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ENHANCEMENT OF DISTRIBUTION SYSTEMS PERFORMANCE USING MODERN OPTIMIZATION TECHNIQUES

B. Sc. Project

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ABSTRACT

The major loads are connected to the network through the distribution systems. Therefore, the quality of the service is based on the continuity of power and maintaining the supply voltage within certain limits with specified frequency. Due to the rapid spread in the loads, the long distance of radial structure and the high R/X ratio of lines, the power loss reduction and voltage profile improvement are the challenge. To solve these problems, the distributed generations (DGs) and shunt capacitors are installed on the radial feeders for active and reactive power injections. Therefore, the optimal locations and sizes of DGs and capacitors in distribution systems can be formulated as a constrained optimization problem. In order to solve this problem, the optimization techniques are applied.

This project presents a procedure to determine the optimal placement of DGs and capacitors with an objective of power loss minimization or total voltage deviation minimization. The Archimedes Optimization Algorithm (AOA) is introduced to find the optimal locations and sizes of DGS and Capacitors considering the minimization of total power loss or TVD as objective function, while the security and operational constraints are fully achieved. The backward/forward sweep (BFS) algorithm is introduced for the load flow calculations. The proposed procedure is applied on 34-bus standard radial distribution system and East Delta Network (EDN) distribution system as a part of the Unified Egyptian Network (UEN) in order to solve the optimal DGs and capacitors placement problem. The obtained results are compared with other methods. Simulation results show the capability of the proposed procedure to find the optimal solution for significant minimization in the objective function with more accuracy and efficiency.

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Symbol	Meaning
v_i^k	The velocity of object i at iteration k.
x_i^k	The position of object i at iteration k.
β	Random number of a uniform distribution in the range [0,1].
ε	Random number in the range [-1,1].
V_L	The voltage magnitude at each load bus.
V_L^{min} and V_L^{max}	The minimum and maximum limits of load bus voltage, respectively.
$pf_{overall}$	The overall power factor at substation.
pf^{min}	The minimum limit of overall power factor at substation.
N_C	The optimal number of capacitors placement.
N_C^{max}	The maximum number of possible locations of capacitors.
N_{DG}	The optimal number of distributed generations (DGs).
N_{DG}^{max}	The maximum number of possible locations of DGs.
P_{DGj} and Q_{DGj}	The active and reactive power injections by DGs at bus j.
P_{DG}^{Total}	The total active power injection by DGs.
Q_{DG}^{Total}	The total reactive power injection by DGs.
P_L^{Total}	The total active power load in kW.
Q_L^{Total}	The total reactive power load in kvar.
Q_{Cj}	the reactive power injection at location j.
Q_{Cj}^{min} and Q_{Cj}^{max}	The minimum and maximum limits of reactive power injection at location j, respectively.
P_{Loss}^{Total}	The total power loss.
Q_C^{Total}	The total capacitor banks reactive power.
P_{Lossi}	The power loss in line i.
$P_{eff\ /q}$ and $Q_{eff\ /q}$	The total effective active and reactive power loads beyond the node q, respectively.
V_p	The voltage magnitude at nodes p.
δ_p	The voltage angle at nodes p.
R_k and X_k	The resistance and reactance of branch k, respectively.
S_i	The specified power injection at node i.

Chapter 1

Introduction

The distribution system is at the heart of the emerging smart electrical system and the role of distribution system operators is on the verge of a real revolution. Operators are in fact the ones who will have to master technical complexity, limit the sudden rise in costs and ensure the quality of service expected by customers. The distribution grid, which ensures continuity of supply, is a vital infrastructure for our economies to function effectively. This has been true for a long time and is increasingly becoming the case. The distribution network is one of the most complex industrial facilities currently in use [1].

In fact, until now electricity was very predictable, going from large power plants to large electricity transmission grids, then to the distribution grids to supply customers. The direction of the flow was predictable. With the development of distributed generation (DG), a significant proportion of generation is connected to the distribution grid. Furthermore, the means of DG are mainly wind and solar power stations, whose generation varies depending on the wind and sun. It is therefore possible, for example, to have a generation greater than the local consumption in the middle of the afternoon in a housing development where there are many solar panels, at a time when people are at work or school and when the panels produce at their maximum rate. Therefore, the electricity temporarily flows that will return a higher voltage to the grids. At night, the flow returns to its usual direction. There are therefore varying directions of flow [1].

The term “optimization” refers to a choice that must be made from several possible solutions, while respecting a finite number of constraints. A human desire for perfection finds its expression in the optimization theory, which teaches how to describe and fulfil an optimum. The optimization tries to improve system performances in the direction of the optimal point or points. The optimization can be defined as a part of the applied or numerical mathematics or a method for system design by computer in accordance with either one stress theoretical aspect (existence of the optimum solution conditions) or the practical aspect (procedures for obtaining the optimum solution) [2].

The analytical solution [3] used to solve an optimization problem depends on the form of the criterion and constraint functions. The simplest situation to be considered is the unconstrained optimization problem. In such a problem, no constraints are imposed on the decision variable, and different calculus can be used to analyze them. Another relatively simple form of the general optimization problem is the case in which all the constraints of the problem can be expressed as equality relationships. However, conventional optimization techniques have been developed that can efficiently solve several classes of problems with these inequality restrictions.

Many difficulties such as multi-modality, dimensionality and differentiability are associated with the optimization of large-scale problems. Traditional techniques such as steepest decent, linear programming (LP) and dynamic programming (DP) generally fail to solve non-deterministic polynomial-time hard (NP-hard) problems such large-scale problems especially with nonlinear objective functions. Most of the traditional techniques require gradient information and hence it is not possible to solve non-differentiable functions with the help of such traditional techniques. Moreover, such techniques often fail to solve optimization problems that have many local optima. To overcome these problems, there is a need to develop more powerful optimization techniques and research is going on to find effective optimization techniques since last three decades. One of the population-based optimization techniques developed recently is the Archimedes Optimization Algorithm (AOA).

Archimedes Optimization Algorithm (AOA) [7] is based on Archimedes' principle which states that "Any object, totally or partially immersed in a fluid or liquid, is buoyed up by a force equal to the weight of the fluid displaced by the object.". AOA emulates the behavior of many objects, which have different densities and volumes, immersed in the same fluid and each one tries to reach equilibrium state.

Capacitor banks are commonly used in a distribution system to provide reactive power locally, resulting in reduced maximum kVA demand, improved voltage profile, reduced line/feeder losses and decreased payments for the energy. Capacitor banks are installed close to the load, on the poles, or at the substations. Maximum benefit can be obtained by installing the shunt capacitor banks at the load. This is not always practical due to the size of the load, distribution of the load and voltage level. In distribution and certain industrial loads, the reactive power requirement to meet the required power factor is constant. In such applications, fixed capacitor banks are used. Sometimes such fixed capacitor banks can be switched along with the load. If the load is constant for the 24-hour period, the capacitor banks can be on without the need for switching on and off. In high voltage and feeder applications, the reactive power support is required during peak load conditions. Therefore, the capacitor banks are switched on during the peak load and switched off during off-peak load. The switching schemes keep the reactive power levels more or less constant, maintain the desired power factor, reduce overvoltage during light load conditions, and reduce losses at the transformers and feeders [8].

The distribution feeder is nonlinear because most loads are assumed to be constant complex power loads. The approach of the linear system can be modified to take into account the nonlinear characteristics of the distribution feeder. In this approach, the backward/forward sweep (BFS) algorithm is one of the most common ways used for load flow in distribution system. The BFS algorithm involves mainly an iterative three basic steps based on Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL). The three steps are named as the nodal current calculation, the backward sweep and the forward sweep and they are repeated until the convergence is achieved. In the nodal current calculation, all the current injections at different buses are determined. The backward sweep is primarily a current or a power-flow summation with possible voltage updates. The forward sweep is primarily a voltage drop calculation with possible current or power-flow updates. This algorithm is based on the fact that, the current at the end of the sub-lateral is zero whereas the voltage at the source node is specified. Therefore, by the application of the three steps in iterative scheme, a radial distribution feeder can be solved.

Distributed generation (DG), also called on-site generation, dispersed generation, embedded generation, decentralized generation, decentralized energy, or distributed energy generates electricity from many small energy sources. A DG is the use of small-scale power generation technologies located close to the load being served. DG stakeholders include energy companies, equipment suppliers, regulators, energy users, and financial and supporting companies. For some customers, DG can lower costs, enhance efficiency, improve reliability, reduce emissions, or expand their energy options. DG may add redundancy that increases grid security even while powering emergency lighting or other critical systems [9].

The optimal placement of DGs and capacitor banks [10-18] is considered as a single objective optimization problem in distribution systems to determine the optimal locations and sizes of DGs and capacitors in different combination cases of them to achieve performance enhancement of distribution systems. The objective function is power loss reduction. In order to solve these objectives, the optimization algorithm should be used under security and operational equality and inequality constraints.

1.1.Project Contributions

The main contributions of the project can be summarized as follows:

1. An efficient optimization algorithm, called AOA is used to find the optimal locations and sizes of DGs and capacitors according to single objective function to enhancement the performance of distribution systems.
2. An efficient BFS algorithm is used for the load flow calculations in distribution systems.
3. A comparison between the proposed procedure using the AOA and other optimization techniques such as DP, fuzzy, GA and PSO to find the optimal combination of DGs and capacitors is presented.

1.2. Scope of the Project

The project contains seven Chapters followed by two appendices for test systems data and the BFS algorithm. These contents can be summarized as follows:

CHAPTER 1 presents a brief introduction of the distribution system problems with introducing proposed solutions for some optimization problems and the optimization techniques. Hence, it summarizes the objectives and contributions of the project.

CHAPTER 2 presents a survey on the methods used to enhancement the performance of distribution networks such as DGs capacitor banks.

CHAPTER 3 presents the problem formulation of the optimal placement of DGs and capacitors in radial distribution systems by introducing the objective function and system constraints.

CHAPTER 4 presents the AOA to determine the optimal locations and sizes of DGs and capacitors with minimizing the objective of power loss or TVD and improving the voltage profile in distribution systems.

CHAPTER 5 presents the different test systems which are used to apply the proposed procedure. Moreover, the results and comments are presented.

CHAPTER 6 presents the conclusions of this project.

Chapter 2

Distributed Generation and Capacitor Technologies

2.1. Introduction

Recently, electric grid was designed to operate as a vertical structure consisting of generation, transmission and distribution and supported with controls and devices to maintain reliability, stability and efficiency. However, system operators are now facing new challenges including the penetration of renewable energy resources (RER) in the legacy system, rapid technological change and different types of market players and end users.

Enhancement of distribution system performance requires modeling of renewable energy sources and technologies such as wind, photovoltaic (PV), solar, biomass and fuel cells, analyzing their levels of penetration and conducting impact assessments of the legacy system for the purpose of modernization. The roadmap envisions widespread deployment of distributed energy resources (DERs) in the near future. Renewable energy technologies and their integration introduce several issues including enhancement of efficiency and reliability and the development of state of the art tracking to manage variability. Architecture designs, which include optimal interconnections, optimal sizing and siting DERs for optimum reliability, security and economic benefits are also critical aspects [19].

In this chapter, the different types, benefits and applications of distributed generation (DG) are presented in the distribution networks. In addition, the fixed and switched capacitor banks are presented to improve the distribution network reliability.

2.2. Distributed Generations (DGs)

DG is not a new concept. A number of utility consumers have been using DG for decades. Over the last 10 years, the DG market has been somewhat turbulent. In the late 1990s, new regulations/subsidies, such as net metering and renewable portfolio requirements, and the development of new DG technologies have sparked broader interests in DG [9].

2.2.1. Definition of DG

DG generally applies to relatively small generating units of 30 MW or less sited at or near customer sites to meet specific customer needs or to support economic operation of the existing distribution grid, or both. Reliability of service and power quality are enhanced by the proximity to the customer and efficiency is often boosted in on-site applications by using the heat from power generation. While central power systems remain critical to the nation's energy supply, their flexibility is limited. Large power generation facilities are capital-intensive undertakings that require an immense transmission and distribution grid to move the power [20]. DG complements central power by providing a relatively low capital cost response to incremental jumps in power demand. It avoids transmission and distribution capacity upgrades by siting the power where it is most needed and by having the flexibility to send power back into the grid when needed.

In the literature, a large number of terms and definitions are used in relation to DG. For example, Anglo-American countries often use the term ‘embedded generation’, North American countries use the term ‘dispersed generation’, and in Europe and parts of Asia, the term ‘decentralized generation’ is applied for the same type of generation. Moreover, in regard to the rating of DG power units, the following different definitions are currently used:

- The electric power research institute defines DG as generation from “a few kilowatts up to 50 MW”.
- According to the gas research institute, DG is “typically between 25 kW and 25 MW”.
- Preston and Rastler define the size as “ranging from a few kilowatts to over 100 MW”.
- Cardell defines DG as generation “between 500 kW and 1 MW”.
- The international conference on large high voltage electric systems defines DG as “smaller than 50–100 MW”.

