People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

University M'Hamed BOUGARA – Boumerdes

Institute of Electrical and Electronic Engineering

Department of Power and Control Engineering

Final Year Project Report Presented in Partial Fulfilment of

the Requirements for the Degree of

MASTER

In **Power Engineering**

Option: **Power Engineering**

Title:

Optimal Placement of Smart Meters for fault detection in the Distribution System

Presented by:

Baali Habiba.

Supervisor:

Prof. Recioui. A.

2022/2023

Abstract

This work presents a method that combines a power system analysis program and genetic algorithm to identify a faulty section in a typical medium distribution network with DGs based on the optimal placement of smart meters. The project consists of two main parts, the first part deals with the penetration of DG units into the simple radial system. In this part, the analytical optimization method is used for optimal placement of DG units and Backward/Forward method is used for the load flow analysis. The optimal locations and size of the DGs have been determined by minimizing the power distribution loss. After the penetration of DGs, the second part introduces a method for fault detection in the presence of DGs based on the measurement of smart meters. The GA (genetic algorithm) is used for optimal placement of smart meters. For each part, the proposed method was evaluated and tested using MATLAB software and Matlab_Simulink. Results show that the power losses of the system were reduced after the penetration of DG units. In addition to the improvement of the voltage profile and the stability of the system in general. For the second part, the results show that the fault locating method by the optimal number of meters has good efficiency and accuracy in detecting three-phase faults.

Dedication

I would like to dedicate my dissertation work to my family and my friends. A special feeling of gratitude to my beloved parents, they did their best to help me and supported me to get where I am; their words of encouragement and push for tenacity ring in my ears. I also dedicate my work to my brothers: ***Amine****,* ***Abdou,*** *and* ***Ishak****, to my Beautiful sisters* ***Kaouthar*** *and* ***Maria,*** *to my cousins* ***Maroua*** *and* ***Nour El-Houda****. To the family* ***Hammal****,* ***Feriel*** *and* ***Sarrah****. I express my sincere appreciation and gratitude to* ***Mohamed Yassine****. I also dedicate this work to all my friends. A special feeling of gratitude to* ***Mermat. S****,* ***Mansouri. H****, and* ***Boucetta.M*** *for their help.*

Acknowledgment

First, I thank Allah Almighty who paved the path for me in achieving the desired goal. My foremost and profound gratitude goes to my supervisor ***Prof. Recioui .A*** *for his proficient guidance, assistance, valuable suggestions, useful criticism, continuous encouragement, and immense help throughout the project. I would like to express my sincere gratitude to our mentor* ***Dr*. *Belmadani*. *H*** *for his help, for his patience, motivation, enthusiasm, and immense knowledge. My appreciation is extended to all institute teachers for their helps during the whole five academic years. A special feeling of gratitude to* ***Mermat. S***, ***Mansouri. H***, *and* ***Boucetta .M*** *who contributed in the realization of this work. Finally, I thank my family who supported and encouraged me over the whole project.*

Table of contents

List of tables

List of figures

List of Abbreviations

DG: Distributed Generation.

VSI: Voltage Stability Index.

AC: Alternative Current.

DC: Direct Current.

HVDC: High Voltage Direct Current.

MV: Medium Voltage.

RES: Renewable Energy Sources.

VDI: Voltage Deviation Index.

PoVC: Point of Voltage collapse.

L-G : Line-to-Ground.

L-L: Line-to-Line.

L-L-G: Line-to-Ground.

SM: Smart Meter.

AMI: Advanced Meter Infrastructure.

DSLF: Distribution System Load Flow.

B/FS: Backward/Forward Sweep.

BFS: Breadth First Search Method.

KVL: Kirchhoff's Voltage Law.

KCL: Kirchhoff's current Law.

GA: Genetic Algorithm.

LP: Linear Programing.

NLP: Nonlinear Programing.

TS: Tabu Search.

