KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

PROJECT TOPIC: LOSS MINIMISATION IN HIGH VOLTAGE DISTRIBUTION SYSTEM BY CAPACITOR PLACEMENT USING A MODIFIED PARTICLE SWARM OPTIMIZATION ALGORITHM.

NAME: SONIA ENAM DEKPOR

SUPERVISED BY: Mr. E. O. K ADDO

ABSTRACT

Power losses due to the growth in load is a major issue affecting the quality of electric power being delivered in the distribution system. One of the efforts in solving this problem is by the optimal placement of capacitors. The effectiveness of the capacitor installation depends on the location and size of the capacitor. In this work, the sizing and placement of the shunt capacitors was achieved using an improved particle swarm optimization algorithm with a modified inertia weighted control. The objective function for optimal sizing of the capacitor banks is the cost which is associated with the capacitor bank purchase, installation and cost of power loss. The loss sensitivity factor and backward forward sweep load flow algorithm was used in the selection of candidate buses for the placement of the capacitors. The effectiveness of the approach was tested on the IEEE 34-bus and simulated in the MATLAB environment. The proposed approach proved to be effective with a reduction in active power loss by 27.97%, reactive power loss by 28.13%, and a net saving of $9174.74

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

We would like to acknowledge and express our sincere gratitude to our project supervisor, Mr. E. O. K Addo who made this work possible. His invaluable advice, help in difficult periods, and motivation contributed tremendously to the successful completion of this project.

We would also like to thank all the lectures especially Mr. Daniel Kwegyir for taking the time to give us the understanding of concepts that were needed to carry out this project.

CHAPTER ONE
INTRODUCTION

Background and problem statement

Electric power systems play a vital role in modern society through generating and delivering electrical energy to the end user with high level of power quality[12]. The rising demand for reliable electrical services, enhanced quality, and an increasing introduction of distorting devices have resulted to a higher demand by both users and stakeholders[13]. In order for power to be supplied efficiently, it is important to minimize system losses that affect the system efficiency. The electric energy supplied to customers passes through three segments; generation, transmission and distribution[12]. Distribution networks however contribute more to losses in the power system. Researchers and Engineers have become more focused on the reduction of losses in the power system to ensure efficiency and the overall satisfaction of consumers.

It is essential to control the flow of reactive power under prescribed limits in order to reduce losses in the power system. The importance of reactive power compensation is meant to maintain voltage profile, reduce losses and ultimately improve efficiency of the distribution system[14]. Also the increase in electricity demands has increased the loading of radial distribution feeders which has led to more losses and voltage drops[15].

These issues in the power system have raised the need for the optimal placement of capacitors. The optimal placement of capacitors primarily concerns quantifying the optimal location and capacitor size to be placed in a radial distribution network to minimize the losses that result from the flow of reactive currents. The effectiveness of the impact of capacitors installation depends on the location of their installation and the size of the capacitors[3]. By proper planning and intensive investigation, the best location and size of the capacitor can be found. The optimal placement of capacitors improves the efficiency of the system by enhancing the voltage profile, improving the power factor, improving system reliability, reducing energy losses, lowering the annual cost and increasing the net saving.

Researchers have proposed a number of approaches such as analytical techniques, algorithmic techniques, heuristic techniques and artificial intelligence techniques. However, the method being used in recent years are the intelligent optimization techniques such as; particle swarm optimization[1], artificial electric field algorithm[5], dragonfly algorithm[9], and bacteria foraging algorithm[2].

These optimization methods still have search problems in finding the local optima hence the need to find a more efficient optimization method with a larger search space and fewer local optima entrapment problems. Also, another problem with the algorithms mentioned above is that before the global solution is achieved, the training must be restarted with different solutions. The aim of this research is to use a more efficient algorithm to optimally place capacitors in a high voltage distribution network.

Aim of research

To optimally size and place shunt capacitors in a radial distribution network using a modified particle swarm optimization.

Objectives

- **i.** To review literature on heuristic-based algorithms for optimal placement of capacitors in distribution networks.
- **ii.** Adopt an improved algorithm to optimally place shunt capacitors in a distribution network.
- **iii.** Simulate the proposed method in MATLAB.

CHAPTER TWO
LITERATURE REVIEW

Introduction

The review of several methods for the optimal capacitor placement in distribution systems are being carried out in this chapter. They include works done using conventional methods like estimating techniques, graphical methods, load flow, and so on, as well as metaheuristic optimization algorithms like Genetic Algorithm, Cuckoo Search Optimization, Bacterial Foraging Algorithm and Artificial Electric Field Algorithm and so on. The following are the various reviews;

Technical and Economic performance evaluation for efficient capacitor sizing and placement in real distribution network by Theophilus et al, 2019[1]**.**

In this paper, Particle Swarm Optimization technique (PSO) is used to solve the problem of capacitor placement in a distribution network. The main objective of this paper was to reflect a minimum capital investment, maximum savings and credible improvement of voltage profile and power loss reduction. A combination of backward forward sweep (BFS) load flow and Loss sensitivity analysis are used to selected candidate buses for capacitor placement. The work was tested on an IEEE 33-bus system in MATLAB environment and applied to a real 48 bus network in Freetown, Sierra Leone. Three different cases were considered in solving the capacitor placement problem: base case system, first case which is optimal sizing and placement of fixed capacitors and a second case which is optimal sizing and placement of switched capacitors. On the IEEE 33-bus system, results showed a total active power and reactive power loss reduction of

52.99kW (26.12% reduction) and 35.48kVAr for the first case. For the second case, active power loss reduction was 55.67kW (27.44% reduction) and reactive power loss reduction was 36.75kVAr. On the practical 48 bus system in Freetown, the results are as follows: active power loss reduction of 170.96kW in the first case and 208.81kW in the second case. Reactive power loss reduction was 79.16kVAr for the first case and 96.72kVAr in the second case. Again, a net saving of $8,902.41 and $9,352.43 were recorded for the first and second cases respectively in the IEEE 33-bus system. The net savings were $28,722.05 and $35,081.44 for the first and second cases respectively in the 48 bus system.

Economically, the second case presented a greater advantage with a higher benefit to investment ratio than that of the first case. Technically, the first case presented a slight technical advantage over the second case because the values of the control variables in the switch capacitors are restricted to specified values whereas the fixed capacitors pose a greater flexibility to select random appropriate values within the specified limits of capacitor values. The PSO algorithm has the tendency to fall into local optimum in high-dimensional space. It also has a low convergence rate.

Optimal Capacitor Placement in Distribution Systems Using Improved Bacterial Foraging Algorithm. Salamatu et al, 2019[2]**.**

In this paper, an improved Bacterial Foraging Algorithm was used to optimally site and size capacitors for the purpose of improving voltage profiles at various buses and also reducing system losses. The objective of the paper was to (i) reduce active power loss and (ii) minimize voltage deviation. The BIBC (Bus Injection to Branch Current) matrix with forward sweep method is used to perform the load flow. The work was tested on an IEEE 33-bus Radial Distribution System and a practical 50-bus canteen Feeder located in Kaduna State, Nigeria. The simulation tool that was employed in this work is MATLAB 2016. The IBFA, when compared with various existing techniques, showed greater percentage power loss reduction and a much higher overall percentage voltage improvement. Compared with a base-case power loss of 201.19kW on the IEEE 33-bus, the results showed that active power loss of the IBFA was reduced to 171.99kW (14.81% improvement), that of BFA was reduced to 172.255kW (14.68% improvement) and that of Analytical method to 138.72kW (31.05% improvement). When compared with the BFA and analytical method, the IBFA showed an increment of 4.68% and 0.59% respectively in overall voltage profile improvement. On the practical 50-bus Feeder, percentage power losses was 20.70 for the IBFA and 22.84 for the BFA. Also the voltage profile improvement was 3.67% more in the IBFA than the BFA. The proposed method required less computational time (7.01s) as compared with BFA (11.30s).

Optimization of Capacitor Placement in Radial Distribution System using Integer Encoding Genetic Algorithm by Ketut Suryawan et al, 2020[3]**.**

The authors employed an integer encoding genetic algorithm (IEGA) to optimally locate and place capacitors in a radial distribution system. The objective of the paper was to increase annual cost savings while reducing active power loss using optimal placement of capacitors. The method considered various constraints including capacitor cost, voltage limits and reactive power limits. The proposed method was simulated using two different distribution systems, the 10-bus and 34-bus systems, on MATLAB. With a total capacitor size of 3,500kVAr for the 10-bus system, active power loss was reduced from 783.77kW (before compensation) to 690.11kW making a percentage cost saving of $15,735 (11.11%). On the 34-bus system, there was a power loss reduction from 221.72kW to 163.11kW with total capacitor size of 2,400kVAr. Net savings was $ 9,846 annually.

When compared with a modified artificial bee colony algorithm, the proposed method proved to be efficient, cost effective and required relatively less computational time (1.13s on the 10-bus system and 2.73s on the 34-bus system).

Optimal placement of shunt capacitor to enhance distribution system reliability by Pravin Sonwane et al, 2021[4]

This paper proposes an optimal capacitor placement technique in distributed systems using the genetic algorithm (GA) in the first section and the Optimal Capacitor Placement- Particle swarm optimization (OCP-PSO). In this paper, a hybrid approach was used to achieve the energy efficiency in distribution systems. The OCP- PSO was used in the estimation of the optimal size of the capacitors and the genetic algorithm (GA) was used for the optimal capacitor. It is observed from the graphs, tables, results and comparison tables that voltage constraint applied with limits Vmin =0.95pu and Vmax =1.05 is applied to newly developed and tested software OCP-PSO simulator and reliability cost and overall objective function cost is evaluated and observed that the cost is decreased after appropriate number of capacitors placed in bus. So, it can be concluded that in voltage constraint case for the given limit the capacitor placement and sizing is optimal, losses are decreased, reliability indices are improved and cost function is optimum. The efficiency of the technique is proved on the basis of comparison between the proposed and traditional technique.