Other definitions of DG include some or all of the following [9]:

- Any qualifying facilities under the public utility regulatory policies act of 1978 (PURPA).
- Any generation interconnected with distribution facilities.
- Commercial emergency and standby diesel generators installed, (i.e., hospitals and hotels).
- Residential standby generators sold at hardware stores.
- Generators installed by utility at a substation for voltage support or other reliability purposes.
- Any on-site generation with less than “X” kW or MW of capacity. “X” ranges everywhere from 10 kW to 50 MW.
- Generation facilities located at or near a load center.
- Demand side management (DSM), energy efficiency and other tools for reducing energy usage on the consumer’s side of the meter. The alternative to this definition would be to abandon the term “DG” completely and use instead “distributed resources (DR)” or “distributed energy resources (DER)”.

2.2.2.Types of DGs

DG is referred to small generators, starting from a few kWs up to 10 MW, whether connected to the utility grid or used as stand-alone at an isolated site. Normally small DGs, in the 5-250 kW range serve households to large buildings (either in isolated or grid-connected configuration). In grid-connected configuration, DGs with larger capacities are managed by a utility or an independent power producer (IPP). They are located at strategic points, normally at the distribution level, near load centers, and used for such purposes as capacity support, voltage support and regulation, and line loss reduction. DG technologies can be categorized to renewable and nonrenewable DGs [21]. DGs have many different types ranging from conventional fossil fuel-based combustion engines to the renewable energy including wind, photovoltaic cells, micro-turbines, small hydro turbines, combined heat and power (CHP) or hybrid.

2.2.3. Applications of DGs

The main applications for DG so far tend to fall into five main categories [20]:

- Standby power.
- Combined heat and power.
- Peak shaving.
- Grid support.
- Stand alone.

Standby power is used for customers that cannot tolerate interruption of service for either public health and safety reasons, or where outage costs are unacceptably high. Since most outages occur as a result of storm or accident-related transmission and distribution system breakdown, on-site standby generators are installed at locations such as hospitals, water pumping stations and electronic dependent manufacturing facilities

Combined heat and power applications make use of the heat from the process of generating electricity, increasing the efficiency of the fuel use. Most power generation technologies create a great deal of heat. If the generating facility is located at or near a customer's site, that heat can be used for combined heat and power (CHP) or cogeneration applications.

Power costs can fluctuate hour to hour depending on demand and generation availability. These hourly variations are converted into seasonal and daily time-of-use rate categories such as on-peak, off-peak, or shoulder rates. Customer use of DG during relatively high-cost on-peak periods is called peak shaving. Peak shaving benefits the energy supplier as well, when energy costs approach energy prices.

The transmission and distribution grid are an integrated network of generation, high voltage transmission, substations and lower-voltage local distribution. Placing DG at strategic points on the grid to make grid support can assure the grid's performance and eliminate the need for expensive upgrades.

Stand-alone DG serves the customer but is not connected to the grid, either by choice or by circumstance. Some of these applications are in remote areas, where the cost of connecting to the grid is cost prohibitive. Such applications include users that require stringent control of the quality of their electric power such as computer chip manufacturers.

2.3. Capacitor Banks

In power systems, the reactive power compensation is provided locally at all voltage levels using fixed capacitors, switched capacitors, substation capacitor banks, or static VAR compensators. Whatever the nature of the compensation, capacitors are the common elements in all the devices. The power factor correction approach using capacitor banks has been employed for the past several decades. The capacitor banks used for power factor correction include fuses, circuit breakers (CBs), protective relaying, surge arresters and various mounting approaches. Capacitor banks are important in power factor correction. Series capacitors are vital to improving the performance of long-distance transmission [8].

Power factor correction is the main application for capacitor banks in the power system. The advantage of improved power factor is reduced line and transformer losses, improved voltage profile, reduced maximum demand and improved power quality. The capacitor banks are installed in a distribution system on pole-mounted racks, substation banks, and high voltage (HV) or extra-high voltage (EHV) units for bulk power applications. In industrial systems, the power factor correction using capacitor banks are utilized for group or individual loads. The ratings are expressed in kVAR, voltage and frequency of operation within an ambient temperature range of -40 to +46 ^{o}C [8].

2.3.1. Fixed versus switched capacitor banks

Capacitor banks applied to distribution systems are generally located on the distribution lines or in the substations. The distribution capacitor banks may be in pole-mounted racks, pad mounted banks, or submersible installations. The distribution banks often include three to nine capacitor units connected in three-phase grounded wye, ungrounded wye, or in delta configuration. The distribution capacitor banks are intended for local power factor correction by supplying reactive power and minimizing the system losses. The distribution capacitor banks can be fixed or switched depending on the load conditions. The following guidelines apply:

- Fixed capacitor banks for minimum load condition.
- Switched capacitor banks for load levels above the minimum load and up to the peak load.

Usually, the fixed capacitor banks satisfy the reactive power requirements for the base load and the switched capacitor banks compensate the inductive kVAR requirements of the peak load. To obtain the best results of sizing and locations of capacitor banks, capacitor banks should be located where they produce maximum loss reduction, provide better voltage profile, and are close to the load. Usually, the capacitor banks are placed at the location of minimum power factor by measuring the voltage, current, kW, kVAR, and kVA on the feeder to determine the maximum and minimum load conditions. Many utilities prefer a power factor of 0.95.

2.3.2. Benefits of capacitor banks

Using capacitor banks to supply, the leading currents required by the load relieves the generator from supplying that part of the inductive current. The system benefits due to the application of capacitor banks include [8]:

- **Reactive power support**

In distribution systems, the voltage at the load end tends to get lower due to the lack of reactive power. In such cases, local VAR support is offered using capacitor banks. In the case of long transmission lines, the reactive power available at the end of the line during peak load conditions is small and hence needs to be supplied using capacitor banks.

- **Voltage profile improvements**

The capacitor banks reduce the amount of inductive current in an electric circuit. The reduction in the line current decreases the *IR* and *IX* voltage drops, thereby improving the voltage level of the system from the capacitor banks location back to the source. In both the distribution and transmission systems, there is a need to maintain a voltage in the range 0.95–1.05 p.u.

- **Line and transformer loss reductions**

When capacitor banks are installed for power factor correction, the line current magnitude is decreased. Therefore, both I^2R and I^2X losses are reduced.

- **Release of power system capacity**

Power factor correction using capacitor banks provide the reactive current requirements locally and reduce the line current. Reduced line current means less kVA for transformers and feeder circuits. Therefore, the capacitor banks compensation helps to reduce the thermal overloads on transformers, transmission lines, generator and cables.

- **Savings due to reduced energy losses**

If the reactive compensation is provided in a feeder circuit, then the current through the feeder and the transformer circuit is reduced. Therefore, the cost of energy due to reduced losses will be reduced to increase the net saving

Chapter 3

Problem Formulation

3.1. Introduction

Many optimization techniques were applied to solve the optimal DGs and capacitors placement problem. Esmaili *et al.* [10] presented the optimal locations and sizes of DGs to enhance voltage stability and to reduce system losses simultaneously. The optimal locations of DGs were determined based on vulnerable buses from voltage stability point of view using bifurcation analysis. Then, the dynamic programming search (DPS) method was used to find the optimal sizes of DGs. Gözel and Hocaoglu [11] introduced the optimal locations and sizes of DGs so as to minimize total power losses by an analytical method using a loss sensitivity factor based on the equivalent current injection in the distribution systems. Devi and Geethanjali [12] used the modified bacterial foraging optimization (MBFO) algorithm to find the optimal locations and sizes of DGs to reduce the total power loss and to improve the voltage profile in radial distribution systems. However, only DGs at unity power factor were considered. Biswas *et al.* [13] used the GA to find the optimal locations and sizes of DGs to reduce the line loss, the voltage sag and the total cost of DGs as a multi-objective function. However, only DGs at unity power factor were considered.

In [14], two-stage method was used to solve the optimal capacitors placement problem based on the loss sensitivity factors to determine the optimal locations and the plant growth simulation algorithm (PGSA) to estimate the optimal sizes of capacitors. However, the optimal solution may be not obtained because the optimization technique is restricted only to find the sizes of capacitors. In [15,16], the fuzzy approach was used to find the optimal locations of capacitors. Then, the bacteria foraging algorithm (BFA) was utilized to find optimal sizes of capacitors in [15], while the genetic algorithm (GA) was employed to find the optimal sizes of the capacitors in [16]. In [17], the authors presented power loss index (PLI) to determine the high potential buses for capacitors placement. Then, the optimal sizing and placement of capacitors were obtained using accelerated particle swarm optimization (APSO) technique.

Devi and Geethanjali [22] used the PSO to find the optimal locations and sizes of DGs and distribution static compensator (DSTATCOM) for power loss reduction in radial distribution systems. However, a single objective function and DGs at unity power factor were considered. Selvi [23] presented the optimal locations and sizes of DGs and capacitors to reduce the system losses. First, the suitable locations for placing DGs and capacitors were identified through loss and voltage sensitivity factors. Then, the fuzzy adaptation of evolutionary programming (Fuzzy-EP) was used to find the optimal sizes of DGs and capacitors. However, DGs at unity power factor was considered.

3.2. Problem Formulation

3.2.1. Objective functions

3.2.1.1. Total power loss minimization

One of the main benefits of optimal DGs and capacitors placement in distribution systems is to minimize the real power loss. Mathematically, the real power loss can be expressed as [23]:

$$f_1 = \text{Min} \quad P_{\text{Loss}} = \sum_{i=1}^{N_b}\sum_{j=1}^{N_b}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \tag{3.1}$$

$$\text{where, } \alpha_{ij} = \frac{R_{ij}}{V_iV_j}\cos\left(\delta_i - \delta_j\right), \qquad \beta_{ij} = \frac{R_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right)$$

where, P_{Loss} is the total real power loss to be minimized, P_i and Q_i are the net active and reactive power at bus i, respectively. V_i and V_j are the voltage magnitudes at buses i and j, respectively. δ_i and δ_j are the phase angle of the voltages at buses i and j, respectively. R_{ij} is the line resistance between buses i and j. N_b is the number of system buses.

3.2.1.2. TVD minimization

The optimal placement of DGs and capacitors in distribution systems improves the voltage profile of the system and minimize the total voltage deviation (TVD). Mathematically, TVD can be calculate using the equation (3-2):

$$f_2 = \text{Min TVD} = \sum_{1}^{Nb}(1 - V_i)^2 \tag{3-2}$$

Where V_i is the voltage at bus i.

3.2.2.System constraints

The above-mentioned single objective function in Equation (3.1) is subjected to the following constraints:

3.2.2.1. Equality constraint

- **Load balancing constraint**

For each bus, the following load balancing equations must be satisfied:

$$P_{gj} - P_{dj} - V_j\sum_{j=1}^{N_b} V_iY_{ij}\cos(\delta_j - \delta_i - \theta_{ij}) = 0 \tag{3.3}$$

$$Q_{gj} - Q_{dj} - V_j\sum_{j=1}^{N_b} V_iY_{ij}\sin(\delta_j - \delta_i - \theta_{ij}) = 0 \tag{3.4}$$

where, P_{gj} and Q_{gj} are the active and reactive power output from the generator at bus j, respectively. P_{dj} and Q_{dj} are the active and reactive power demand at bus j, respectively. V_i and V_j are the voltages at sending end i and receiving end j, respectively. Y_{ij} and θ_{ij} are the admittance magnitude and angle between buses i and j, respectively. δ_i and δ_j are the phase angles of voltages at buses i and j, respectively.

3.2.2.2. Inequality constraints

- **Bus voltage constraint**

The voltage at each bus (V_i) must be within its permissible minimum and maximum limits as:

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{3.5}$$

- **Overall Power factor constraint**

The overall system power factor ($pf_{overall}$) must be greater than or equal to the minimum limit of overall power factor ($pf^{\min}$) as:

$$\left| pf_{overall} \right| \ge pf^{\min} \tag{3.6}$$

- **Number of DGs constraint**

This constraint aims to reduce the number of DGs placement. Therefore, the optimal number of DGs (N_{DG}) must be less than or equal to the maximum number of possible locations ($N_{DG}^{\max}$) as:

$$N_{DG} \le N_{DG}^{\max} \tag{3.7}$$

- **Number of capacitors constraint**

This constraint aims to reduce the number of capacitors placement. Therefore, the optimal number of capacitors (N_C) must be less than or equal to the maximum number of possible locations ($N_C^{\max}$) as:

$$N_C \le N_C^{\max} \tag{3.8}$$

- **DG size constraint**

The active and reactive power injections by DGs must be within their permissible minimum and maximum limits as:

$$P_{DGj}^{\min} \le P_{DGj} \le P_{DGj}^{\max} \tag{3.9}$$

$$Q_{DGj}^{\min} \le Q_{DGj} \le Q_{DGj}^{\max} \tag{3.10}$$

where, P_{DGj} and Q_{DGj} is the active and reactive power injections by DGs at location j, respectively.