ILS : Iterated Local Search.

BA: Bees algorithm.

FA: Firefly Algorithm.

GWO: Grey Wolf optimization.

ACROA: Aritificial Chemical Reaction optimization Algorithm.

RMS: Root Mean Square.

General Introduction

An efficient electric power system is characterized by complex and broad distribution networks to fulfill the electrical power demand of the connected loads at all the locations within power network economically and reliably as possible. The vastness of distribution networks mainly results in huge electric power losses. The penetration of distributed generation (DG) sources into the medium-voltage distribution system is an effective solution to the latter problem. However, the growth of distributed generators makes the distribution system even more complex and affects other important issues in employing distribution networks. One of the most important issues is the detection of the fault location in the distribution system. Due to the presence of DG units, the detection of the fault location is difficult and expensive with the common methods. The aim of this work is to present a method based on voltage-distributed meters in a medium-voltage distribution network in order to detect the fault location in the presence of DG sources. The idea is to employ the voltage drop measurement of smart meters installed in the network to calculate a fault location index. Smart meters are smart sensors that can be installed across the distribution system, from sub-transmission substations to the consumer location. Due to the vastness of the distribution system and the installation cost of smart meters, it is not economical to install smart meters in all the buses on the network. To overcome this problem, in this work, a combination of fault detection algorithm and the genetic algorithm has been used for optimal placement of smart meters. In order to evaluate the efficiency of this method, first, optimal placement of DG units in the distribution network for loss reduction has been implemented using analytic optimization method in MATLAB software for IEEE 33 radial distribution system. Since the penetration of DG units also affects the stability of the system, Voltage Stability Index (VSI) method is used to monitor the stability of the system. After that, the genetic algorithm has been used to find the installation points of smart meters in the network with the presence of DG units. Then the fault location algorithm has been tested for different fault locations, the simulation of the faults has been done using MATLAB Simulink.

This report is divided into four main chapters:

-Chapter 1: this chapter introduces and presents an overview about distribution power system, distributed generators, faults in distribution system and ending up with generalities about smart meters.

-Chapter 2: This chapter represents the load flow method used in this work, which is the Backward Forward load flow method.

-Chapter 3: This chapter highlights the optimization techniques used and their various parameters.

-Chapter 4: Problem, results, and discussion chapter. It includes two parts, the first part is dedicated to solve the optimal placements of DG units for loss reduction and the second part deals with the optimal placement of smart meters for fault detection where in each part the problem statement, the objective functions used, results and discussion is presented.

Chapter 1: Overview

1.1 Electric power system

The electric power system is one of the largest and most complex infrastructures, which has a critical effect on the operation of society and other infrastructures. It delivers generated electricity to customers and aims to meet the electric power demand of the connected loads most reliably and efficiently. The electric power system consists mainly of three major parts: generation, transmission, and distribution systems sprawled across a broad geographical area. Figure 1.1 represents the three parts of an electrical system . Electrical power is generated in power plants, which are frequently found distant from inhabited regions. Power is generated from two main sources, namely conventional energy sources and non-conventional energy sources. Non-conventional energy sources, also known as renewable energy resources, include wind, hydroelectric and photovoltaic cells. On the other hand, nonrenewable or traditional energy resources include thermal, nuclear, and fossil fuels. The operation of a power system relies on a centralized control unit. However, electric power systems are evolving from a centralized bulk system, with generation plants connected to the transmission network, to a more decentralized system, with smaller generating units connected directly to distribution networks near demand consumption [1]. This type of generating unit is defined as Distributed Generation (DG). This transition, from centralized systems to more decentralized ones, is due to the draining of conventional energy resources, the high costs of transmission, the expansion and complexity of distribution systems, power losses, technological developments, and environmental concerns.