Shunt capacitors optimal placement in distribution networks using artificial electric field algorithm by Abdelazee A. Adelsalam et al, 2019 [5]**.**

This paper presents a novel on the use of the artificial electric field algorithm (AEFA) to solve the problem of optimal locations and sizes of capacitor banks (C-Bs) in the various configurations of radial distribution systems. The AEFA is a meta-heuristic optimization algorithm that is deduced from Coulomb's laws. Two strategies are considered in this paper; first, using combined loss sensitivity factor (LSF) and second, using AEFA only. The AEFA is tested on 69-bus and 118-bus radial distribution systems. The objective function is to maximize the annual net saving of loss reduction. A comparison with other optimization techniques is conducted to assess the effectiveness and robustness of the AEFA for solving the C-Bs optimization problem. The proposed approach has been applied using the MATLAB programming environment with different scenarios of single and multi-capacitor banks installation. In the first strategy, candidate buses were selected according to the loss sensitivity factor. The second strategy involved the determination of both the optimal locations and sizes of C-Bs according to the AEFA. For each strategy, two scenarios are examined to determine the number of C-Bs. For the 118-bus radial distribution system, percentage net saving equals 26.19% and the percentage reduction of the active power loss equals 34.76%. For the 69-bus radial distribution system, the percentage net saving equals 26.19% and the percentage reduction of the active power loss equals 32.42%. The obtained results show that the presented algorithm is able to maximize the annual net saving with a small capacity of capacitor banks. Results obtained through the second strategy are preferred to those of the first one. The superiority of the proposed AEFA is verified by comparing its results with other optimization algorithms.

Optimal capacitor placement for IEEE 118 bus system by using the genetic algorithm by Hartono et al, 2019[3]

This paper proposes an optimal capacitor placement technique in distributed systems using the genetic algorithm (GA). Genetic algorithms mimic the mechanisms of the evolutionary process. This study focused on reducing power losses and increasing voltage profiles. The proposed method was tested on the IEEE 118 bus system. In the first stage, the optimal location of the capacitor is determined and in the second stage, the number of capacitors used in a specific location is determined. The GA is used by the optimal placement in the Etap software with all simulations being carried out on the Etap power station. The method of placement of bank capacitors used in the Etap software is the genetic algorithm method. This method proved to be a more efficient one in the reduction of power losses and improving the voltage profile.

Optimal shunt capacitors' placement and sizing in radial distribution systems using multiverse optimizer by Thomson P .M. Mtonga et al, 2021[6]

This paper uses the conventional loss sensitivity factors (LSFs) together with the multiverse optimizer (MVO) to solve the radial distribution systems optimal shunt capacitors' placement and sizing problem. This approach is tested on 10-, 33- and 69- bus radial distribution systems. The effectiveness of this technique is proved on the basis of several simulations being carried out on several buses and the results obtained were good. The performance of the MVO algorithm compared against the other 11 different algorithms is outstanding in all instances. The MVO also has a better convergence characteristic as compared to the other optimization algorithms. This proposed method minimized the overall cost of the total real power losses and shunt capacitors' purchase. With this technique, the highly ranked bus in the modified LSFs vector is used in reducing the search space and thereafter, the MVO is used to do a concurrent search of the most optimal buses within the reduced search space for the installation of shunt capacitors as well as the corresponding capacitor sizes. The active power losses for the 10 - 33- and 69-bus radial distribution system reduced per hour by a percentage of 13.79%, 34.54%, 34.8% respectively. The percentage cost reduction per year for the 10-, 33- and 69- bus is 12.36%, 33.33% and 33.91% respectively. The proposed approach slightly falls behind the other approach with regards to the voltage level improvement. Due to the incorporation of a search space reduction technique within the proposed approach it helps in the reduction of the computation time.

Positioning of multi-capacitors in a radial distribution network using new analytical methods by Hassane Oussenyi et al, 2021[7]

This paper gives a constructive approach on the positioning of multiple capacitors at multi-nodes in the Maradi HV distribution network in Niger by a new modern analytical method based on the calculation of a stability identification index (BVSI). The distribution networks in Maradi are in a state of near collapse. Several customers connected to this network are confronted with the poor quality of supply that is reserved for them. This paper proposed a quick calculation index of the stability state (BVSI) that allowed to identify the impacting nodes that could receive compensators to the effect of improving this network. Three capacitors were positioned at optimal points, resulting in a 20.7% reduction in network losses and 31.70% of the nodes still remained within out-of normative range. The change from three capacitors at three nodes to four capacitors at four nodes shows that the tendency to increase the number of capacitors in a network does not improve its technical performance much. It can be concluded that no matter how capacitors are positioned in the network, they are always limited in their effectiveness in improving the performance of an electrical system. The BVSI is an efficient, accurate and effective index to detect early the vulnerability of a distribution network in order to predict the first signs of voltage collapse, the effects of which are often catastrophic. It can be deduced that node indices are more accurate and are recommended to search for vulnerable points in distribution networks in order to improve their technical performance through compensation.

Dynamic capacitor placement to mitigate disaster in distribution systems: A fuzzy approach by Shyam Mohan Parashar et al, 2019[8]**.**

This paper focuses on using a fuzzy control technique to deal with the problem of nonlinearity in the power system that degrade the power quality. To enhance the power quality a feedback linearization with fuzzy control system is very helpful to find out the location and size of the capacitor. Capacitor placement is done with FLC technique on IEEE 14 bus radial distribution system, that yields benefit due to peak power loss reduction, due to released generation, increased transmission, substation capacity and increased revenue due to voltage improvements and net power savings. By analyzing the results, it can be concluded that the minimum reactive power requirement can be met by fixed capacitor placement with intelligent approach for deciding place and size of capacitors.

Optimal Capacitor Sizing and Placement Using Dragonfly Algorithm: A case Study in Kazakhstan. Baimakhan et al, 2021[9]**.**

This paper presents a heuristic technique, Dragonfly algorithm (DA), to find a near optimal location and sizes for capacitor placement. The objective of the paper was to determine the sizes and locations of capacitors by minimizing voltage deviations and active power losses. Costs of capacitors are not taken into consideration during the determination of optimal location of capacitors. In an attempt to find an optimal location for the capacitors, the authors randomly created varied load conditions taking the base case as reference. The capacities and node locations of capacitors providing smallest voltage deviations and active power losses are selected as solutions. The proposed method is tested on the real radial 17-bus system of the Almaty power grid in Kazakhstan. The tests were performed by varying each load between a range of 70% - 130% of the base value and the problem was tackled by employing 5 capacitors.

Siting and Sizing of Capacitors in Distribution Systems for Annual Cost Savings using ISSA-WF. G. Srinivasan et al, 2021[10]**.**

This paper presents a weight factor based improved Salp swarm algorithm for optimal placement and capacity determination of reactive power compensating device in a radial distribution system. Reduction of power loss with capacitor installation and purchase cost are the objectives of this paper. The proposed method does not utilize loss sensitivity factor (LSF) based node identification for optimal capacitor placement. Instead, algorithms are used to search and identify the most suitable nodes for capacitor location and sizing. The proposed method was tested on two radial bus systems: IEEE 33-bus and Indian 118-bus distribution systems under three different loading levels. With an average cost of capacitors being $293.85/kVAr, results obtained after simulation showed active power loss reduction, on the IEEE-33 bus system, from a base-case of 48.7903kW to 33.13kW representing a 32.097% reduction. A net saving of $2,337.08 was recorded. On the Indian-118 bus system, power loss reduction was 34.355% and a net saving of $11,692.9 was recorded. The authors compared the results from their work with different methodologies including grey wolf algorithm, analytical technique and particle swarm optimization and dragon-fly optimization algorithm. It was found out that the proposed method performed better cost-wise than the others.

An advantage of the proposed method is that is has a better convergence acceleration and a higher feasibility and efficiency in producing a global optimum.

Optimal Shunt Capacitor Placement in Distribution Networks for Power Loss Reduction using Voltage Sensitivity Approach by Bilal Khan et al, 2019[16]**.**

This paper proposes a voltage-to-load sensitivity-based strategy to find an optimal placement for capacitor bank in a distribution network. The objective of the paper was to reduce distribution losses without taking into account the cost of capacitor purchase and installation. In this method, shunt capacitor values were determined based on system losses and allowable voltage limits as defined by ANSI C84.1-2006 standard. Power flow analysis based on voltage-to-load sensitivity was used to determine candidate buses for capacitor placement. The proposed method was carried out in two stages: first, finding an optimal location and second, determining the feasible set of capacitor values that can be installed without affecting performance. A 14-bus primary distribution system built in DIgSILENT PowerFactory environment is used to test the proposed algorithm.

A main disadvantage of this method is that the approach was more of a trial-and-error. For example, in choosing the feasible set of capacitors, the authors varied capacitor sizes and observed the corresponding losses. Computational time may be long for adopting this approach and also the approach may lead to a wrong choice of capacitor.