- **Capacitor size constraint**

The reactive power injection by capacitors must be within its permissible minimum and maximum limits as:

$$Q_{Cj}^{\min} \le Q_{Cj} \le Q_{Cj}^{\max} \tag{3.11}$$

where, Q_{Cj} is the reactive power injection at location j.

- **Total active and reactive power constraints**

The total active and reactive power injections by DGs (P_{DG}^{Total},Q_{DG}^{Total}) and the total reactive power from capacitors (Q_C^{Total}) must be less than or equal to the total load active and reactive power (P_L^{Total}, Q_L^{Total}) as:

$$P_{DG}^{Total} \leq P_L^{Total} \tag{3.12}$$

$$\left(Q_{DG}^{Total} + Q_C^{Total}\right) \leq Q_L^{Total} \tag{3.13}$$

Chapter 4

Archimedes Optimization Algorithm

4.1. Modern Optimization Methods

The modern optimization methods (also called nontraditional optimization methods) have emerged as powerful and popular methods for solving complex engineering optimization problems in recent years. These methods are simulated annealing, evolutionary programming (EP), Tabu search (TS), Neural-network based methods, genetic algorithm (GA), differential evolution (DE) algorithm, particle swarm optimization (PSO) technique [6] , seeker optimization algorithm (SOA), ant colony optimization (ACO) [5] algorithm, Bat algorithm (BA) [4] and Archimedes Optimization Algorithm (AOA)[7]. Most of these methods are labeled on certain characteristics and behavior of biological, molecular, swarm of insects and neurobiological systems. These new meta-heuristic tools have been combined among themselves and with knowledge elements, as well as with more traditional approaches such as statistical analysis to solve extremely challenging problems.

4.2.Archimedes Optimization Algorithm

4.2.1. Introduction

Archimedes Optimization Algorithm (AOA) [7] is based on Archimedes' principle which states that "Any object, totally or partially immersed in a fluid or liquid, is buoyed up by a force equal to the weight of the fluid displaced by the object.". AOA emulates the behavior of many objects, which have different densities and volumes, immersed in the same fluid and each one tries to reach equilibrium state.

4.2.2.AOA Theory

If we assume that many object are immersed in the same fluid and each one of them tries to reach equilibrium state. The object will be in the equilibrium state if the buoyant force F_b equal to the object's weight W_o:

$$\begin{gathered} F_b = W_o \\ p_b v_b a_b = p_o v_o a_o \end{gathered} \tag{4-1}$$

Where p is the density, v is the volume, and a is the gravity or acceleration, subscripts b and o are for fluid and immersed object, respectively. This equation can be rearranged as:

$$a_o = \frac{p_b v_b a_b}{p_o v_o} \tag{4-2}$$

If there is another force influenced on the object like collision with another neighbouring object (r), the equilibrium state will be:

$$F_b = W_o \tag{4-3}$$

$$W_b - W_r = W_o$$
$$p_b v_b a_b - p_r v_r a_r = p_o v_o a_o$$

4.2.3.Algorithmic steps

AOA can be considered as a global optimization algorithm as it encompasses both exploration and exploitation processes.

- **Step 1: initialize the positions of all objects using (4-4)**

$$O_i = lb_i + rand \times (ub_i - lb_i) \quad (4\text{-}4)$$

Where O_i is the ith object in a population of N objects. lb_i and ub_i are the lower and upper bounds of the search-space, respectively.

Initialize volume (vol) and density (den) for each ith object using (4-5):

$$\begin{gathered} den_i = rand \\ vol_i = rand \end{gathered} \quad (4\text{-}5)$$

Where rand is a random number between [0, 1]. Then, initialize acceleration (acc) of ith object using (4-6):

$$acc_i = lb_i + rand \times (ub_i - lb_i) \quad (4\text{-}6)$$

Finally, evaluate initial population and select the object with the best fitness value. Assign x_{best}, den_{best}, vol_{best} and acc_{best}.

- **Step 2: update densities, volumes using (4-7)**

$$\begin{gathered} den_i^{t+1} = den_i^t + rand \times (den_{best} - den_i^t) \\ vol^{t+1} = vol_i^t + rand \times (vol_{best} - vol_i^t) \end{gathered} \quad (4\text{-}7)$$

- **Step 3: calculate Transfer operator and density factor using (4-8) and (4-9)**

$$TF = e^{\left(\frac{t - t_{max}}{t_{max}}\right)} \quad (4\text{-}8)$$

where transfer TF increases gradually with time until reaching 1. Here t and t_{max} are iteration number and maximum iterations, respectively. Similarly, density decreasing factor d also assists AOA on global to local search. It decreases with time using (9):

$$d^{t+1} = e^{\frac{t_{max} - t}{t_{max}}} - \left(\frac{t}{t_{max}}\right) \quad (4\text{-}9)$$

where d^{t+1} decreases with time that gives the ability to converge in already identified promising region. Note that proper handling of this variable will ensure balance between exploration and exploitation in AOA.

- **Step 4.1: Exploration phase (collision between objects occurs)**

  if $TF \leq 0.5$, collision between objects occurs, select a random object (mr) and update object's acceleration for iteration $t + 1$ using (4-10):

$$acc_i^{t+1} = \frac{den_{mr} + vol_{mr} \times acc_{mr}}{den_i^{t+1} \times vol^{t+1}} \quad (4\text{-}10)$$

- **Step 4.2: Exploitation phase (no collision between objects)**

  If $TF > 0.5$, there is no collision between objects, update object's acceleration for iteration $t+1$ using (4-11):

$$acc_i^{t+1} = \frac{den_{best} + vol_{best} \times acc_{best}}{den_i^{t+1} \times vol_i^{t+1}} \quad (4\text{-}11)$$

- **Step 4.3: Normalize acceleration using (4-12)**

$$acc_{i-norm}^{t+1} = u \times \frac{(acc_i^{t+1} - \min(acc))}{\max(acc) - \min(acc)} + l \quad (4\text{-}12)$$

  where u and l are the range of normalization and set to 0.9 and 0.1, respectively. The $acc_{i,norm}^{t+1}$ determines the percentage of step that each object will change.

- **Step 5: update position**

  If $TF \leq 0.5$ (exploration phase), the i^{th} object's position for next iteration $t+1$ using (4-13)

$$x_i^{t+1} = x_i^t + C_1 \times rand \times acc_{i-norm}^{t+1} \times d \times (x_{rand} - x_i^t) \quad (4\text{-}13)$$

Where C_1 is constant equals to 2.

Otherwise, if $TF > 0.5$ (exploitation phase), the objects update their positions using (4-14)

$$x_i^{t+1} = x_{best}^t + F \times C_2 \times rand \times acc_{i-norm}^{t+1} \times d \times (T \times x_{best} - x_i^t) \quad (4\text{-}14)$$

where C_2 is a constant equals to 6. T increases with time and it is directly proportional to transfer operator and it is defined using $T = C_3 \times TF$. T increases with time in range $[C_3 \times 0.3, 1]$ and takes a certain percentage from the best position, initially. It starts with low percentage as this results in large difference between best position and current position, consequently step-size of random walk will be high. As the search proceeds, this percentage increases gradually to decrease difference between the best position and the current position. This leads to achieving an appropriate balance between exploration and exploitation.

F is the flag to change the direction of motion using (4-15):

$$F = \begin{cases} +1 \text{ if } P \leq 0.5 \\ -1 \text{ if } p > 0.5 \end{cases} \quad (4\text{-}15)$$

Where $P = 2 \times rand - C_4$

- **Step 6: Evaluation**

Evaluate each object using the objective function and remember the best solution found so far. Assign x_{best}, den_{best}, vol_{best} and acc_{best}.

Algorithm 2 Pseudo code of AOA.

procedure AOA(population size N, maximum iterations $t_{\max}$, C_1, C_2, C_3, and C_4)

  Initialize objects population with random positions, densities and volumes using (4), (5), and (6), respectively.

  Evaluate initial population and select the one with the best fitness value.

  Set iteration counter $t = 1$

  while $t \leq t_{max}$ **do**

    for each object i **do**

      Update density and volume of each object using (7)

      Update transfer and density decreasing factors TF and d using (8) and (9), respectively.

      if $TF \leq 0.5$ **then** ▷ Exploration phase

        Update acceleration using (10) and normalize acceleration using (12)

        Update position using (13)

      else ▷ Exploitation phase

        Update acceleration using (11) and normalize acceleration using (12)

        Update direction flag F using (15)

        Update position using (14)

      end if

    end for

    Evaluate each object and select the one with the best fitness value.

    Set $t = t + 1$

  end while

  return object with best fitness value.

end procedure

Chapter 5

APPLICATIONS AND RESULTS

5.1.Test Systems

The proposed procedure (AOA) is applied on 34-bus standard radial distribution system and East Delta Network (EDN) radial distribution system as a part of the Unified Egyptian Network (UEN) in order to solve the optimal DGs and capacitors placement problem. The test systems data is shown in Appendix A. The results are compared with those obtained using other reported methods.

The proposed DG units can be classified into two types based on real and reactive power delivering as follows:

- DG injects only active power (i.e., operating at unity power factor), such as fuel cells, photovoltaic and micro-turbines.
- DG injects both active and reactive power (i.e., operating at power factor < 1), such as wind turbines and induction generators.

One type of capacitors is considered, which is fixed capacitors.

5.2.Case Studies

The proposed procedure is applied on the test systems with four different cases are:

Case 0: without DGS and Capacitors (BFS algorithm results).
Case 1: With only DGs operating at unity power factor (p.f.), means that only active power injections.
Case 2: With only DGs operating at p.f. = 0.9, means that active and reactive power injections.
Case 3: With only capacitors, means that only reactive power injections.
Case 4: with both DGs at unity power factor and capacitors.
Case 5: with DGs at power factor 0.9 and capacitors

5.3.Assumption and limits

The assumptions and the limits of constraints are considered as follows:

- The minimum and maximum limits of DG active power are 500 and 2000 kW, respectively.
- The minimum and maximum limits of capacitors are 150 and 2000 kVAR, respectively.
- The operating p.f. of DGs is unity in case 1, while it is 0.9 in cases 2 and 5.
- The minimum and maximum limits of voltage magnitude are 0.95 and 1.05 p.u., respectively.
- The maximum number of DGs possible locations (N_{DG}^{max}) is 4.
- The maximum number of capacitors possible locations (N_{C}^{max}) is 4.
- The maximum limit of the power of all DGs is 4000 kW

- The maximum limit of the power of all capacitors is 4000 kVAR

5.4.Results

5.4.1.Total power losss minimization

5.4.1.1. 34-bus radial distribution system

Tables 5.1-5.5 show the optimal locations and sizes of DGs and the capacitors required to reduce the total active power loss as an objective function for cases 1-5 for the 34-bus test system. Moreover, a comparison between the proposed procedure and other methods is presented.

Table 5.1 presents the optimal solution for case 1 using the proposed procedure, when only active power from DGs is injected. It can be observed that, the initial power loss without DGs is reduced from 221.752 kW to 74.4167 kW after placement of DGs. The optimal locations of DGs are at buses {23,31} with total rating power 3000 kW. Moreover, the minimum and maximum voltage magnitudes are improved.

Table 5-1 A comparison between the power loss minimization using the proposed procedure with other methods using only the DGs at unity power factor (case 1) for 34-bus test system

Items	Un-compensated (Case 0)	Compensated (Case 1)									
		DPS [10]		Analytical Method [11]		MBFO [12]		GA [13]		Proposed procedure	
Optimal locations and sizes of DGs (kW)	-	27	2500	21	2884.8	21	2951.7	4	500	23	1847.5
		-	-	-	-	-	-	7	500	31	1152.5
		-	-	-	-	-	-	17	500	-	-
		-	-	-	-	-	-	21	500	-	-
		-	-	-	-	-	-	25	500	-	-
		-	-	-	-	-	-	28	500	-	-
Total size	-	2500		2884.8		2951.7		3000		3000	
Total losses (kW)	**221.752**	**118.8**		**93.838**		**93.751**		**83.84**		**74.416**	
TVD	0.0483	0.0086		0.0079		0.0074		0.0108		0.0046	
Minimum bus voltage(p.u.)	0.9417 (#27)	0.9750 (#34)		0.9773 (#34)		0.9777 (#34)		0.9723 (#27)		0.9832 (#27)	
Maximum bus voltage(p.u.)	0.9941 (#2)	1.0034 (#27)		0.9971 (#2)		0.9971 (#2)		0.9972 (#2)		0.9972 (#2)	
Overall power factor	0.85	0.5967		0.5205		0.5058		0.4949		0.4949	

Table 5.2 presents the optimal solution for case 2 using the proposed procedure, when active and reactive power from DGs are injected. It can be observed that, the initial power loss without compensation is reduced from 221.752 kW to 25.348 kW after placement of DGs. The optimal locations of DGs are at buses {23,10} with total rating power 3000 kW and 1452.9 kVAR. Moreover, the minimum and maximum voltage magnitudes are improved after placement of DGs.