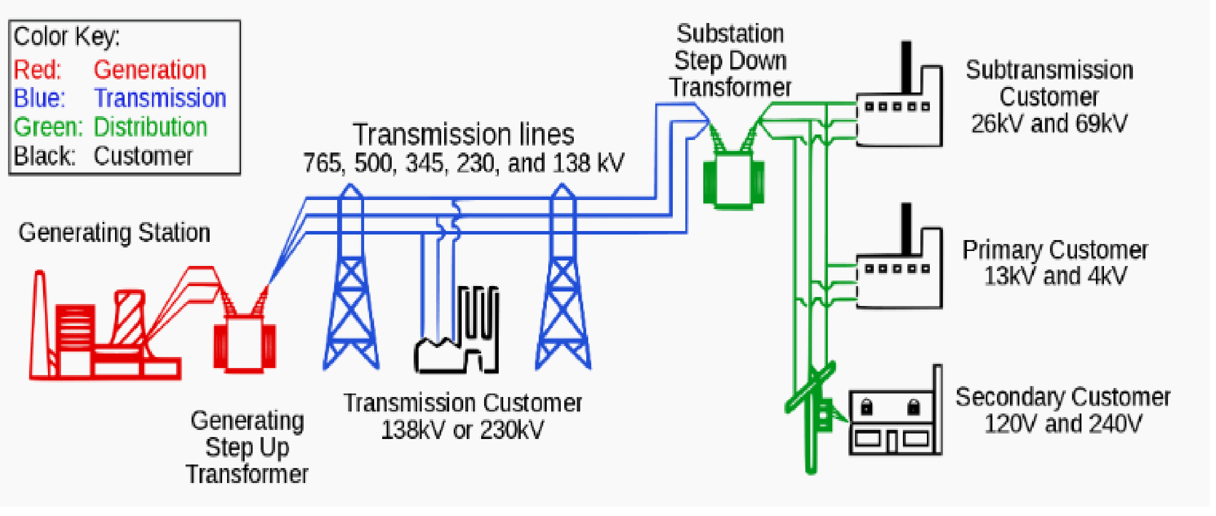


Figure 1.1 Electric power system [2]

The generation is connected to the transmission system through step-up transformers to increase the voltage of the generated electrical power thereby reducing its current and electric losses since the electrical losses are directly proportional to the current square. Therefore, improving transmission efficiency. Transmission voltage levels typically range from 220kV to 765kV 3-phase AC power. However, for long-distance power transmission, a high voltage DC (HVDC) transmission system is used. Where AC power must be converted into HVDC power at a converter station for the transmission, after that, at the end of the (HVDC) transmission system, the electric power is converted back into AC power. At the end of the transmission, the voltage is decreased using a step-down transformer to the distribution voltage level. Then electricity is supplied to customers through the distribution system, which is the final stage of the power system.

1.2 Distribution system

The distribution network is an important part of a power system since the supply of electricity to consumers is ensured by an efficient distribution system. It is the most critical part of the electrical power system due to its ubiquity and complexity. Based on the current nature, distribution systems are classified into two types: Direct current (DC) distribution system and alternative current (AC) distribution system. The AC distribution system is divided into two systems namely the primary distribution system and the secondary distribution system. The former starts with voltage levels of 132 kV (or 110kV in some places) or 66 kV. These high voltage (HV) levels can be found in (European) distribution networks. However, voltage levels below that (e.g., 30, 20, 10 kV) are commonly found in medium voltage (MV) distribution networks, these voltage levels are directly distributed to industries and heavy loads. The latter is an electricity distribution system with domestic consumer's voltage usage levels such as 440V and 230V.