Multi-Point Optimal Placement of Shunt Capacitor in Radial Distribution Network: A Comparison by Dibya Bharti et al, 2020[11]**.**

Electrical centrality index is used as a tool to search for an optimal location for the placement of shunt capacitors in distribution systems. The main objective of the paper was to minimize voltage deviations at various buses. Power flow analysis using backward/forward sweep analysis was performed. After the power flow, average centrality index of each bus is determined and the results ranked in descending order. Buses with highest average centrality index are selected for the placement of capacitors. The proposed method was tested on a 34-bus radial distribution test network. The results of the proposed method were compared with results of a similar work (referred to as "Method 1" by the authors of this paper). Real power loss was 167.50kW with a total capacitor size of 1700kVAr in the proposed method. In method 1, real power loss was 194.21kW with a total capacitor size of 1800kVAr. The computational time of the proposed method was 0.86146s and that of method 1 was 3.23000s.

Though the proposed method converges faster, it provides a solution to the shunt capacitor placement which is not optimal (as compared to other existing methods). Also, it can be seen that proposed method yields a reduction in voltage profiles and an increase in power losses.

CHAPTER 3
THEORY FOR OPTIMAL CAPACITOR PLACEMENT

3.1 Introduction

This chapter highlights the various theories used to optimally place shunt capacitors in the radial distribution system. They include particle swarm optimization with adaptive weighted delay velocity algorithm, shunt capacitor and backward forward sweep load flow algorithms and load sensitivity.

3.2 Particle swarm optimization

Particle swarm optimization (PSO)[1] is a population-based heuristic algorithm developed by Kennedy and Eberhart in 1995. The PSO mimics the social behaviour of birds flocking together or fish schooling and it harnesses the searching capability of the swarm. In PSO, each member of the swarm is called a particle and the position of each particle represents a potential solution based on the fitness function or objective function. The optimization process of the PSO begins with a randomly initialized population of particles which search for the optimal solution in an N-dimensional search space by updating the velocities and positions of each particle. During the search process, each particle's movement is guided by its own best-known position as well as the entire swarm's best-known position. The information obtained by the particles as they explore in the search space is used to determine the best particle in the swarm known as the global best (gbest). The position of this particle is communicated to all the particles in the swarm, causing the particles' flight paths to be adjusted in the direction the swarm's gbest and its own pbest[1]. Since each particle's position in represent a potential position, the fitness function assesses the extent to which a particle is good or bad. The process of PSO is iterative and it is shown in in the flow chart in Fig. 3.1. The velocity and position of each particle during the iteration process is updated using (3.1) and (3.2) respectively.

$$v_i(t+1) = v_i(t) + c_1 r_1\big(p_{best}(t) - s_i(t)\big) + c_2 r_2\big(g_{best}(t) - s_i(t)\big) \qquad (3.1)$$

$$s_i(t+1) = s_i(t) + v_i(t+1) \qquad (3.2)$$

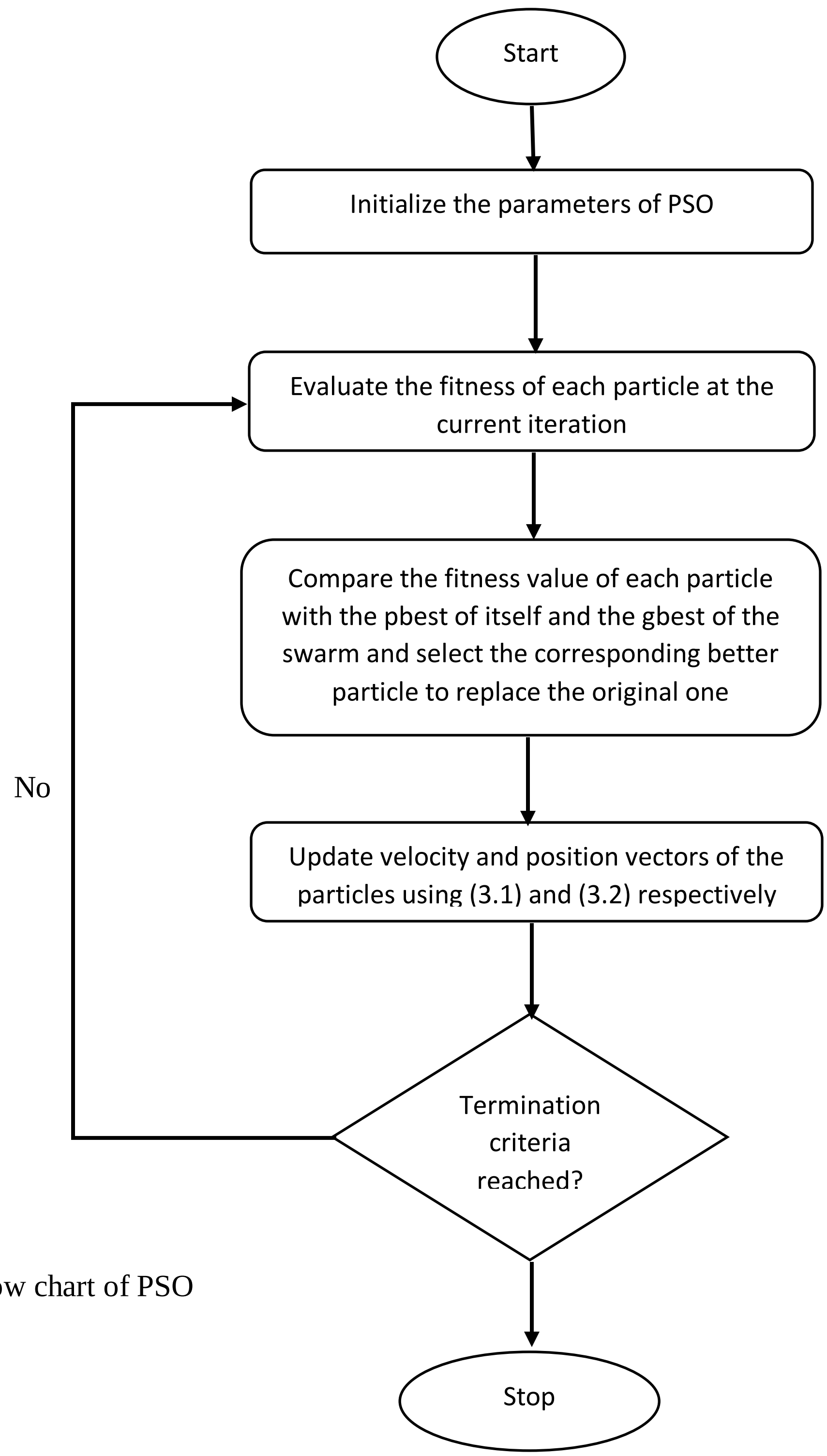

Fig.3.1: Flow chart of PSO

A Modified Inertia Weight Control Particle Swarm Optimization Algorithm

Despite its reputation as being computationally efficient and robust to control parameters[1], the canonical PSO in (3.1) and (3.2) suffers search problems such as local optima entrapment and premature convergence. The issues highlighted above may give rise to undesirable results and hence the need for an improved PSO. Variants of PSO have been proposed in literature[17], [18], [19], [20], [21],[22]. In this work, we adopt a double dynamic exponential function based dynamic inertia weight PSO (DEDIW-PSO)[23]. In DEDIW-PSO, the updating equations are expressed as (3.3) and (3.4) respectively.

$$v_i(t+1) = wv_i(t) + c_1 r_1\big(p_{best}(t) - s_i(t)\big) + c_2 r_2\big(g_{best}(t) - s_i(t)\big) \qquad (3.3)$$

$$s_i(t+1) = s_i(t) + v_i(t+1) \qquad (3.4)$$

The inertia weight, $w,$ is initialized with a constant value of 0.8 and subsequent values of w are calculated as follows:

$$w(t+1) = \exp\big(-\,exp\big(-F(t)\big)\big) \qquad (3.5)$$

The function $F(t)$ is calculated as $F(t) = \frac{\max(t) - t}{\max(t)}$ (3.6)

The pseudocode for the DEDIW-PSO algorithm is shown below:

1. Initialize the parameters of the DEDIW-PSO algorithm

2. **Loop**

3. Evaluate the fitness function of each particle in the swarm and estimate its evolutionary state $E(t)$ at the current iteration using (3.8)

4. Compare the fitness value of each value of each particle with its pbest and the gbest of the swarm and select the best particle
5. Compute the acceleration factors and inertia weight using $(3.5) - (3.7)$
6. Update the velocity and position vectors of the particles at the current iteration using $(3.3)\ and\ (3.4)$
7. **Until** Maximum iteration.

3.3 Shunt capacitor

A shunt capacitor[1] is a necessary component of any power system. It is normally located at the load side of the power system. As can be seen in fig.3.2, the shunt capacitor is connected in parallel with the load. A shunt capacitor is normally used for compensation by improving the power factor of the system. It normally draws a fixed amount of leading current and therefore reduces the reactive component of the load current, thereby improving the power factor. By improving the power factor, voltage drops along the distribution line is reduced. In this work, shunt capacitor is optimally placed using an optimization algorithm to reduce power losses, improve voltage profile and reduce annual operation cost per unit power loss.