Table 5-2 A comparison between the power loss minimization using the proposed procedure with other methods using only the DGs at 0.9 power factor (case 2) for 34-bus test system

Items	Un-compensated (Case 0)	Compensated (Case 2)				
		Analytical Approach [18]			Proposed procedure	
Optimal locations and sizes of DGs (kW, kVAR)	-	Locations	DG Size (kW)	-	Locations	DG size (kW)
		20	3231.8	-	23	1863.3
		-	-	-	10	1136.7
		-	-	-		
Total size	-	-	3231.8	-	-	3000
Total losses (kW)	**221.752**	**49.415**			**25.348**	
TVD	0.0483	0.004			0.0023	
Minimum bus voltage(p.u.)	0.9417 (#27)	0.9832 (#34)			0. 9888 (#27)	
Maximum bus voltage(p.u.)	0.9941 (#2)	1.0015 (#20)			0.9978 (#2)	
Overall power factor	0.85	0.85			0. 7552	

Table 5.3 presents the optimal solution for case 3 using the proposed procedure, when only reactive power from capacitors is injected. It is clear that, the initial power loss without compensation is reduced from 221.752 kW to 160.4252 kW after placement of capacitors. The optimal locations of capacitors are at buses {18,9,24} with total rating power 2482.5 kVAR. Moreover, the minimum and maximum voltage magnitudes and overall system power factor are improved.

Table 5-3 A comparison between the power loss minimization using the proposed procedure with other methods using only the capacitors (case 3) for 34-bus test system

Items	Un-compensated (Case 0)	Compensated (Case 3)									
		PGSA [14]		BFA [15]		GA [16]		APSO [17]		Proposed procedure	
Optimal locations and sizes of capacitors (kVAR)	-	19	1200	9	600	7 buses	1629	19	1050	18	896.88
		20	200	22	900			25	750	9	758.562
		22	639	-	-			-	-	24	862.755
Total size	-	2039		1500		1629		1800		2482.5	
Total losses (kW)	**221.752**	**169.167**		**169.07**		**168.955**		**168.023**		**160.4252**	
TVD	0.0483	0.0368		0.0394		0.0408		0.0375		0.0344	
Minimum bus voltage(p.u.)	0.9417 (#27)	0.9492 (#27)		0.9503 (#27)		0.9491 (#27)		0.9416 (#27)		0.9503 (#27)	
Maximum bus voltage(p.u.)	0.9941 (#2)	0.995 (#2)		0.9948 (#2)		0.9948 (#2)		0.9949 (#2)		0.9952 (#2)	
Overall power factor	0.85	0.9842		0.9588		0.9658		0.9738		0.9965	

Table 5.4 presents the optimal solution for case 4 using the proposed procedure, when active power from DGs is injected and reactive power is injected from capacitors. It can be observed that, the initial power loss without compensation is reduced from 221.752 kW to 18.15 kW after placement of DGs and capacitors. The optimal locations of DGs are at buses {9,21,25} with total rating power 3000 kW and the optimal locations of capacitors are at buses {7,24} with total power rating 1927 kVAR. Moreover, the minimum and maximum voltage magnitudes are improved after placement of DGs and capacitors.

Table 5-4 A comparison between the power loss minimization using the proposed procedure with other methods using DGs at unity power factor and capacitors (case 4) for 34-bus test system

Items	Un-compensated (Case 0)	Compensated (Case 4)	
		Proposed procedure	
Optimal locations and sizes of DGs (KW)	-	9	952.8
		21	1125.5
		25	921.6
Total DGs size		3000	
Optimal locations and sizes of capacitors (KVAR)		7	1110.4
		24	816.6
Total capacitors size	-	1927	
Total losses (kW)	**221.752**	**18.15**	
TVD	0.0483	0.0023	
Minimum bus voltage(p.u.)	0.9417 (#27)	0.9892 (#33)	
Maximum bus voltage(p.u.)	0.9941 (#2)	0.998 (#2)	
Overall power factor	0.85	0.8656	

Table 5.5 presents the optimal solution for case 5 using the proposed procedure, when active power and reactive power from DGs are injected and reactive power is injected from capacitors. It can be observed that, the initial power loss without compensation is reduced from 221.752 kW to 17.11 kW after placement of DGs and capacitors. The optimal locations of DGs are at buses {31,24,21} with total rating power 3000 kW and the optimal locations of capacitors are at buses {8} with total power rating 1112.9 kVAR. Moreover, the minimum and maximum voltage magnitudes are improved after placement of DGs and capacitors.

Table 5-5 A comparison between the power loss minimization using the proposed procedure with other methods using DGs at .9 power factor and capacitors (case 5) for 34-bus test system

Items	Base case	Case 5	
		FPA [9]	Proposed method
DG size (kW, kVAR) and location	-	2086, 1292.8 (#26)	799.3, 387.09 (#31), 946.5, 458.37 (#24), 1254.2, 607.39 (#21)
Capacitor size (kVAR) and location	-	1250 (#26)	365.568 (#8)
Total size of DGs (kW, kVAR)	-	2086, 1292.8	3000, 1452.86
Total size of capacitors (kVAR)	-	1250	1112.9
***f_1* [Loss (kW)]**	**221.752**	**58.8298**	**17.1153**
TVD	0.0483	0.007	0.0021
Min. voltage (p.u.)	0.9417 (#27)	0.9751 (#34)	0.99 (#12)
Overall p.f.	0.85	0.8436	0.8405

From these Tables, the total power loss, the total active and reactive power injections using the proposed procedure are lower than that obtained using the other methods. Case 2 gives better results than other cases. Moreover, the overall power factor is improved after placement of DGs and capacitors. In addition, the overall power factor is within permissible limits. Therefore, this comparison reflects to the great capability of the proposed procedure to find the optimal locations and sizes of DGs and capacitors in order to reduce the total power loss and improve the system reliability.

Fig. 5.1 and Fig. 5.2 shows the convergence curves of the AOA algorithm to reduce the total power loss using the DGs and capacitors for 34-bus test system. It is clear that, the AOA algorithm is able to reach the optimal solution with more accuracy and efficiency.

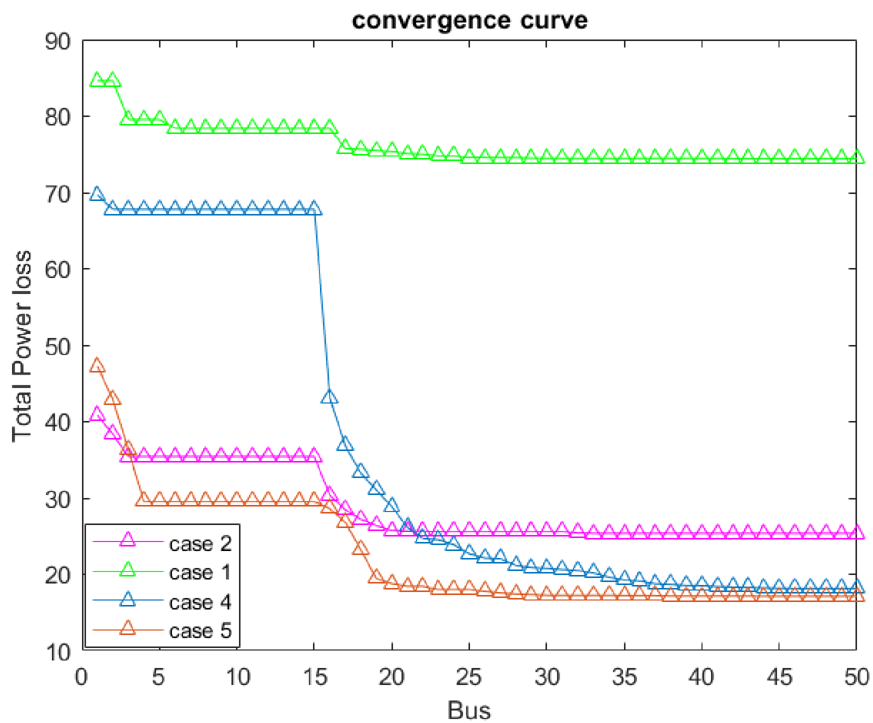

Figure 5-1 convergence curve for IEEE-34 network (objective function: Total power loss minimization)

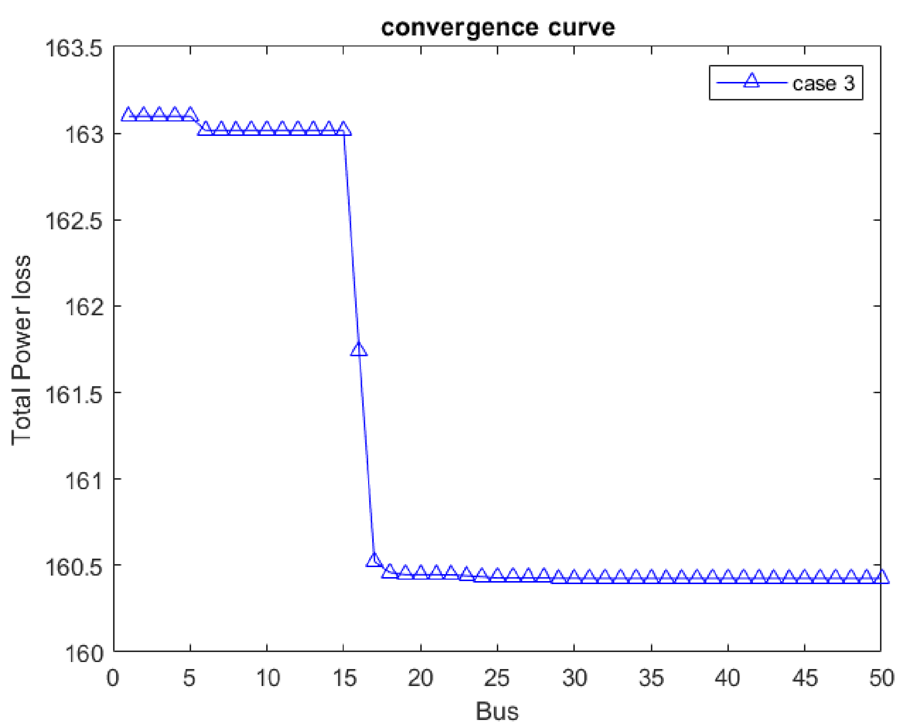

Figure 5-2 convergence curve for IEEE-34 network (objective function: Total power loss minimization)

Fig. 5.3 shows the voltage profiles for cases 0-5, when the total power loss minimization is considered as an objective function. The voltage profiles are improved at cases 1-5, where the voltage profile improvement based on case 2 is better than that obtained from other cases, while the average values of voltages are 0.9658,0.9855, 0.9913, 0.9706 and 0.9895 for cases 1-5, respectively. Moreover, the minimum voltage limit is violated at buses starts from 22 to 27 in case 0.

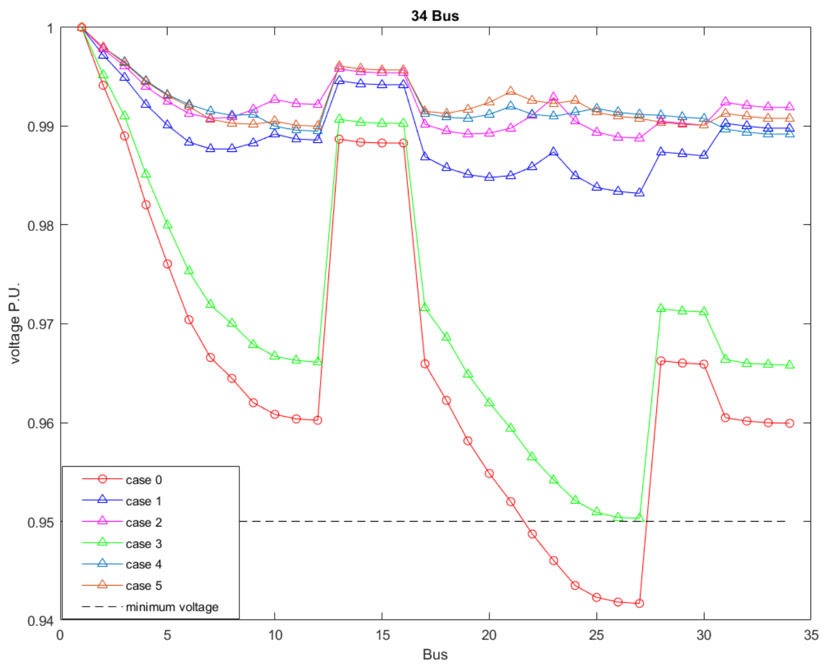

Figure 5-3 voltage profile for IEEE-34 network (objective function: Total power loss minimization)

5.4.1.2. EDN radial distribution system

Tables 5.6-5.10 show the optimal locations and sizes of DGs and the capacitors required to reduce the total active power loss as an objective function for cases 1-5 for the EDN system.

Table 5.6 presents the optimal solution for case 1 using the proposed procedure, when only active power from DGs is injected. It can be observed that, the initial power loss without DGs is reduced from 805.73 kW to 542 kW after placement of DGs. The optimal locations of DGs are at buses {21,25} with total rating power 4000 kW. Moreover, the minimum and maximum voltage magnitudes are improved.