1.2.1 Distribution system topologies

MV distribution system topologies can be classified into three groups [3]

1.2.1.1 Radial topology

The radial system is the most basic electrical distribution system. It is the least expensive distribution circuit in terms of initial equipment costs and maintenance costs. In this system, separate feeders radiate from a single substation and feed the distributors at one end only. One of its features is the absence of loops. Figure 1.2 shows a single line diagram of a radial system for AC distribution where a feeder OC supplies a distributor AB at point A. The distributor is fed at one end only (point A in this case). The radial network is most preferable when power is generated at low voltage and the substation is located at the center of the load. It is also widely used in sparsely populated areas because each bus is connected to the source via exactly one path. However, the loss of the utility supply, transformer, or any damage to distribution equipment will result in an electrical service interruption for consumers who are on the side of the fault away from the substation. In addition, the consumers at the distant end of the distributor would be subject to serious voltage fluctuations when the load on the distributor changes. Moreover, the power loss in a radial distribution system compared to a ring main system is significantly high because of lower voltage and high current [4]. Due to these limitations, this system is used for short distances only. Radial system configuration can be seen as tree-shaped especially when the system is vast.

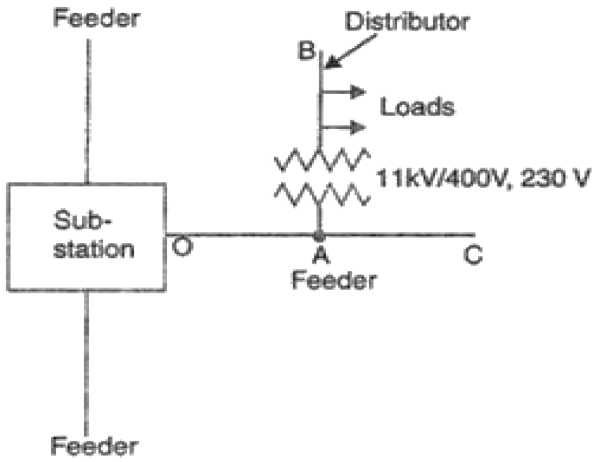


Figure 1.2 Simple radial system [4].

1.2.1.2 Ring topology

Ring or mesh topology is a fault-tolerant topology to mainly overcome the weakness of radial topology in the presence of failures. This is done by connecting substations to other lines to create redundancy. Independently of the physical configuration, the grid is operated radially, but in the event of a failure in a feeder, other elements are maneuvered to reconfigure the grid in such a way that outages are avoided. In this system, the primaries of distribution transformers form a loop. The loop circuit starts from the substation bus bars, makes a loop through the area to be served, and returns to the substation. Figure 1.3 shows the single line diagram of a ring main system for ac distribution where substation supplies to the closed feeder LMNOPQRS. The distributors are tapped from different points M, O, and Q of the feeder through distribution transformers. Using this system, voltage fluctuations at consumers' terminals can be reduced. Furthermore, it is very reliable as two feeders are used to feed each distributor; hence, in the event of a fault on any section of the feeder, the continuity of supply is maintained. For instance, suppose that fault occurs at any point F of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time, continuity of supply is maintained to all the consumers via the feeder SRQPONM [4].

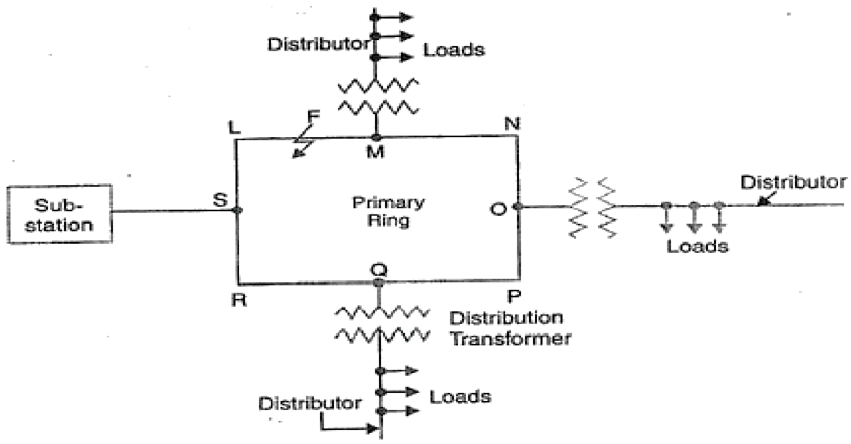


Figure 1.3 Ring main system [4].