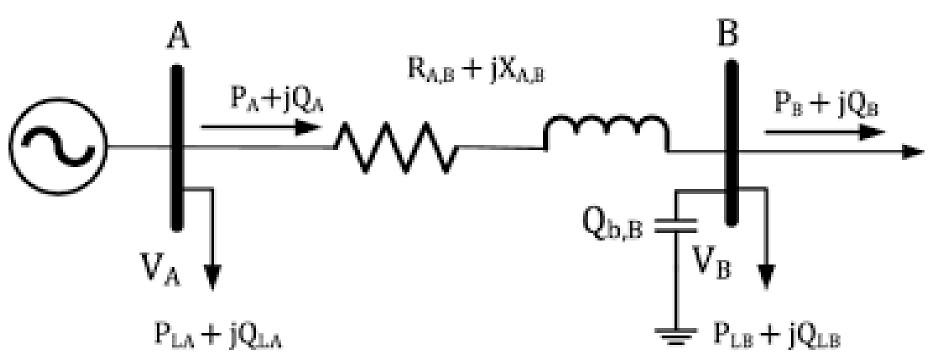

Fig. 3.2

3.4 Backward/Forward Sweep load flow

Backward/Forward Sweep (BFS)[1] is a fast and robust method used to determine branch currents, bus voltages and power flows in a power system. It is employed in this work due to its fast convergence rate and low memory requirement. In addition, the BFS does not require the use of matrices and complex renumbering of nodes and branches. BFS is normally used in radial distribution networks. The process of BFS is divided into three steps namely nodal current calculation, Backward Sweep and Forward Sweep. The Backward Sweep process involves the determination of branch currents. In this method, Kirchhoff's current law is employed in determining the branch currents. Normally, the current in the last branch of the distribution network is determined first followed by the next branch until the current in the very first branch is determined. Hence the name Backward Sweep. The Forward Sweep method involves the determination of bus voltages. In this method the voltage of the first bus (excluding the slack bus) is determined and Kirchhoff's voltage law is applied to determine subsequent bus voltages and hence the name Backward Sweep. The process of determining nodal current, Backward Sweep and Forward Sweep is iterative and convergence is reached only when the magnitude of the maximum error obtained at a certain iteration count is within a prescribed tolerance limit. The equations for nodal current, Backward Sweep, Forward Sweep and power flow are shown by (3.9) $through$ (3.12) respectively as follows:

$$I_i^k = \left(\frac{S_i}{V_i^{k-1}}\right)^* - \left(Y_i\right)\left(V_i^{k-1}\right) \qquad (3.9)$$

$$I_L{}^k = -I_j{}^k - \sum_{m=1}^{M} \left(\frac{S_m}{V_j{}^k} \right)^* \tag{3.10}$$

$$V_q^k = V_p{}^k - Z_L \times I_L{}^k \tag{3.11}$$

$$S_L{}^k = \left(V_j^k + Z_L \times I_L{}^k \right) \left(I_L{}^k \right)^* \tag{3.12}$$

CHAPTER FOUR

METHODOLOGICAL STEPS FOR OPTIMAL PLACEMENT OF SHUNT CAPACITOR IN RADIAL DISTRIBUTION SYSTEM

4.1 Introduction

This chapter presents the methodological steps employed to optimally size and place shunt capacitors in the radial distribution system. The steps are highlighted below with a summary in Fig. 4.1 below.

i. The optimal shunt capacitor placement starts with the problem formulation of the objective function and its respective constraints.
ii. The next step is the modelling of the fixed shunt capacitor for the placement in the distribution network.
iii. Loss sensitivity factors for the system buses are determined.
iv. Load flow analysis using the backward forward sweep method is performed to determine the power loss, voltage, and current of the system.
v. This is followed by the optimal placement of the fixed shunt capacitor with the particle swarm optimization with adaptive weighted delay velocity.
vi. After the case study distribution network is modelled with its data.
vii. Finally, the method is implemented in MATLAB simulation software.

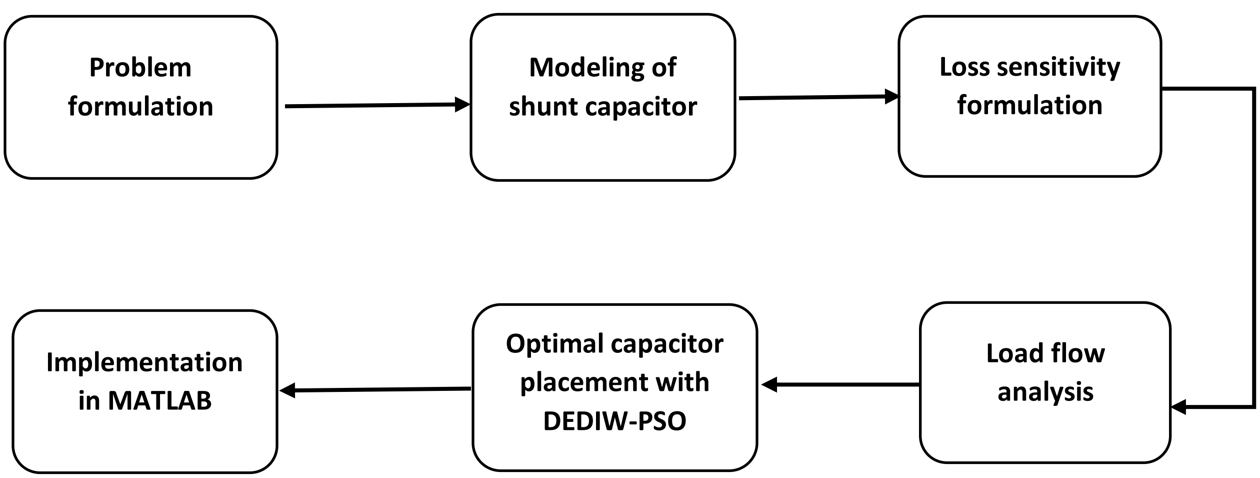

Fig. 4.1: Methodological steps for optimally placing a shunt capacitor

4.2 Objective Function

The placement of capacitors in a radial distribution system is capital intensive. The cost is brought about by the size, number and location of the capacitors in the distribution network. The objective function of installing capacitors in this work is to reflect minimum investment in the installation of capacitors while improving upon the system bus voltage profile and credibly reducing power loss. Mathematically, the objective function is given by:

$$Min(C_{total}) = \alpha_{pr} P_L + \beta_{cp} Q \tag{4.1}$$

Where:

C_{total} is the total costs per year ($/year)

α_{Pr} is the energy cost per unit power loss ($/kW-year).

P_L is the total active power loss on the line.

Q is the total reactive power loss on the line.

β_{cp} is the total capacitor investment cost ($/kVAr).

Extending to a number of N buses, (1.1) can be rewritten as:

$$Min(C_{\cos t}) = \alpha_{pr} \sum_{i=1}^{N_{bus}-1} P_L(i) + \beta_{cp} \sum_{j=1}^{N_c} QC(j) \tag{4.2}$$

From equation (1.2), N_{bus} is the total number of buses, N_c is the optimum number of capacitors to the placed, i is the sending end bus and j is the receiving end bus. The annual cost of capacitor placement is calculated as shown below:

$$Total\ capacitor\ cost = \frac{\beta_{cp} \times QC(total)}{Life\ expentancy\ of\ capacitor}\ (GH₵\ per\ year) \quad (4.3)$$

4.2.1 *Subject to the following constraints:*

i. Voltage limits

The voltages at each bus must be within acceptable limits in order to ensure quality of supplied power.

Mathematically:

$$V_{min} < |V| < V_{max} \quad (4.4)$$

where $V_{min} = 0.95pu\ and\ V_{max} = 1.05pu$

ii. Reactive power limits.

The total reactive power injected into the system by the capacitors should not exceed the total reactive power required by the distribution network.

$$Q_C \leq Q_T \quad (4.5)$$

where $Q_C = injected\ reactive\ power\ and\ Q_T = required\ reactive\ power$

iii. Quantity of capacitor

Optimal number of capacitors, N_C, should not exceed the maximum number of capacitor locations, N_{max}.

$$N_C \leq N_{max} \quad (4.6)$$

iv. Power flow

The amount of power flowing in each bus, $P_f(i)$, should be less than or equal to the thermal limit of the line, $P_i(\max)$.

$$|P_f(i)| \leq P_i(\max) \tag{4.7}$$

4.3 Modelling of capacitors

In this work, the shunt capacitors are modelled as fixed capacitors whose ratings are commercially available in[1]. The $\alpha_{Pr}\ and\ \beta_{cp}$ are chosen to be 168$/kW-year and 5$/kVAr-year. Life expectancy of the capacitors are taken as 10 years. Maintenance and operational costs are assumed to be negligible. The capacitors are limited to operate within a voltage range of 0.95pu and 1.05pu. The sizes of the capacitors are chosen to be within a range of 150kVAr (minimum) and 1200kVAr (maximum) and maximum number of locations taken to be four.

4.4 Backward/Forward Sweep Load Flow

In this work, load flow analysis using backward forward sweep is used to determine system bus voltages, bus currents, branch currents, real and reactive power losses and bus angles. From the figure below, the real, P_{Li} and reactive Q_{Li} power losses are calculated using (4.8) and (4.9).

$$P_{L_i} = R_i \frac{(P_i^2 + Q_i^2)}{V_i^2} \tag{4.8}$$

$$Q_{L_i} = X_j \frac{(P_i^2 + Q_i^2)}{V_i^2} \tag{4.9}$$

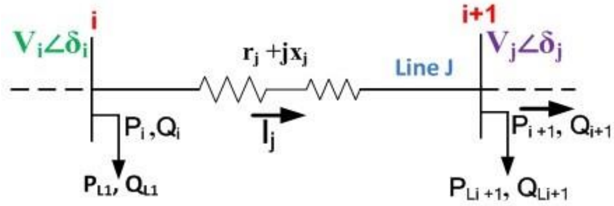

Fig 4.2: Backward/Forward sweep load flow

Also, the active and reactive power flow between the two buses is given by (4.10) and (4.11)

$$P_i = p'_{i+1} + x_i \frac{\left(P'_{i+1} + Q'_{i+1}\right)}{V'_{i+1}} \tag{4.10}$$

$$Q_i = Q'_{i+1} + x_i \frac{\left(P'_{i+1} + Q'_{i+1}\right)}{V'_{i+1}} \tag{4.11}$$

The process is summarized using the flow chart below:

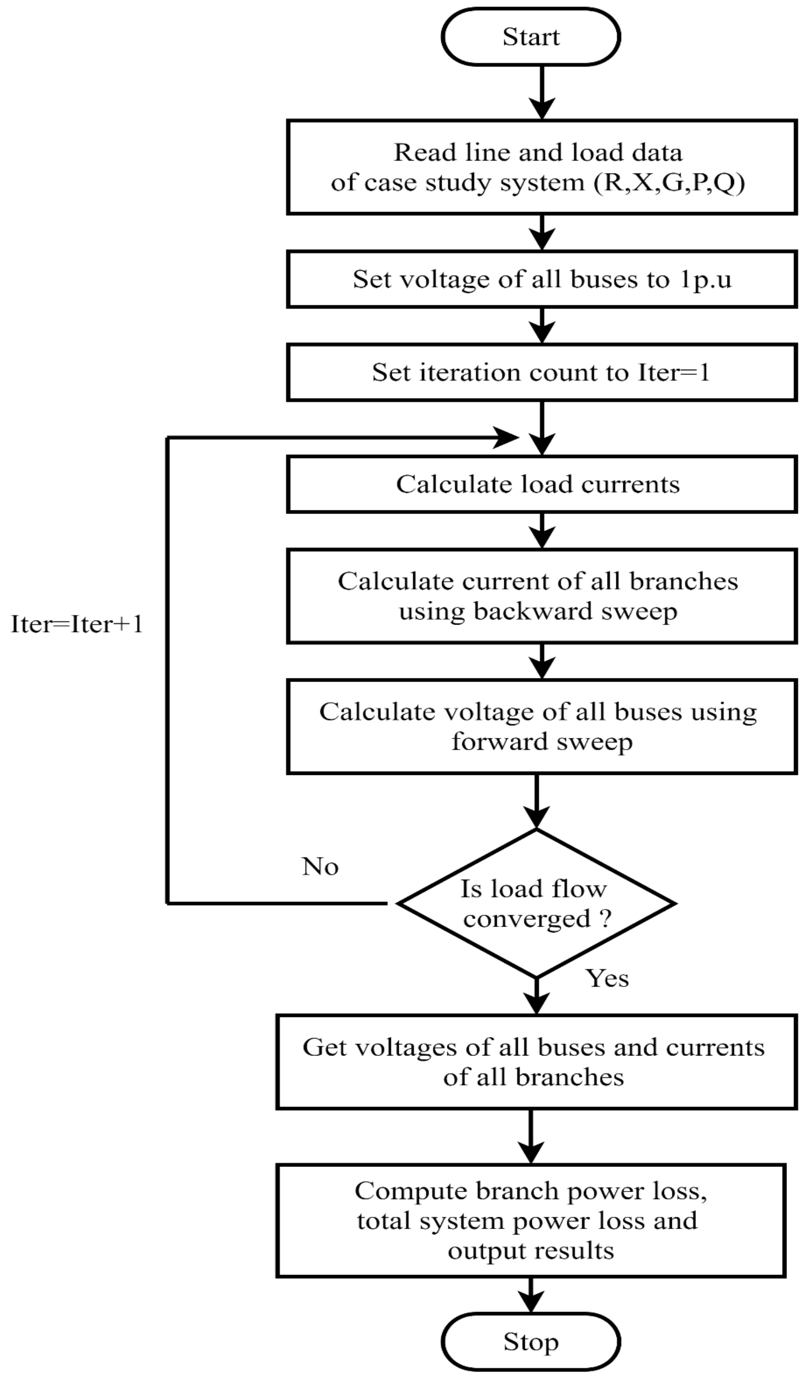

Fig 4.3: Implementation of capacitor placement with PSO

4.5 Loss sensitivity factor

Loss sensitivity factor is used together with the search space to determine the optimal location of placing the shunt capacitors. Developed in [1], loss sensitivity factors are used to predict how buses experience reduction in losses by placement of capacitors. It also reduces the number of capacitors and hence the installation cost. From (4.12) and (4.13) below, loss sensitivity factors are calculated as change in active load per change in voltage and change in active power per change in reactive power. In (4.12), buses with largest negative LSF_1 values are considered as candidate buses for the placement of capacitors. In similar vein buses with largest positive LSF_2 values in (4.13) are considered as candidate buses for placing the capacitors.

$$LSF_1 = \frac{\partial P_{Lj}}{\partial V_{i+1}} = -2 \times R_j \times \left(\frac{P_{i+1}^2 + Q_{i+1}^2}{V_{i+1}^3}\right) \tag{4.12}$$

$$LSF_2 = \frac{\partial P_{Lj}}{\partial Q_{i+1}} = \left(\frac{2 \times Q_{i+1} \times r_j}{V_{i+1}^2}\right) \tag{4.13}$$

4.6 Modelling of the case study system: IEEE-34 bus

The proposed fixed shunt capacitor placement is tested on IEEE bus 34 radial distribution network. The original system is 60Hz, 24.9kV, 12 MVA with various fixed loads and distributed loads connected to a main utility substation. The load type includes constant current, constant impedance and constant power models (three phase and single phase). The system line data is shown in table 4.1 and the load data is shown in table 4.2. The entire configuration is as shown below in figure 4.4.

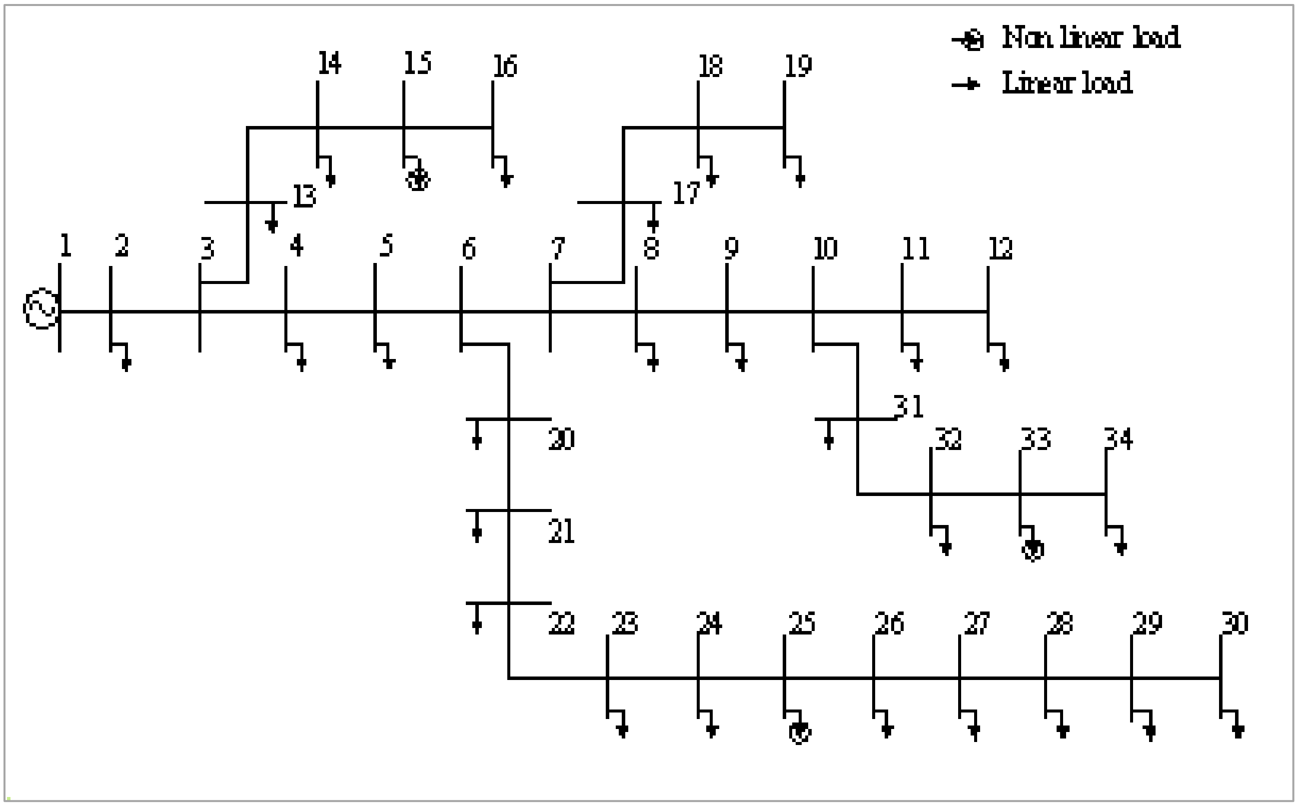

Figure 4.4: IEEE bus 34 radial distribution network

Table 4. 1: Line data of IEEE bus 34 radial distribution network

From Bus	To Bus	Length(km)	Line impedance	
			Resistance (Ohm/km)	Reactance (Ohm/km)
1	2	1	0.0922	0.047
2	3	1	0.493	0.2511
3	4	1	0.366	0.1864
4	5	1	0.3811	0.1941
5	6	1	0.819	0.707
6	7	1	0.1872	0.6188
7	8	1	1.7114	1.2351
8	9	1	1.03	0.74
9	10	1	1.044	0.74
10	11	1	0.1966	0.065
11	12	1	0.3744	0.1238
12	13	1	1.468	1.155
13	14	1	0.5416	0.7129

14	15	1	0.591	0.526
15	16	1	0.7463	0.545
16	17	1	1.289	1.721
17	18	1	0.732	0.574
2	19	1	0.164	0.1565
19	20	1	1.5042	1.3554
20	21	1	0.4095	0.4784
21	22	1	0.7089	0.9373
3	23	1	0.4512	0.3083
23	24	1	0.898	0.7091
24	25	1	0.896	0.7011
6	26	1	0.203	0.1034
26	27	1	0.2842	0.1447
27	28	1	1.059	0.9337
28	29	1	0.8042	0.7006
29	30	1	0.5075	0.2585
30	31	1	0.9744	0.963
31	32	1	0.3105	0.3619
32	33	1	0.341	0.5302

Table 4. 2:Load data for IEEE bus 34 radial distribution network

Load at bus	
P(kW)	Q(kW)
0	0
100	60
90	40
120	80
60	30
60	20
200	100
200	100
60	20
60	20
45	30
60	35
60	35
120	80

60	10
60	20
60	20
90	40
90	40
90	40
90	40
90	40
90	50
420	200
420	200
60	25
60	25
60	20
120	70
200	600
150	70
210	100

4.1. Simulation of proposed method for optimal placement of shunt capacitor

The proposed method is simulated in MATLAB 2019a simulation software. The modified inertia weight control Particle Swarm optimization algorithm (PSO) was real-coded in the software. The parameters of the Particle Swarm Optimization Algorithm are shown in table 4.3. Each optimization algorithm is run for 1000 iterations. The initial load sensitivity factors LSF_1 and LSF_2 for the base case scenario is shown in table 4.4 and the converted radial network of the IEEE bus 34 by the BFS algorithm is shown in figure 4.5.