Table 5-6 Optimal locations and sizes of DGs at unity power factor using the proposed method for EDN system (case 1)

Items	Un-compensated (Case 0)	Compensated (Case 1)	
Optimal locations and sizes of DGs (kW)	-	21	1999.9
		25	2000
Total size	-	3999.9	
Total losses (kW)	**805.73**	**542.459**	
TVD	0.0439	0.0225	
Minimum bus voltage(p.u.)	0.9463 (#30)	0.9669 (#23)	
Maximum bus voltage(p.u.)	0.9854 (#2)	0.9874 (#2)	
Overall power factor	0.8457	0.7932	

Table 5.7 presents the optimal solution for case 2 using the proposed procedure, when active and reactive power from DGs are injected. It can be observed that, the initial power loss without compensation is reduced from 805.73 kW to 458 kW after placement of DGs. The optimal locations of DGs are at buses {25,21} with total rating power 4000 kW and 1937 kVAR. Moreover, the minimum and maximum voltage magnitudes are improved after placement of DGs.

Table 5-7 Optimal locations and sizes of DGs at 0.9 power factor using the proposed method for EDN system (case 2)

Items	Un-compensated (Case 0)	Compensated (Case 2)	
Optimal locations and sizes of DGs (kW)	-	Locations	DG size (kW)
		25	2000
		21	2000
Total size	-	-	4000
Total losses (kW)	**805.73**	**458.85**	
TVD	0.0439	0.0193	
Minimum bus voltage(p.u.)	0.9463 (#30)	0. 9699 (#23)	
Maximum bus voltage(p.u.)	0.9854 (#2)	0.9879 (#2)	
Overall power factor	0.8457	0.8335	

Table 5.8 presents the optimal solution for case 3 using the proposed procedure, when only reactive power from capacitors is injected. It is clear that, the initial power loss without compensation is reduced from 805.73 kW to 673.69 kW after placement of capacitors. The optimal locations of capacitors are at buses {26, 21, 8, 18} with total rating power 4000 kVAR. Moreover, the minimum and maximum voltage magnitudes and overall system power factor are improved.

Table 5-8 Optimal locations and sizes of capacitors using the proposed method for EDN system (case 3)

Items	Un-compensated (Case 0)	Compensated (Case 3)	
Optimal locations and sizes of capacitors (kVAR)	-	26	963.8
		21	1198.9
		8	782.9
		18	1054.4
Total size	-	4000	
Total losses (kW)	**805.73**	**673.69**	
TVD	0.0439	0.036	
Minimum bus voltage(p.u.)	0.9463 (#30)	0.9521 (#30)	
Maximum bus voltage(p.u.)	0.9854 (#2)	0.9865 (#2)	
Overall power factor	0.8457	0.9108	

Table 5.9 presents the optimal solution for case 4 using the proposed procedure, when active power from DGs is injected and reactive power is injected from capacitors. It can be observed that, the initial power loss without compensation is reduced from 805 kW to 474 kW after placement of DGs and capacitors. The optimal locations of DGs are at buses {22,25,18} with total rating power 4000 kW and the optimal locations of capacitors are at buses {11,25} with total power rating 1657 kVAR. Moreover, the minimum and maximum voltage magnitudes are improved after placement of DGs and capacitors.

Table 5-9 A comparison between the power loss minimization using the proposed procedure with other methods using DGs at unity power factor and capacitors (case 4) for EDN system

Items	Un-compensated (Case 0)	Compensated (Case 4)	
		Proposed procedure	
Optimal locations and sizes of DGs (KW)	-	22	1458.3
		25	1374.3
		18	1167.4
Total DGs size		4000	
Optimal locations and sizes of capacitors (KVAR)		11	495.3
		25	1162.6
Total capacitors size	-	1657.9	
Total losses (kW)	**805.73**	**474.879**	
TVD	0.0439	0.0208	
Minimum bus voltage(p.u.)	0.9463 (#30)	0.9682 (#24)	
Maximum bus voltage(p.u.)	0.9854 (#2)	0.9879 (#2)	
Overall power factor	0.8457	0.8277	

Table 5.10 presents the optimal solution for case 5 using the proposed procedure, when active power and reactive power from DGs are injected and reactive power is injected from capacitors. It can be observed that, the initial power loss without compensation is reduced

from 805 kW to 411 kW after placement of DGs and capacitors. The optimal locations of DGs are at buses {23,21,26} with total rating power 4000 kW and 1937 kVAR and the optimal locations of capacitors are at buses {18,4} with total power rating 1830 kVAR. Moreover, the minimum and maximum voltage magnitudes are improved after placement of DGs and capacitors.

Table 5-10 A comparison between the power loss minimization using the proposed procedure with other methods using DGs at .9 power factor and capacitors (case 5) for EDN system

Items	Base case	Case 5
		Proposed method
DG size (kW, kVAR) and location	-	687.7, 333.05 (#23), 1873.1, 907.19 (#21), 1439.2, 697.02 (#26)
Capacitor size (kVAR) and location	-	1200 (#18) 630.8 (#4)
Total size of DGs (kW, kVAR)	-	4000, 1937.156
Total size of capacitors (kVAR)	-	1830.8
f_1 [Loss (kW)]	**805.73**	**411.4659**
TVD	0.0439	0.0180
Min. voltage (p.u.)	0.9463 (#30)	0.9714 (#24)
Overall p.f.	0.8457	0.8711

Fig. 5.4 shows the voltage profiles for cases 0-5, when the total power loss minimization is considered as an objective function. The voltage profiles are improved at cases 1-5, where the voltage profile improvement based on case 2 is better than that obtained from other cases.

From these Tables, the total power loss is reduced using the proposed method. Case 2 gives the better results for the considered objective function and constraints than the other cases. Moreover, the overall power factor is improved after placement of DGs and capacitors. In addition, the overall power factor is within permissible limits.

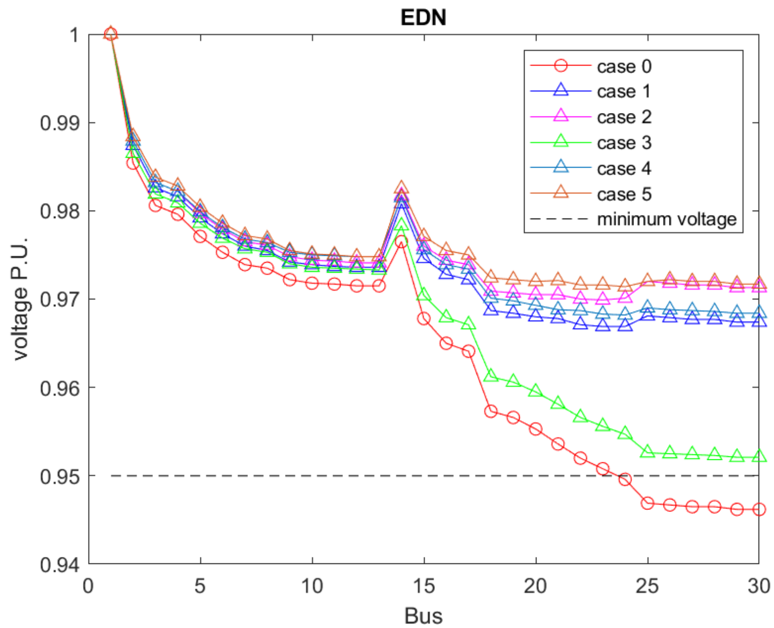

Figure 5-4 Voltage profile for EDN system (objective function: Total power loss minimization)

Fig. 5.5 and Fig. 5.6 shows the convergence curves of the AOA algorithm to reduce the total power loss using the DGs and capacitors for 34-bus test system. It is clear that, the AOA algorithm is able to reach the optimal solution with more accuracy and efficiency.

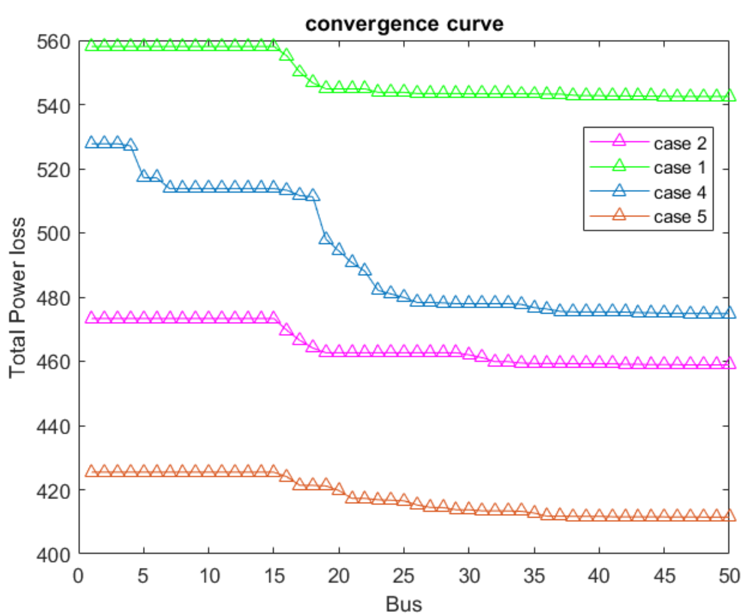

Figure 5-5 convergence curve for EDN system (objective function: Total power loss minimization)

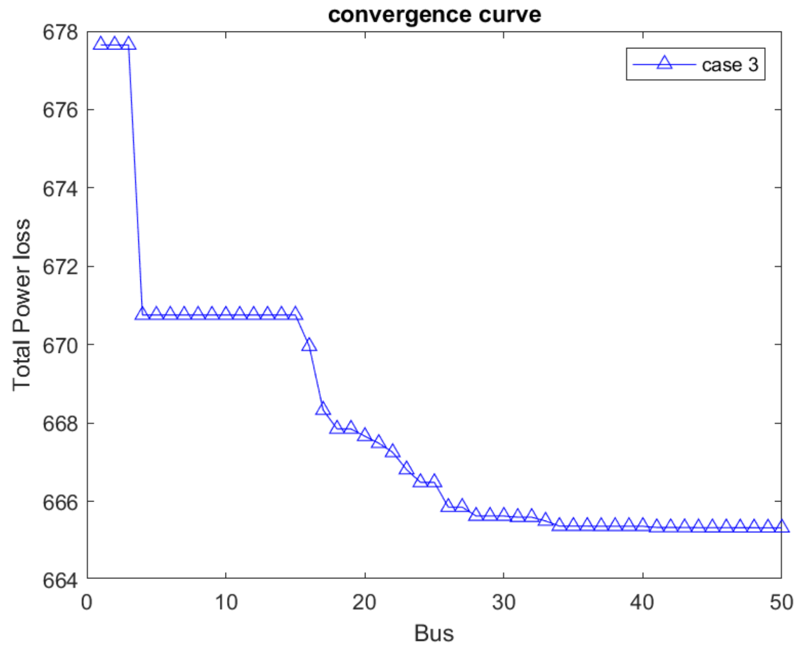

Figure 5-6 convergence curve for EDN system (objective function: Total power loss minimization)

5.4.2.TVD minimization

5.4.2.1. 34-bus radial distribution system

Tables 1.11-1.15 show the optimal locations and sizes of DGs and the capacitors required to reduce the total voltage deviation (TVD) as an objective function for cases 1-5 for the 34-bus test system. Moreover, a comparison between the proposed procedure and other methods is presented.

Table 5.11 presents the optimal solution for case 1 using the proposed procedure, when only active power from DGs is injected. It can be observed that, the initial TVD without DGs is reduced from 0.0483 to 0.0017 after placement of DGs. The optimal locations of DGs are at buses {26, 32} with total rating power 3500 kW. Moreover, the minimum and maximum voltage magnitudes are improved.

Table 5-11 A comparison between the TVD minimization using the proposed procedure with other methods using only the DGs at unity power factor (case 1) for 34-bus test system

Items	Un-compensated (Case 0)	Compensated (Case 1)	
		Proposed procedure	
Optimal locations and sizes of DGs (kW)	-	26	1951.4
		32	1548.6
Total size	-	3500	
Total losses (kW)	221.752	82.9864	
TVD	**0.0483**	**0.0017**	
Minimum bus voltage(p.u.)	0.9417 (#27)	0.9883 (#20)	
Maximum bus voltage(p.u.)	0.9941 (#2)	0.9977 (#2)	
Overall power factor	0.85	0.3678	

Table 5.12 presents the optimal solution for case 2 using the proposed procedure, when active and reactive power from DGs are injected. It can be observed that, the initial TVD without compensation is reduced from 0.0483 to 0.000496 after placement of DGs. The optimal locations of DGs are at buses {31, 24} with total rating power 3500 kW.