1.2.1.3 Interconnected topology

When two or more than two generating stations or substations energize the feeder ring, this is called inter-connected system. This configuration increases the service reliability and efficiency since any area fed from one generating station during peak load hours can be fed from the other generating station. Figure 1.4 shows the single line diagram of interconnected system where the closed feeder ring ABCD is supplied by two substations S1 and S2 at points D and C respectively. Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers. Thus, the reconfiguration options to overcome faults are multiple, and in the event of failure, alternative solutions may be found to reroute electricity [4].

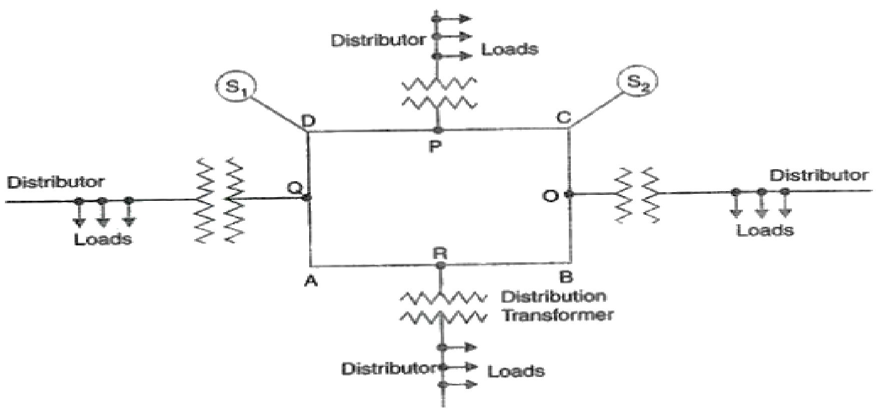


Figure 1.4 Interconnected system [4].

1.2.2 Losses in distribution networks

Radial systems are characterized by having unidirectional electricity transportation from the substation to each load. Therefore, without adding DG units, a radial distribution system is considered passive. However, by inserting DG units into the network the system will be active, as the power flow becomes bidirectional. In general, the radial distribution network has a high R / X ratio, which leads to more power losses and voltage drop. A large amount of total power losses in the power grid occurs in the distribution network accounting for about 13 % of the total network generation [5]. However, the penetration of DGs into the radial distribution system, close to the customer side, leads to reduce electrical losses. In other words, an active distribution system has fewer power losses compared to a passive distribution system. The penetration of DGs into the distribution system also uptrend other aspects in the distribution system such as voltage profile improvement, minimized pollutants emission, improved power quality, high overall efficiency, and stability improvement. Voltage stability improvement and loss reduction are the most crucial interests used to determine the location and size of the DG unit to be inserted into the distribution system. Improper size would increase the losses in the system beyond the losses for the case without DG [6]. Hence, the optimization of the location and the size of DGs is used to avoid this problem.

1.3 Distributed Generation

1.3.1 Distributed generation: A definition

There is a wide range of terminologies used for “distributed generation,” such as “embedded generation,” “dispersed generation,” or “decentralized generation” [7] but the most used term is distributed generation, DG for short. DG essentially means a small-scale power station different from a traditional or large central power plant. There are numerous technologies ranging from traditional to nontraditional used in DG applications. The former is nonrenewable technologies such as internal combustion engines, combined cycles, combustion turbines, and micro-turbines. The latter technologies include fuel cells, storage devices, and several renewable energy-based technologies such as photovoltaic, biomass, wind, geothermal, ocean, etc. [6]. Unlike conventional power plants, which have a high potential to provide energy for load centers from a far distance by transmission and distribution lines, distributed generation leads to a decentralized power system in which DG units meet local demand. In other words, DG can be seen as electric power generation within distribution networks or on the customer side of the network to meet local demand.

