQC-S
7	23	10	UPQC-S
8	27	17.5000	UPQC-P
9	29	17.5000	UPQC-S
10	30	20	UPQC-P

Fig 10: location of UPQC / DG

Table 4 shows the Types of UPQC with the best locations to installed the UPQC.

Table 4: UPQC Location & Type

Selected Bus	Injection Power	UPQC -Type
16	17.5000	UPQC-P
18	17.5000	UPQC -P

23	20	UPQC- S	
25	10	UPQC - P	
26	17.5000	UPQC - S	
		1	17.5000
		7	17.5000
		8	17.5000
		13	17.5000
	14	10	

6.4 Load flow after PSO optimization: Load flow analysis of the 30 bus distribution system is performed after the placement of UPQC and DG using the PSO algorithm.

The loss calculated using backward forward sweep load flow analysis method before optimization is 43.208 , and the loss calculated after optimal placement of UPQC & DG is 10.8287. Therefore we can conclude that the placement of UPQC can minimize the losses in the distribution system up to a certain extent.

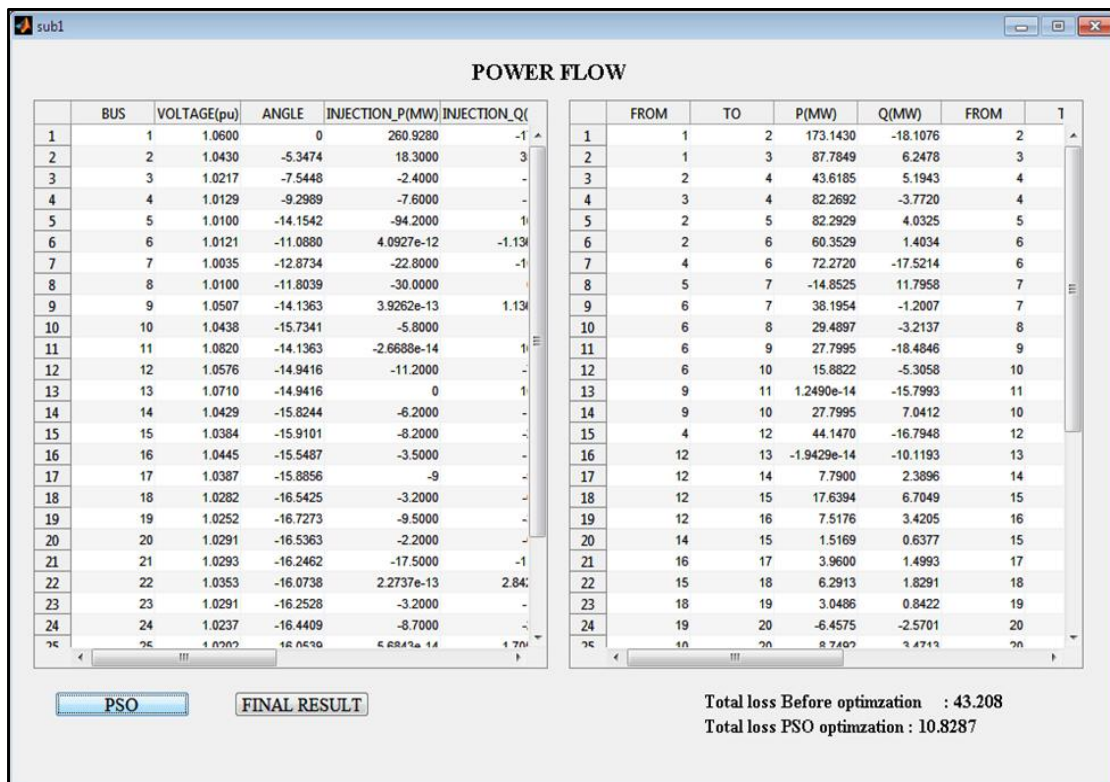


Fig 11: load flow analysis after optimisation

6.5 Cost analysis using abc optimisation: Cost analysis of the 30 bus distribution system is done using ABC algorithm.

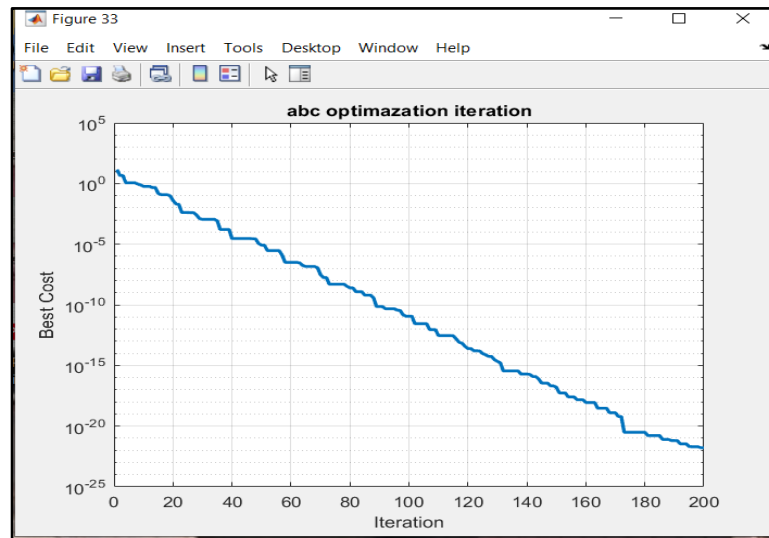


Fig 12: Best cost using ABCoptimization

For optimisation of DG and UPQC placement, a hybrid Genetic Algorithm–Particle Swarm Optimisation (GA–PSO) method was used. The GA–PSO aided in minimising real power loss and enhancing system voltage and power quality. The GA–PSO resulted in faster global optimum solution convergence with less local optimum trapping. In this optimisation problem, suitable buses were identified based on operating modes of UPQC (UPQC-P, UPQC-Q, and UPQC-S) depending on active and reactive power compensation requirements. After optimisation, load flow analyses were performed for DG and UPQC placement with a similar backward and forward sweep method. The total system loss was observed to be reduced from 43.208 kW without compensation to 10.8287 kW with optimisation, showing a marked improvement in system efficiency and performance. Further, system voltages were improved and remained within permissible limits, showing that voltages are within normal limits and system power quality has improved. In order to evaluate economic