Table 5-12 A comparison between TVD minimization using the proposed procedure with other methods using only the DGs at 0.9 power factor (case 2) for 34-bus test system

Items	Un-compensated (Case 0)	Compensated (Case 2)	
		Proposed procedure	
Optimal locations and sizes of DGs (kW, kVAR)	-	Locations	DG size (kW)
		31	1500.1
		24	1999.9
Total size	-	-	3500
Total losses (kW)	221.752	24.32	
TVD	**0.0483**	**0. 000496**	
Minimum bus voltage(p.u.)	0.9417 (#27)	0. 9932 (#19)	
Maximum bus voltage(p.u.)	0.9941 (#2)	1.0013 (#24)	
Overall power factor	0.85	0. 6942	

Table 5.13 presents the optimal solution for case 3 using the proposed procedure, when only reactive power from capacitors is injected. It is clear that, the initial TVD without compensation is reduced from 0.0483 to 0.0295 after placement of capacitors. The optimal locations of capacitors are at buses {11, 10,26} with total rating power 3599.9 kVAR.

Table 5-13 A comparison between TVD minimization using the proposed procedure with other methods using only the capacitors (case 3) for 34-bus test system

Items	Un-compensated (Case 0)	Compensated (Case 3)	
		Proposed procedure	
Optimal locations and sizes of capacitors (kVAR)	-	11	1200
		10	1199
		26	1200
Total size	-	3599.9	
Total losses (kW)	221.752	202.691	
TVD	**0.0483**	**0.0295**	
Minimum bus voltage(p.u.)	0.9417 (#27)	0.9532(#27)	
Maximum bus voltage(p.u.)	0.9941 (#2)	0.9956 (#2)	
Overall power factor	0.85	0.9879	

Table 5.14 presents the optimal solution for case 4 using the proposed procedure, when active power from DGs is injected and reactive power is injected from capacitors. It can be observed that, the initial TVD without compensation is reduced from 0.0439 to $7.7835 * 10^{-4}$ after placement of DGs and capacitors. The optimal locations of DGs are at buses {25 25 11} with total rating power 3500 kW and the optimal locations of capacitors are at buses {19, 6} with total power rating 1377.4 kVAR.

Table 5-14 A comparison between the power loss minimization using the proposed procedure with other methods using DGs at unity power factor and capacitors (case 4) for 34-bus test system

Items	Un-compensated (Case 0)	Compensated (Case 4)	
		Proposed procedure	
Optimal locations and sizes of DGs (KW)	-	25	818.3
		25	1043.9
		11	1637.8
Total DGs size		3500	
Optimal locations and sizes of capacitors (KVAR)		19	821.6635
		6	555.721
Total capacitors size	-	1377.4	
Total losses (kW)	221.752	38.4743	
TVD	**0.0483**	$\mathbf{7.7835 * 10^{-4}}$	
Minimum bus voltage(p.u.)	0.9417 (#27)	0.9914 (#20)	
Maximum bus voltage(p.u.)	0.9941 (#2)	1.0002 (#11)	
Overall power factor	0.85	0.6049	

Table 5.15 presents the optimal solution for case 5 using the proposed procedure, when active power and reactive power from DGs are injected and reactive power is injected from capacitors. It can be observed that, the initial power loss without compensation is reduced from 0.0439 to 2.3238e-04 after placement of DGs and capacitors. The optimal locations

of DGs are at buses {10, 20, 25} with total rating power 3500 kW and the optimal locations of capacitors are at buses {17} with total power rating 1059.4 kVAR.

Table 5-15 A comparison between the power loss minimization using the proposed procedure with other methods using DGs at .9 power factor and capacitors (case 5) for 34-bus test system

Items	Base case	Case 5
		Proposed method
DG size (kW, kVAR) and location	-	1166.4, 564.8893 (#10), 993.1, 480.9892(#20), 1340.5, 649.2350 (#25)
Capacitor size (kVAR) and location	-	1059.4 (#17)
Total size of DGs (kW)	-	3500
Total size of capacitors (kVAR)	-	1059.4
f1 [Loss (kW)]	221.752	9.2909
TVD	**0.0483**	**2.3238e-04**
Min. voltage (p.u.)	0.9417 (#27)	0.9955(#30)
Overall p.f.	0.85	0.9946

Fig. 5.7 and Fig. 5.8 shows the convergence curves of the AOA algorithm to reduce the TVD using the DGs and capacitors for 34-bus test system. It is clear that, the AOA algorithm is able to reach the optimal solution with more accuracy and efficiency.

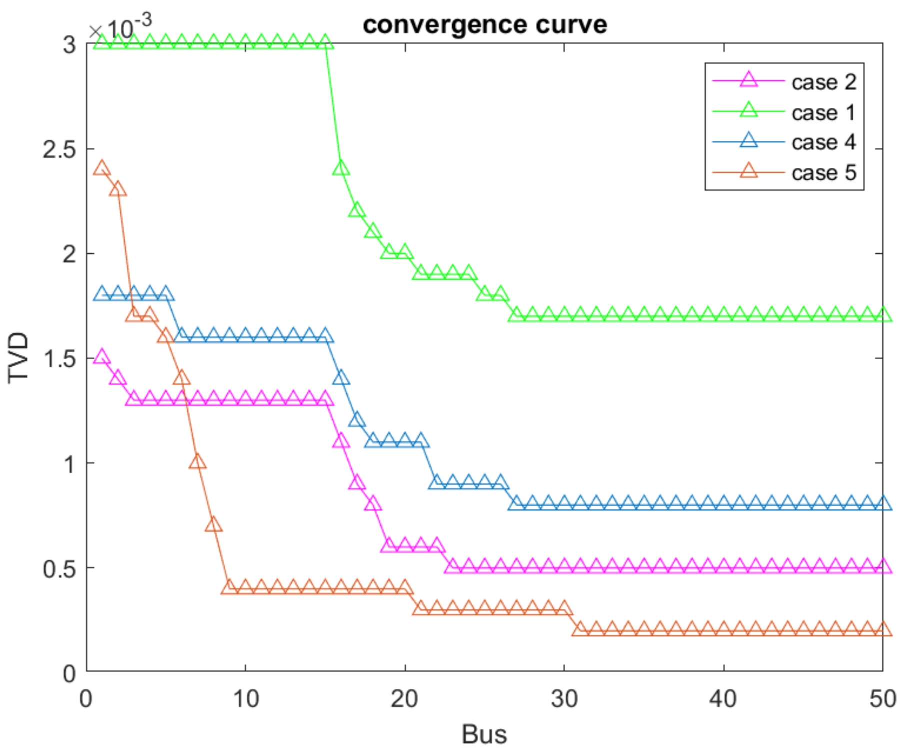

Figure 5-7 convergence curve for IEEE-34 system (objective function: TVD minimization)

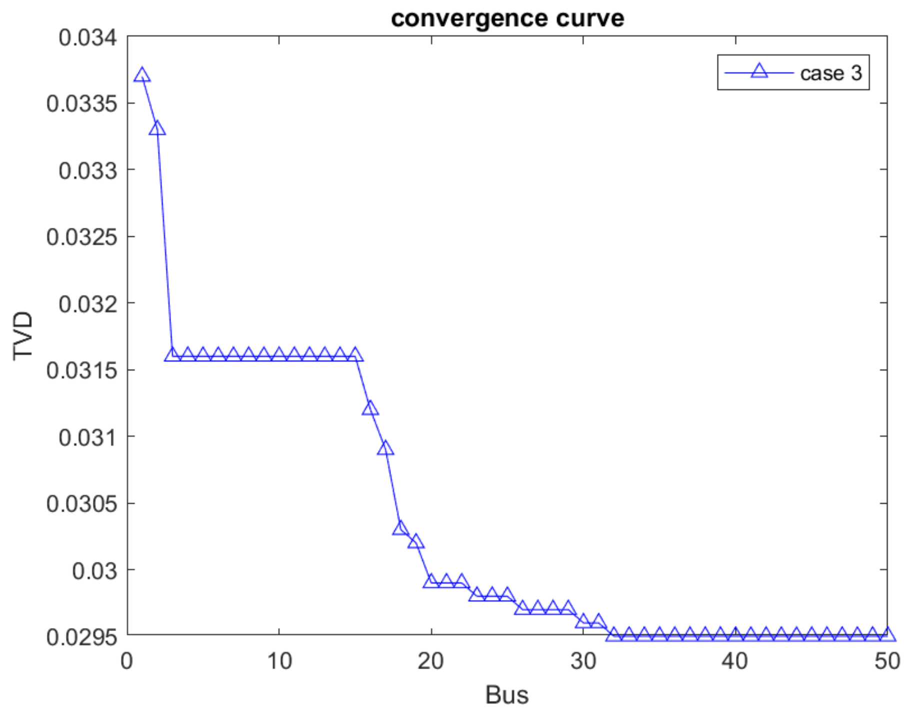

Figure 5-8 convergence curve for IEEE-34 system (objective function: TVD minimization)

Fig. 5.9 shows the voltage profiles for cases 0-5, when the TVD minimization is considered as an objective function. The voltage profiles are improved at cases 1-5. Moreover, the minimum voltage limit is violated at buses starts from 22 to 27 in case 0.

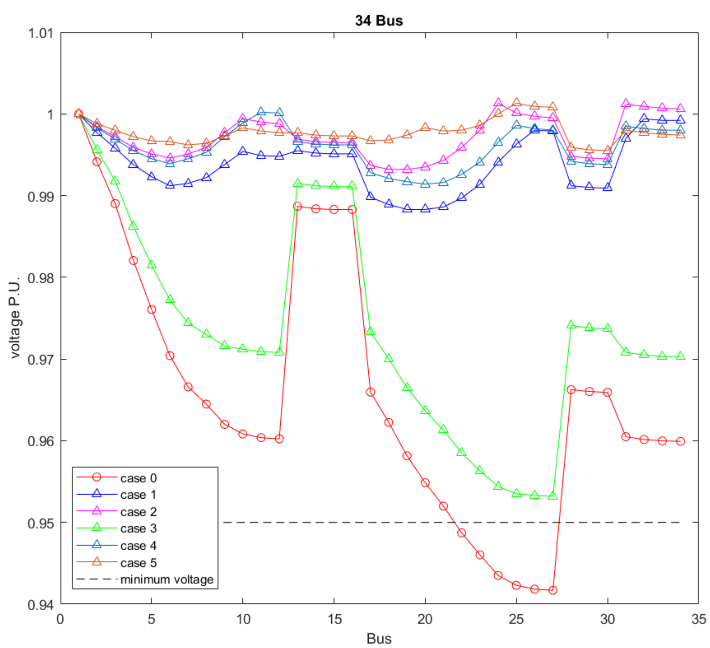

Figure 5-9 Voltage profile for IEEE-34 system (objective function: TVD minimization)

5.4.2.2. EDN radial distribution system

Tables 5.16-5.20 show the optimal locations and sizes of DGs and the capacitors required to reduce the total voltage deviation (TVD) as an objective function for cases 1-5 for the EDN system. Moreover, a comparison between the proposed procedure and other methods is presented.

Table 5.16 presents the optimal solution for case 1 using the proposed procedure, when only active power from DGs is injected. It can be observed that, the initial TVD without DGs is reduced from 0.0439 to 0.0193 after placement of DGs. The optimal locations of DGs are at buses {26 29} with total rating power 4000 kW.

Table 5-16 Optimal locations and sizes of DGs at unity power factor to reduce TVD using the proposed method for EDN system (case 1)

Items	Un-compensated (Case 0)	Compensated (Case 1)	
Optimal locations and sizes of DGs (kW)	-	26	1999.9
		29	2000
Total size	-	3999.9	
Total losses (kW)	805.73	572.0918	
TVD	**0.0439**	**0.0193**	
Minimum bus voltage(p.u.)	0.9463 (#30)	0.9677 (#21)	
Maximum bus voltage(p.u.)	0.9854 (#2)	0.9874 (#2)	
Overall power factor	0.8457	0.7932	

Table 5.17 presents the optimal solution for case 2 using the proposed procedure, when active and reactive power from DGs are injected. It can be observed that, the initial TVD without compensation is reduced from 0.0439 to 0.0163 after placement of DGs. The optimal locations of DGs are at buses {28, 28} with total rating power 3999 kW.

Table 5-17 Optimal locations and sizes of DGs at 0.9 power factor using the proposed method for EDN system (case 2)

Items	Un-compensated (Case 0)	Compensated (Case 2)	
Optimal locations and sizes of DGs (kW)	-	Locations	DG size (kW)
		28	1999.7
		28	1999.3
Total size	-	-	3999
Total losses (kW)	805.73	491.164	
TVD	**0.0439**	**0.0163**	
Minimum bus voltage(p.u.)	0.9463 (#30)	0. 9703 (#20)	
Maximum bus voltage(p.u.)	0.9854 (#2)	0.9879 (#2)	
Overall power factor	0.8457	0.8335	

Table 5.18 presents the optimal solution for case 3 using the proposed procedure, when only reactive power from capacitors is injected. It is clear that, the initial power loss without

compensation is reduced from 0.0439 to 0.0326 after placement of capacitors. The optimal locations of capacitors are at buses {25 26 29 29} with total rating power 4000 kVAR.