Table 4. 3: Parameters of Particle Swarm optimization Algorithm

Parameter	Value
Number of iterations	200
Number of runs	1

Total number of Particles (Swarm Population)	200
Inertia weight (w)	0.8
C1(Personal acceleration coefficient)	2
C2(Personal acceleration coefficient)	2

Table 4. 4: Loss sensitivity for base case scenario

Bus number	**LSF1**	**Bus number**	**LSF2**
4	-2.07773934230214e-06	2	5.11418725365400e-07
5	-2.02487628174988e-06	4	5.05017427810715e-07
2	-1.96957411515646e-06	5	4.98920641733881e-07
19	-1.87639395804104e-06	24	4.81295106458119e-07
17	-1.87592813636561e-06	25	4.80442055001007e-07
22	-1.86719582841703e-06	17	4.80413226162398e-07
24	-1.86213597844105e-06	26	4.80063345944416e-07
23	-1.85997719275922e-06	23	4.79877098958307e-07
20	-1.85688178225311e-06	22	4.79233082396332e-07
18	-1.85371539309460e-06	19	4.79048125053846e-07
21	-1.85018176284840e-06	18	4.78055752186827e-07
25	-1.84612715160881e-06	21	4.78008794720525e-07
26	-1.83943867794413e-06	20	4.77852923743130e-07
9	-1.75521532463416e-06	9	4.62822520940040e-07
8	-1.74461678963742e-06	11	4.61709152022213e-07
11	-1.73490965130313e-06	8	4.60718756966565e-07
27	-6.52584710807150e-07	27	1.70779717706214e-07
12	-6.11529381843293e-07	12	1.60411088156376e-07
28	-1.84605549632365e-07	29	5.17644547745194e-08
29	-1.84519933101211e-07	30	5.17641244193019e-08
30	-1.84455488023393e-07	28	5.17609406691849e-08
14	-1.56702809675429e-07	14	4.34679093560369e-08
13	-1.56682945317857e-07	15	4.34579636349421e-08
15	-1.56562324524720e-07	13	4.34530625346465e-08
32	-1.05342904005918e-07	32	2.70815992829711e-08
31	-1.05305778487666e-07	33	2.70776310709038e-08
33	-1.05249123167536e-07	34	2.70751029990729e-08
34	-1.05204947206760e-07	31	2.70691924442398e-08

3	-1.69804125980768e-08	3	2.41939154584045e-09
6	-1.65884225326240e-08	16	1.20710480635802e-09
16	-5.17879789459930e-09	6	1.15169489953523e-09
7	-9.67467212771341e-10	7	2.67962042695881e-11
10	-2.03514723588789e-11	10	5.60323683240355e-13

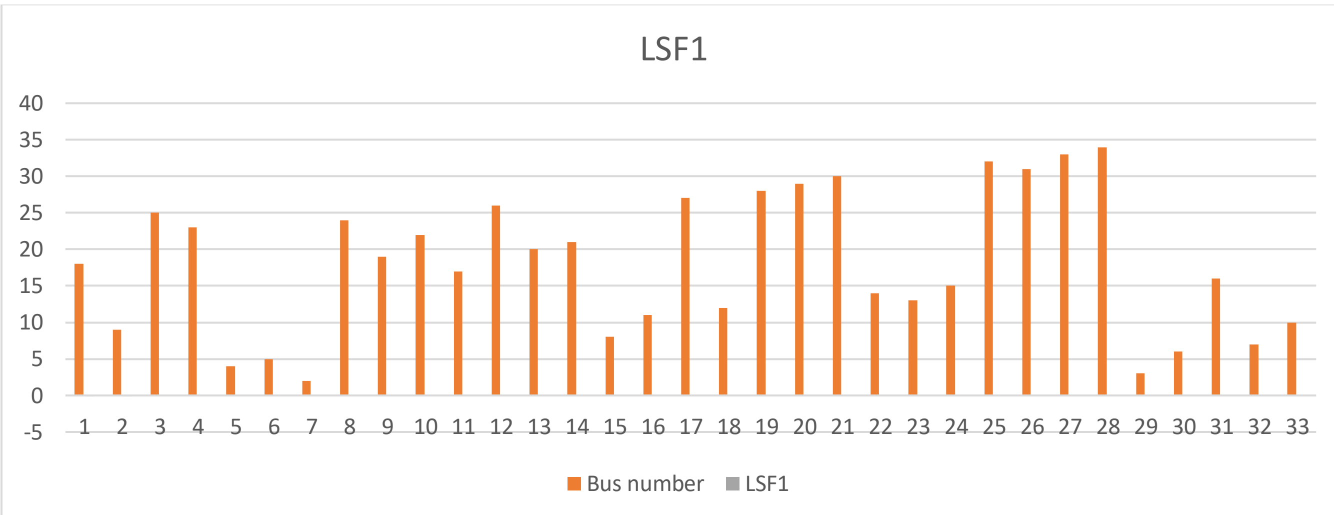

Figure 4. 5: Graph of LSF1 of the modified PSO

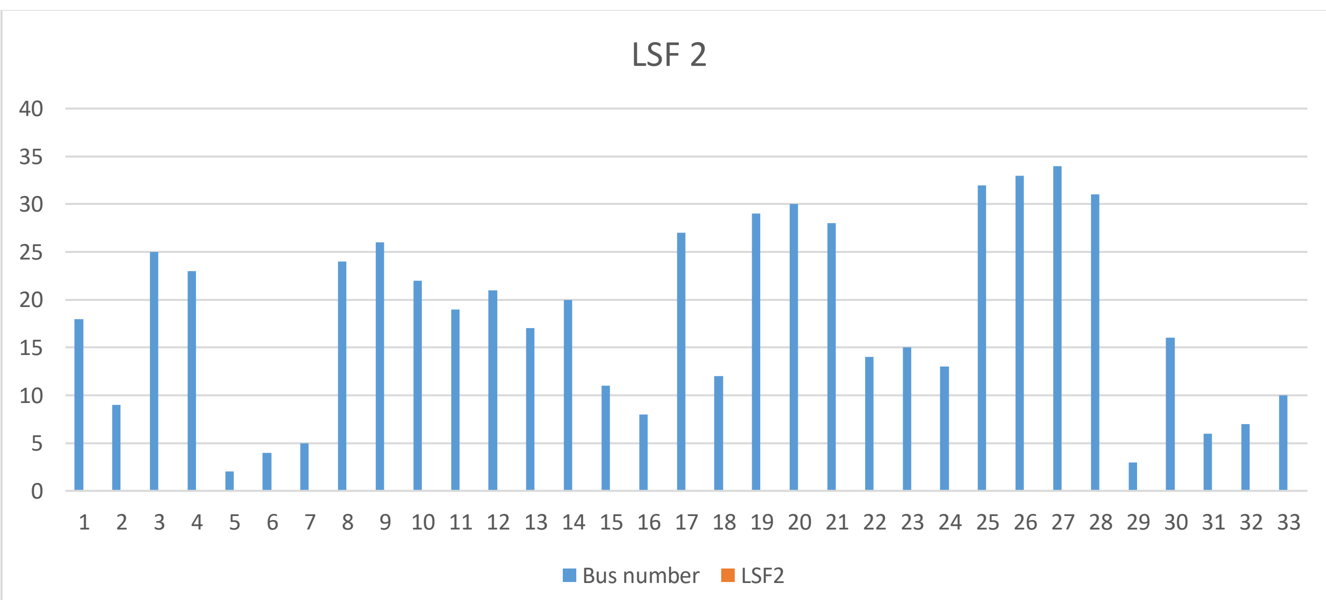

Figure 4. 6: Graph of LSF2 of the modified PSO

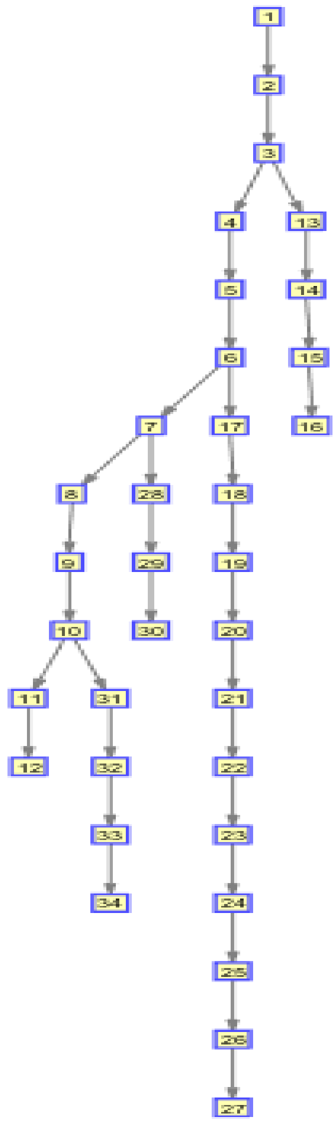

Figure 4. 1: Converted IEEE bus 34 radial network by BFS algorithm

CHAPTER FIVE
RESULTS AND ANALYSIS

5.1. Introduction

The outcomes of the shunt capacitor's ideal placement are shown in this chapter. Under the headings of economical evaluation, investment cost, and technical evaluation, the results are provided. Both the base case and the situation in which the shunt capacitor was placed optimally are discussed.