performance, cost optimization is done using the Artificial Bee Colony Algorithm. The outcome shows that, with the placement of UPQC and DG at optimal points, there is a feasible cost associated with this configuration. The simulation outcome, therefore, confirms that coordination among optimised placement of DG, UPQC, and other algorithms is indeed a useful method of minimized losses, improvement, and enhancement of voltage, as well as general improvement of power quality within AC Distribution Networks. Figure 7 shows the total loss before optimization technique implemented, figure 8 represents the graph between Gbest and epoch of positions in PSO optimization, while figure 9 shows the variation of power loss with respect to UPQC rate in GA-PSO algorithm. Figure 10 represents the best locations for UPQC and DG, Figure 11 represents load flow analysis after superimposing of optimization technique. Figure 12 shows the best cost of power generation when used ABC optimization technique.

7. Conclusion

Microgrids and active distribution networks are critical in improving energy access, reliability, and autonomy, especially in areas where the grid is either non-existing or undeveloped. In networks where the availability of power is inherently limited, the reduction of real and reactive losses is clearly critical in order for the network to function efficiently. In the context of this paper, the optimisation solution for DG placement and UPQC location has been proposed and discussed. Simulation results show that simultaneous DG and UPQC placement at the same bus provides better results than their individual placement. Though individual placement of UPQC results in effective improvement of the voltage profile with a marginal reduction in losses, DG placement results in a substantial reduction in loss, whereas it has less effect on the improvement of the voltage profile. The coordinated placement of both results in a massive reduction in the value of losses, along with a substantial improvement in the voltage profile. Moreover, it has been revealed from this study that ill-planning of DG results in system loss augmentation.

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