Table 5-18 Optimal locations and sizes of capacitors using the proposed method for EDN system (case 3)

Items	Un-compensated (Case 0)	Compensated (Case 3)	
Optimal locations and sizes of capacitors (kVAR)	-	25	441.5
		26	1198.3
		29	1194.8
		29	1165.4
Total size	-	4000	
Total losses (kW)	805.73	712.8063	
TVD	**0.0439**	**0.0326**	
Minimum bus voltage(p.u.)	0.9463 (#30)	0.9572 (#24)	
Maximum bus voltage(p.u.)	0.9854 (#2)	0.9865 (#2)	
Overall power factor	0.8457	0.9108	

Table 5.19 presents the optimal solution for case 4 using the proposed procedure, when active power from DGs is injected and reactive power is injected from capacitors. It can be observed that, the initial TVD without compensation is reduced from 0.0439 to 0.0177 after placement of DGs and capacitors. The optimal locations of DGs are at buses {29, 29, 27} with total rating power 4000 kW and the optimal locations of capacitors are at buses {9, 27} with total power rating 1307 kVAR.

Table 5-19 A comparison between the TVD minimization using the proposed procedure with other methods using DGs at unity power factor and capacitors (case 4) for EDN system

Items	Un-compensated (Case 0)	Compensated (Case 4)	
		Proposed procedure	
Optimal locations and sizes of DGs (KW)	-	29	1143.6
		29	1221
		27	1635.3
Total DGs size		4000	
Optimal locations and sizes of capacitors (KVAR)		9	839.864
		27	467.45
Total capacitors size	-	1307	
Total losses (kW)	805.73	531.637	
TVD	**0.0439**	**0.0177**	
Minimum bus voltage(p.u.)	0.9463 (#30)	0.9686 (#21)	
Maximum bus voltage(p.u.)	0.9854 (#2)	0.9877 (#2)	
Overall power factor	0.8457	0.8204	

Table 5.20 presents the optimal solution for case 5 using the proposed procedure, when active power and reactive power from DGs are injected and reactive power is injected from capacitors. It can be observed that, the initial TVD without compensation is reduced from

0.0439 to 0.017 after placement of DGs and capacitors. The optimal locations of DGs are at buses {23, 25, 29} with total rating power 3756.9 kW and the optimal locations of capacitors are at buses {7, 24} with total power rating 801.7 kVAR.

Table 5-20 A comparison between the power loss minimization using the proposed procedure with other methods using DGs at .9 power factor and capacitors (case 5) for EDN system

Items	Base case	Case 5
		Proposed method
DG size (kW, kVAR) and location	-	730.3, 353.722 (#23), 1026.6, 497.208 (#25), 2000, 968.62 (#29)
Capacitor size (kVAR) and location	-	419.131 (#7) 382.583 (#24)
Total size of DGs (kW)	-	3756.9
Total size of capacitors (kVAR)	-	801.7141
f1 [Loss (kW)]	805.73	469.8317
TVD	**.0439**	**0.017**
Min. voltage (p.u.)	0.9463 (#30)	0.9701 (#20)
Overall p.f.	0.8457	.8508

Fig. 5.10 shows the voltage profiles for cases 0-5, when TVD minimization is considered as an objective function. The voltage profiles are improved at cases 1-5.

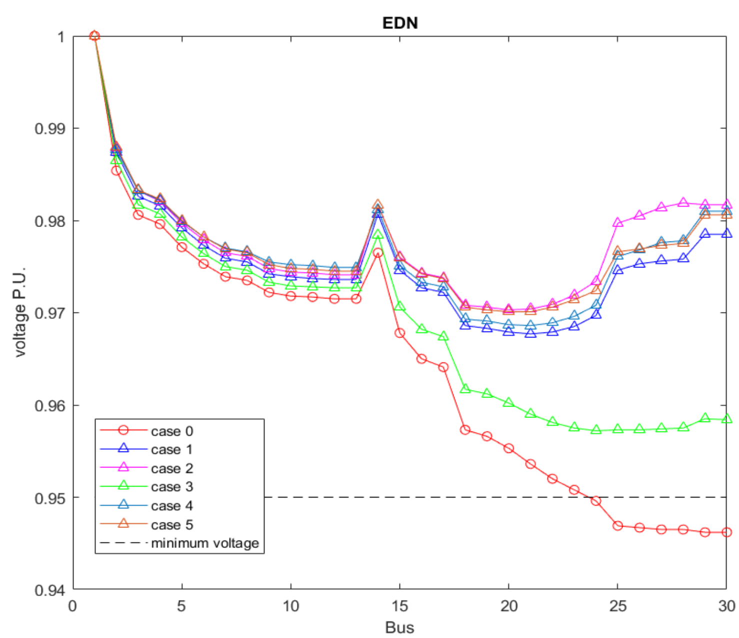

Figure 5-10 Voltage profile for EDN system (objective function TVD minimization)

Fig. 5.11 and Fig. 5.12 shows the convergence curves of the AOA algorithm to reduce TVD using the DGs and capacitors for 34-bus test system. It is clear that, the AOA algorithm is able to reach the optimal solution with more accuracy and efficiency.

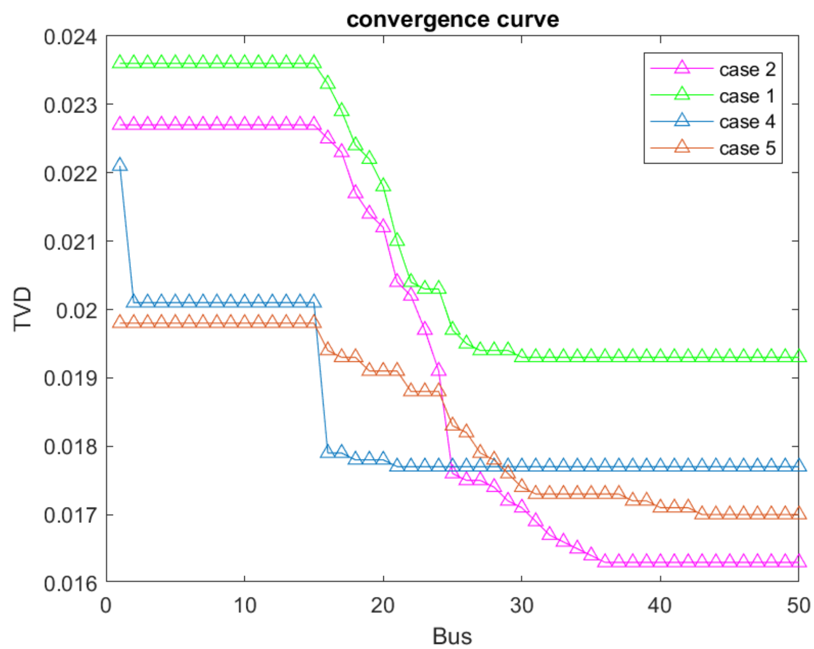

Figure 5-11 convergence curve for EDN system (objective function TVD minimization)

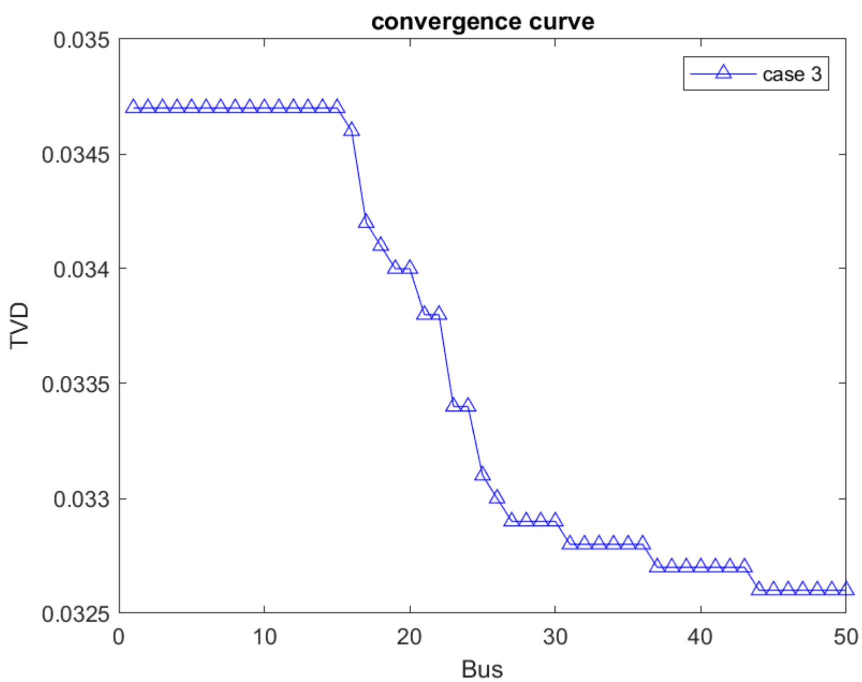

Figure 5-12 convergence curve for EDN system (objective function TVD minimization)

Chapter 6

CONCLUSIONS

In this project, a new procedure has been presented to determine the optimal locations and sizes of DGs and capacitors with two different objective functions; total power loss minimization and TVD minimization. The AOA algorithm has been utilized to find the optimal locations and sizes of DGs and capacitors according to two different single objective functions while satisfying the security and operational constraints. The obtained results are compared with other methods. Through the comparative study, it can be found that:

- Efficient and accurate proposed procedure has been introduced to find the optimal placement of DGs and capacitors using AOA compared with other techniques.
- The optimal results using the proposed procedure have been compared with other methods and have proved the capability of the proposed procedure to find the optimal solution of the objective function with voltage profile and power factor improvement.
- AOA gives convergence curve with more accurate and efficient optimal placement of DGs and capacitors in distribution systems.
- The proposed AOA mathematical model is very simple since it has few parameters.
- The BFS load flow algorithm has been used successfully for the load flow calculations.
- The proposed procedure represents a potential tool to reduce the system losses and improve the voltage profile.
- The proposed procedure has been tested on 34-bus radial distribution system. Moreover, a real distribution system of the East Delta Network (EDN) as a part of the UEN has been used to show the capability of proposed procedure.
- the proposed procedure represents a potential tool to improve the distribution system performance as well as help the system operators.

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Appendix A

Appendix A

TEST SYSTEMS

A.1 34-Bus Distribution System

The single line diagram of 34-bus distribution system is shown in Fig. A.1. Tables A.1 and A.2 show the buses and lines data of 34-bus system, where the rated line voltage is 11 kV and rated MVA is 100.

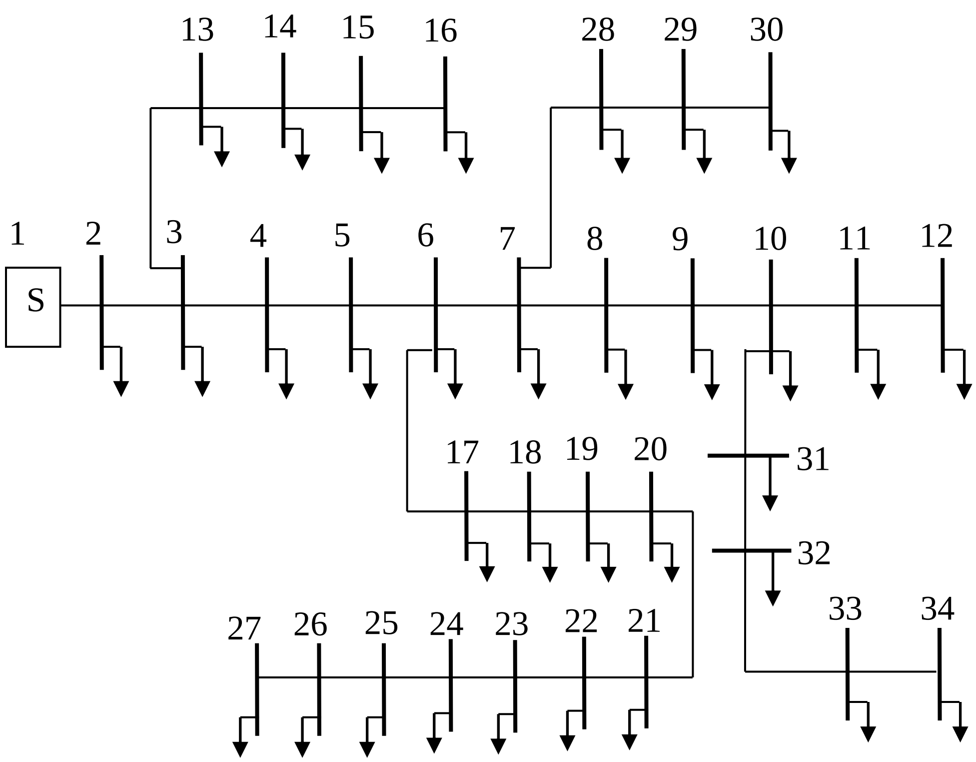

Fig. A.1 Single line diagram of 34-bus radial distribution system

Table A.1 Lines data for 34-bus distribution system

Line No.	Sending bus	Receiving bus	R (Ω)	X (Ω)
1	1	2	0.1170	0.0480
2	2	3	0.1073	0.0440
3	3	4	0.1645	0.0457
4	4	5	0.1495	0.0415
5	5	6	0.1495	0.0415
6	6	7	0.3144	0.0540
7	7	8	0.2096	0.0360
8	8	9	0.3144	0.0540
9	9	10	0.2096	0.0360
10	10	11	0.1310	0.0225
11	11	12	0.1048	0.0180
12	3	13	0.1572	0.0270
13	13	14	0.2096	0.0360
14	14	15	0.1048	0.0180
15	15	16	0.0524	0.0090
16	6	17	0.1794	0.0498
17	17	18	0.1645	0.0457
18	18	19	0.2079	0.0473
19	19	20	0.1890	0.0430
20	20	21	0.1890	0.0430
21	21	22	0.2620	0.0450
22	22	23	0.2620	0.0450
23	23	24	0.3144	0.0540
24	24	25	0.2096	0.0360
25	25	26	0.1310	0.0225
26	26	27	0.1048	0.0180
27	7	28	0.1572	0.0270
28	28	29	0.1572	0.0270
29	29	30	0.1572	0.0270
30	10	31	0.1572	0.0270
31	31	32	0.2096	0.0360
32	32	33	0.1572	0.0270
33	33	34	0.1048	0.0180