5.2. Economic evaluation of shunt capacitor placement

Table 5.1 displays the findings for the chosen buses and each one's individual reactive power injection (kVAr). Buses 2, 24, 19, and 11 were chosen as the best locations for the shunt capacitor because they were the most sensitive buses according to the LSF values for. Their respective sizes were 750kVAr, 750kVAr, 900kVAr, and 600kVAr, which results in a total compensation of 3000kVAr for the base PSO. The results for the modified PSO are also in the table below.

Table 5. 1: Summary of Results

PARAMETERS	BASE	COMPENSATED CASE	COMPENSATED CASE
		BASE PSO	MODIFIED PSO
Optimal capacitor location and sizing	N/A	Bus 2(750) Bus 24(750) Bus 19(900) Bus 11(600)	Bus 23(450) Bus 18(900) Bus 9(750) Bus 25(450)
Total Active Power Loss (Kw)	221.7199	161.3003	159.8076
Total Reactive Power Loss (KVAR)	65.1090	46.9479	46.8229
Active Power Loss Reduction (%)	N/A	27.25	27.92
Reactive Power Loss Reduction (%)	N/A	27.89	28.09

Total Compensation (KVAR)	N/A	3000	2550
Annual Cost ($/year)	37278.94	27522.89	26847.68
Total cost of capacitors ($/year)	N/A	1500	1275
Net Savings ($/year)	N/A	8256	9156.26
Min |Vi| (pu)	0.942(Bus 27)	0.950(Bus 27)	0.950(Bus 27)
Max |Vi| (pu)	0.994(Bus 2)	0.955(Bus 2)	0.955(Bus 2)

The table above displays the expenses related to this total remuneration. Without shunt capacitor adjustment, the base case's annual per-unit power loss was $37278.94. This was decreased to $27522.89, which represents a reduction of 26.17% and a net save of $8256.10. This was accomplished for a total investment in shunt capacitors of $1500.

Again, when the Modified PSO was used, annual per-unit power loss further decreased to $26847.68 which is a 27.98% reduction and a net saving of $9156. This was accomplished for a total investment in shunt capacitor of $1275.

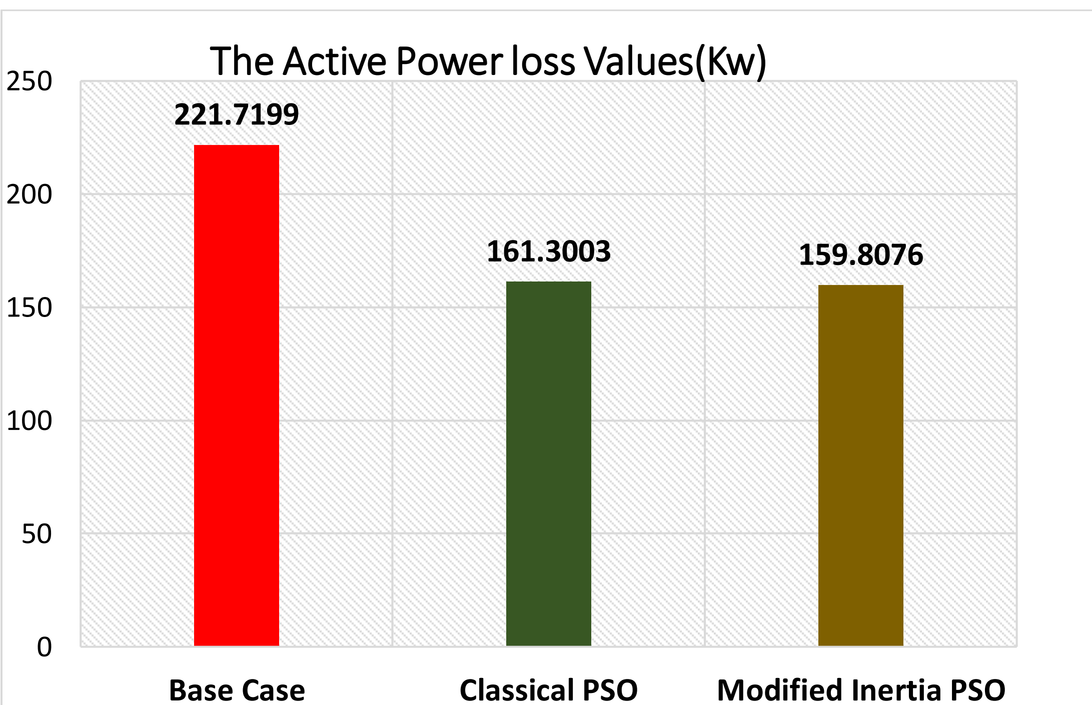

Figure 5. 1: Active Power loss

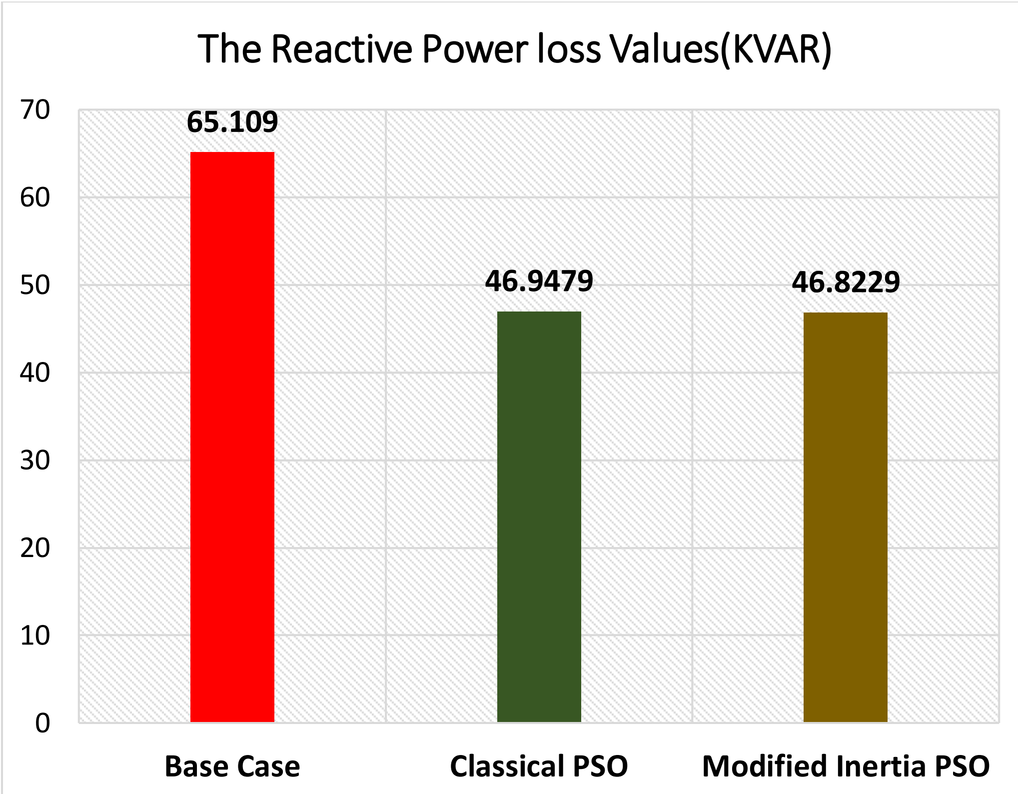

Figure 5. 2: Reactive Power loss

Figures 5.1 and 5.2, respectively, depict the system's power loss before and after correction. The IEEE 33 radial distribution network's active power loss was decreased from 221.7199kW to 161.3003kW and 159.8076kW for the Base PSO and the modified PSO respectively. This represents an active loss reduction of 27.25% and 27.92% respectively. After installing a shunt capacitor, the reactive power was decreased from 65.1090 kVAr to 46.9479 kVAr and 46.8229 kVAr for the Base PSO and the modified PSO respectively. This represents a reactive loss reduction 27.89% and 28.09% respectively.

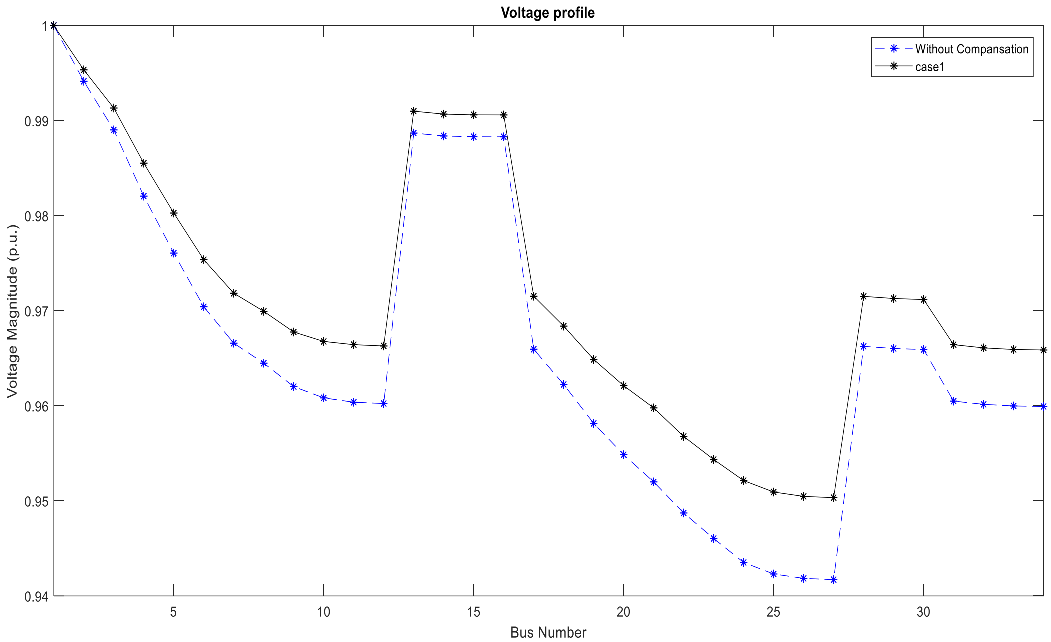

Figure 5. 3: Voltage profile before and after compensation.

CONCLUSION AND RECOMMENDATION

CONCLUSION

In this study, the Modified Inertia Weight Control Particle Swarm Optimization algorithm was used to optimize the placement of the shunt capacitor in the radial distribution network. First, a cost of active power loss and capacitor purchase optimization problem is created with a variety of control parameters (constraints). The best buses for the placement of the capacitor are chosen using a loss sensitivity factor technique.

In MATLAB simulation software, the issue is examined on the IEEE bus 34 radial distribution network. With a total cost of $1275 for the procurement of the shunt capacitor, the cost per unit power loss was decreased from $37278.94 to $26847.68, a reduction of 27.98% and a net save of $9156.26. Once more, the entire active power loss was decreased from 221.7199kW base case to 159.8076kW, which is a reduction of 27.92 percent for the modified PSO.

This outcome was made possible by the modified Particle Swarm optimization algorithm's effectiveness in resolving the optimal placement challenge. It is advised to apply the Modified Particle Swarm optimization algorithm to resolve other power system optimization issues.

RECOMMENDATION

We recommend that future work should take into consideration the effect of capacitor placement on voltage stability on the distribution network and also assess how optimal capacitor placement can facilitate the integration of renewable energy resources.

REFERENCES

[1] T. Amara, S. Asefi, O. B. Adewuyi, M. Ahmadi, A. Yona, and T. Senjyu, "Technical and economic performance evaluation for efficient capacitors sizing and placement in a real distribution network," *2019 IEEE Student Conf. Res. Dev. SCOReD 2019*, pp. 100–105, 2019, doi: 10.1109/SCORED.2019.8896285.

[2] S. A. Sani, G. A. Bakare, Y. S. Haruna, A. I. Isa, and U. Musa, "Optimal Capacitor Placement in Distribution Systems using Improved Bacterial Foraging Algorithm," *IEEE PES/IAS PowerAfrica Conf. Power Econ. Energy Innov. Africa, PowerAfrica 2019*, pp. 233–237, 2019, doi: 10.1109/PowerAfrica.2019.8928867.

[3] I. K. Suryawan and I. G. N. A. D. Saputra, "Optimization of capacitor placement in radial distribution system using integer encoding genetic algorithm," *3rd Int. Conf. Appl. Sci. Technol. iCAST 2020*, pp. 544–548, 2020, doi: 10.1109/iCAST51016.2020.9557646.

[4] P. Sonwane, V. Shirsath, and T. Varshney, "Optimal placement of shunt capacitor to enhance distribution system reliability," *9th IEEE Int. Conf. Power Electron. Drives Energy Syst. PEDES 2020*, 2020, doi: 10.1109/PEDES49360.2020.9379833.

[5] A. A. Abdelsalam and H. A. Gabbar, "Shunt Capacitors Optimal Placement in Distribution Networks Using Artificial Electric Field Algorithm," *Proc. 2019 7th Int. Conf. Smart Energy Grid Eng. SEGE 2019*, pp. 77–85, 2019, doi: 10.1109/SEGE.2019.8859948.

[6] T. P. M. Mtonga, K. K. Kaberere, and G. K. Irungu, "Optimal Shunt Capacitors' Placement and

Sizing in Radial Distribution Systems Using Multiverse Optimizer," *IEEE Can. J. Electr. Comput. Eng.*, vol. 44, no. 1, pp. 10–21, 2021, doi: 10.1109/icjece.2020.3012041.

[7] H. O. Ibrahim, F.-X. Fifatin, A. Oloulade, A. M. Imano, and A. K. Vianou, "Positioning of multicapacitors in a radial distribution network using new analytical methods," no. December, pp. 1–6, 2022, doi: 10.1109/icecet52533.2021.9698665.

[8] S. M. Parashar, G. Leena, M. Pande, Zaheeruddin, and J. Singh, "Dynamic Capacitor Placement to Mitigate Disaster in Distribution System: A Fuzzy Approach," *2019 Int. Conf. Power Electron. Control Autom. ICPECA 2019 - Proc.*, vol. 2019-Novem, no. 2, 2019, doi: 10.1109/ICPECA47973.2019.8975493.

[9] O. Baimakhan, H. Şenyüz, A. Sauchimov, and O. Ceylan, "Optimal capacitor sizing and placement using dragonfly algorithm: A case study in Kazakhstan," *IET Conf. Publ.*, vol. 2020, no. CP780, pp. 208–212, 2020, doi: 10.1049/icp.2021.1276.

[10] G. Srinivasan and B. S. Lokasree, "Siting and Sizing of Capacitors in Distribution Systems for Annual Cost Savings Using ISSA-WF," *3rd IEEE Int. Virtual Conf. Innov. Power Adv. Comput. Technol. i-PACT 2021*, 2021, doi: 10.1109/i-PACT52855.2021.9696659.

[11] Di. Bharti, "Multi-point Optimal Placement of Shunt Capacitor in Radial Distribution Network: A Comparison," *2020 Int. Conf. Emerg. Front. Electr. Electron. Technol. ICEFEET 2020*, 2020, doi: 10.1109/ICEFEET49149.2020.9186968.

[12] A. A. Abdelsalam, H. A. Gabbar, and M. Ieee, "Shunt Capacitors Optimal Placement in Distribution Networks Using Artificial Electric Field Algorithm," pp. 77–85, 2019.

[13] F. Salinas-herrera, D. Jayaweera, M. S. Alvarez-alvarado, and U. Kingdom, "Reliability Study of a Smart Distribution System with Optimal Sizing and Placement of Capacitors".

[14] S. M. Parashar, M. Pande, J. M. Islamia, N. Delhi, J. Singh, and N. Delhi, "DYNAMIC CAPACITOR PLACEMENT TO MITIGATE DISASTER IN DISTRIBUTION SYSTEM : A FUZZY Sensitive System Bus Identification by," no. 2, 2019.

[15] A. Zeinalzadeh, "Simultaneous Optimal Placement and Sizing of DSTATCOM and Parallel Capacitors in Distribution Networks Using Multi-Objective PSO".

[16] B. Khan, S. Shafiq, and A. T. Al-Awami, "Optimal Shunt Capacitor Placement in Distribution Networks for Power Loss Reduction Using Voltage Sensitivity Approach," *2019 9th Int. Conf. Power Energy Syst. ICPES 2019*, 2019, doi: 10.1109/ICPES47639.2019.9105650.

[17] L. Xu, B. Song, and M. Cao, "An improved particle swarm optimization algorithm with adaptive weighted delay velocity," *Syst. Sci. Control Eng.*, vol. 9, no. 1, pp. 188–197, 2021, doi: 10.1080/21642583.2021.1891153.

[18] S. L. Sabat and L. Ali, "Accelerated exploration particle swarm optimizer-AEPSO," *IEEE Reg. 10 Annu. Int. Conf. Proceedings/TENCON*, 2008, doi: 10.1109/TENCON.2008.4766568.

[19] R. F. Mochamad, S. P. Hadi, and B. S. M. Isnaeni, "TVAC PSO for modal optimal control POD and PSS coordination in UPFC," *Proc. - 2014 6th Int. Conf. Inf. Technol. Electr. Eng. Leveraging Res. Technol. Through Univ. Collab. ICITEE 2014*, pp. 5–10, 2014, doi: 10.1109/ICITEED.2014.7007951.

[20] M. Hamed, B. Mahdad, K. Srairi, and N. Mancer, "Solving combined economic emission dispatch problem using time varying acceleration based PSO," *2012 11th Int. Conf. Environ. Electr. Eng. EEEIC 2012 - Conf. Proc.*, pp. 764–769, 2012, doi: 10.1109/EEEIC.2012.6221478.

[21] M. S. Hossen, F. Rabbi, and M. M. Rahman, "Adaptive Particle Swarm Optimization (APSO) for multimodal function optimization," *Int. J. Eng. Technol.*, vol. 1, no. 3, pp. 98–103, 2009.

[22] B. Hussain, A. Amin, A. Mahmood, and M. Usman, "Generation in the Distribution Network by

QPSO," pp. 1–6.

[23] M. Sabir, A. Ahmad, A. Ahmed, S. Siddique, and U. A. Hashmi, "A modified inertia weight control of particle swarm optimization for optimal reactive power dispatch problem," *2021 Int. Conf. Emerg. Power Technol. ICEPT 2021*, 2021, doi: 10.1109/ICEPT51706.2021.9435588.