Table A.2 Bus data for 34-bus distribution system

Line No.	P (kW)	Q (kVAR)
1	0	0
2	230	142.5
3	0	0
4	230	142.5
5	230	142.5
6	0	0
7	0	0
8	230	142.5

9	230	142.5
10	0	0
11	230	142.5
12	137	84
13	72	45
14	72	45
15	72	45
16	13.5	7.5
17	230	142.5
18	230	142.5
19	230	142.5
20	230	142.5
21	230	142.5
22	230	142.5
23	230	142.5
24	230	142.5
25	230	142.5
26	230	142.5
27	137	85
28	75	48
29	75	48
30	75	48
31	57	34.5
32	57	34.5
33	57	34.5
34	57	34.5

A.2 East Delta Network (EDN) System

The single line diagram of EDN 30-bus distribution system is shown in Fig. A.2. Table A.3 shows the buses and lines data of EDN 30-bus system, where the rated line voltage is 11 kV and rated MVA is 100.

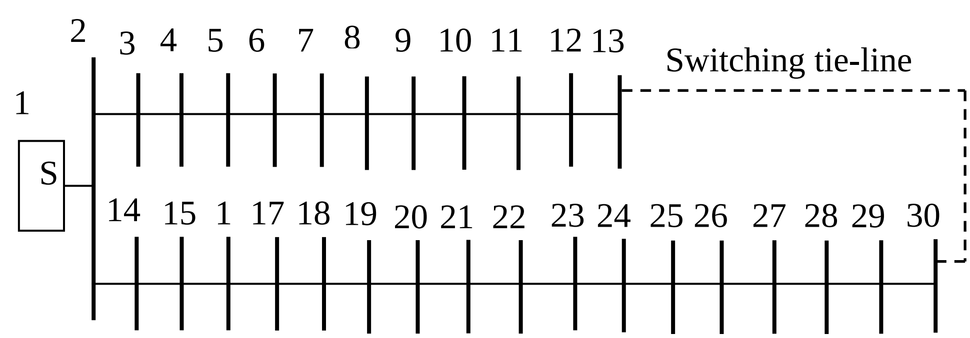

Fig. A.2 Single line diagram of the EDN distribution system

Table A.3 Buses and lines data for EDN distribution system

Line No.	Sending bus	Receiving bus	R (Ω)	X (Ω)	Load at Receiving bus	
					P (kW)	Q (kVAR)
1	1	2	0.05630	0.031500	2875	1814
2	2	3	0.07155	0.025974	1100	695
3	3	4	0.01855	0.006734	1058	669
4	4	5	0.05565	0.020202	899	568
5	5	6	0.05300	0.019240	770	486
6	6	7	0.05300	0.019240	668	423
7	7	8	0.02120	0.007696	598	378
8	8	9	0.10070	0.036556	546	345
9	9	10	0.04505	0.016354	380	240
10	10	11	0.03975	0.014430	210	132
11	11	12	0.11130	0.040404	94.586	59.368
12	12	13	0.01325	0.004810	34.423	21.518
13	2	14	0.06360	0.023088	1772	1118
14	14	15	0.07155	0.025974	1640	1035
15	15	16	0.02650	0.009620	1452	915
16	16	17	0.01060	0.003848	1434	904
17	17	18	0.09275	0.033670	1212	765
18	18	19	0.01060	0.003848	1086	685
19	19	20	0.02650	0.009620	953	602
20	20	21	0.04505	0.016354	827	521
21	21	22	0.05300	0.019240	716	452
22	22	23	0.05300	0.019240	550	347
23	23	24	0.0663	0.0240	434	273
24	24	25	0.2253	0.0818	346	218
25	25	26	0.0265	0.0096	316	199
26	26	27	0.0265	0.0096	184	116
27	27	28	0.0133	0.0048	139	87.911
28	28	29	0.1723	0.0625	113	71.734
29	29	30	0.0080	0.0029	34.25	21.734

Appendix B

Appendix B

BACKWARD/FORWARD SWEEP (BFS) ALGORITHM

The backward/forward sweep (BFS) algorithm is one of the most common ways used for load flow distribution system because it is simple, fast and robust convergence and low memory requirement. The BFS algorithm involves mainly an iterative three basic steps based on Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL). The three steps are named as the nodal current calculation, the backward sweep and the forward sweep and they are repeated until the convergence is achieved. In the nodal current calculation, all the current injection at different buses is determined. In the backward sweep, the section currents and powers are calculated starting from the last node and proceeds towards substation node. In the forward sweep, the voltage at each node is calculated starting from the substation node and proceeds towards last node. The input data required for this algorithm are the numbering of sending and receiving nodes, the branch data represented by resistance and reactance and the active and reactive powers at each node. The BFS utilizes a simple and flexible radial distribution system numbering scheme in order to numbering each branch in the feeder, lateral and sub-lateral [24].

The BFS algorithm can be applied to find the load flow results using the following steps:

<u>Step 1</u>: Initialization- Insert the following:

- The distribution system line and load data.
- The base power and base voltage.
- Calculate the base impedance.
- Calculate the per unit values of line and load data.
- Take the voltage for all buses flat voltage (1 p.u.).
- Set convergence tolerance Є=0.0001 and $\Delta V_{max} = 0$.

<u>Step 2</u>: Radial distribution system numbering scheme

The numbering scheme aims to give a number to each section in the distribution system, where a section is part of a feeder, lateral or sub-lateral that connects two buses in the distribution system. The total number of sections ($N_{Sec}{}^{Total}$) of a distribution system can be calculated as:

$$N_{Sec}^{Total} = N_{bus}^{Total} - 1 \tag{B.1}$$

where, $N_{bus}{}^{Total}$ is the total number of buses. Each section will carry a number which is one less than its receiving end bus number, e.g., the number of sections that connects the sending end p and the receiving end q in Fig. 5.1 can be calculated as:

$$N_{\left(\frac{Sec}{p-q}\right)} = N_{\left(\frac{bus}{q}\right)} - 1 \tag{B.2}$$

where, $N_{(Sec\ /p\text{-}q)}$ is the section number between buses *p* and *q*, $N_{(bus\ /q)}$ is the number of bus *q*.

Now, the radial distribution system numbering scheme should be applied on the distribution system to give a number to each section in the system.

Step 3: Nodal current calculation

At iteration *k*, the nodal current injection at node *i* due to loads and any other shunt elements can be calculated as:

$$I_i^{(k)} = \left(\frac{S_i}{V_i^{(k-1)}}\right)^* - (Y_i)\left(V_i^{(k-1)}\right) \qquad \text{(B.3)}$$

where, $I_i^{(k)}$ is the current injection at node *i*, S_i is the specified power injection at node *i*, $V_i^{(k-1)}$ is the voltage at node *i* at iteration *k-1*, Y_i is the sum of all shunt elements at node *i*.

Step 4: Backward sweep

At iteration *k*, start from the branches at the end nodes and moving towards the branches connected to the substation. Hence, all branch currents can be calculated by applying the KCL and then the powers through these branches can be determined. For the branch *L*, the current and power flows can be calculated as:

$$I_L^{(k)} = -I_j^{(k)} - \sum_{m=1}^{M}\left(\frac{S_m}{V_j^{(k)}}\right)^* \qquad \text{(B.4)}$$

$$S_L^{(k)} = \left(V_j^k + Z_L * I_L^k\right)\left(I_L^k\right)^* \qquad \text{(B.5)}$$

where, $I_L^{(k)}$ is the current flow in branch *L* at iteration *k*, $I_j^{(k)}$ is the current injected due to shunt elements at bus *j*, *M* is the number of branches connected to bus *j*, S_m is the complex power at the sending end of branch *m*, $V_j^{(k)}$ is the voltage at bus *j*, $S_L^{(k)}$ is the power flow in branch *L* and Z_L is the impedance of branch *L*.

Step 5: Forward sweep

At iteration *k*, the nodal voltages are updated in a forward sweep starting from the branches in the first section toward those in the last by applying the KVL. For a branch *L* connected sending end *p* and receiving end *q*, the voltage at receiving end at iteration *k* can be calculated as:

$$V_q^{(k)} = V_p^{(k)} - Z_L * I_L^{(k)} \qquad \text{(B.6)}$$

where, $V_p^{(k)}$ and $V_q^{(k)}$ are the voltages at sending and receiving ends, respectively.

Step 6: Check the voltage mismatches

After the previous steps have been computed, the voltage mismatches for all nodes are calculated, e.g., the voltage mismatch at bus *i* at iteration *k* can be calculated as:

$$\Delta V_i^{(k)} = \left|\left|V_i^{(k)}\right| - \left|V_i^{(k-1)}\right|\right| \qquad \text{(B.7)}$$

After calculating the voltage mismatches, check the convergence of the voltage as:

- If $\Delta V_i^{(k)} > \Delta V_{max}$, then make $\Delta V_{max} = \Delta V_i^{(k)}$.
- If $\Delta V_{max} \leq \epsilon$, go to step 8, otherwise increment the iteration number and go to step 3.

Step 7: Check stopping criterion

The program will be terminated when the maximum iteration is reached or the convergence from the voltage mismatches is verified.

Step 8: Power loss calculation:

After computing the node voltages and branch currents using the BFS algorithm, the total active and reactive power losses in the distribution system are calculated from Equations (4.3) and (4.4).

The steps of the BFS algorithm to find the radial distribution system load flow are shown in Fig. B.1.

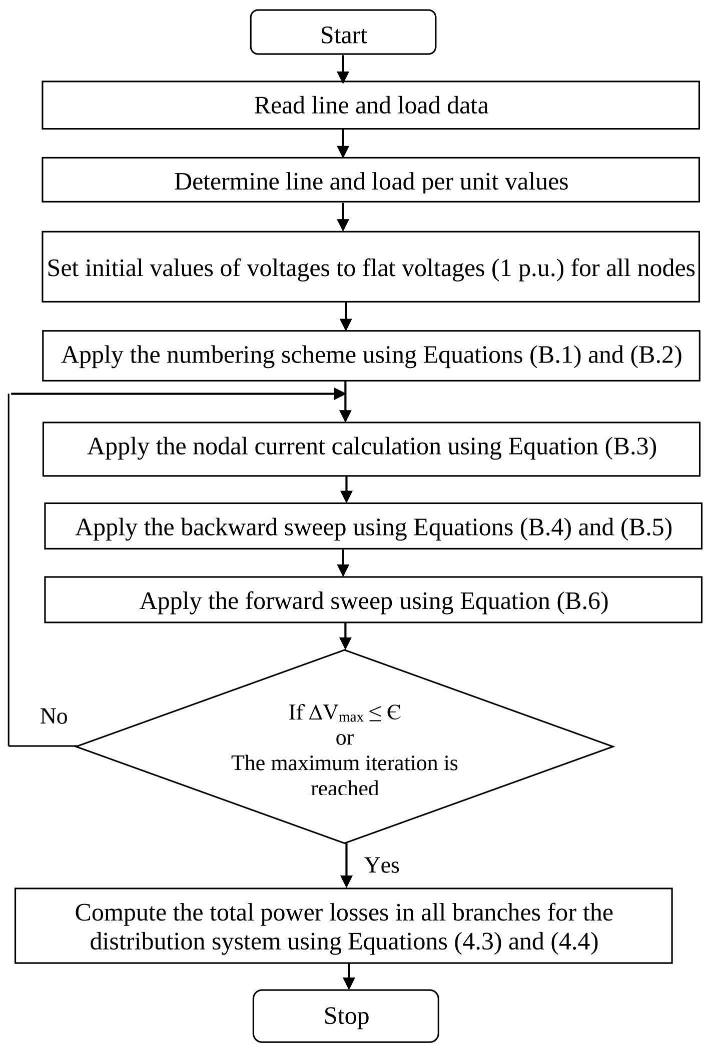

Fig. B.1 Flow chart of backward/forward sweep load flow