In recent years, the penetration of distributed generators (DG) into distribution systems has been increasing rapidly in many parts of the world. The main reasons for the increase in penetration are the liberalization of electricity markets, constraints on building new transmission and distribution lines, and environmental concerns [7] [8]. Technological advances in small generators, power electronics, and energy storage devices for transient backup have also accelerated the penetration of DG into electric power generation plants [9]. Figure 1.5 represents an electrical power system with three DG units.

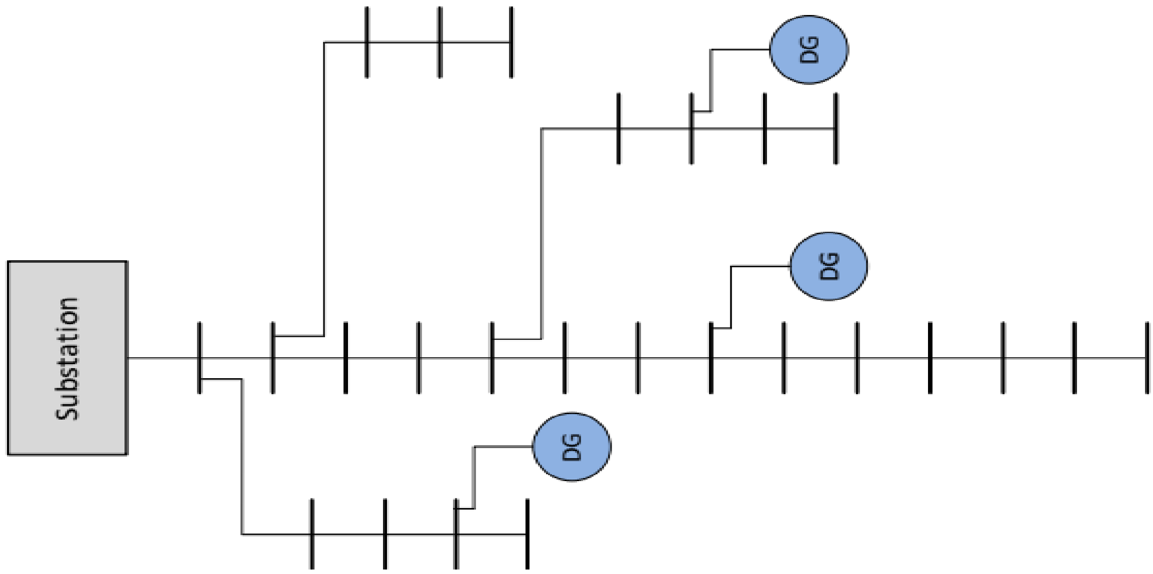


Figure 1.5 Illustrative penetration of distributed generators.

1.3.2 Classification of Distributed Generation

Distributed Generation can be classified based on the primary energy used into two types: Renewable Energy Sources (RES) DGs and non-RES DGs.

The former include wind, solar, tide, small hydropower plant…etc. This class can be classified furthermore based on its terminal characteristics in terms of real and reactive power delivering capability into three types [10]. The first type is only capable of injecting active power such as photovoltaic cells (P-type), whereas the second type is capable of injecting active and reactive power (PQ+-type) by adding smart inverters to them (smart inverters convert direct current into alternating current). Others are capable of injecting active power and consuming reactive power like induction generators of wind turbines (PQ-- type). The main advantage of RES DGs is the minimization of the total cost, given that they are cheaper than conventional DGs, minimizing global warming and reducing system losses.

The latter are DGs based on nonrenewable energy including internal combustion engines, fuel cells, and cogeneration. Some of the Non-RES DGs are capable of injecting both active and reactive power, such as combined combustion technology (PQ+-type), the internal combustion engine, and combined cycle-based DGs. Some are only capable of injecting reactive power; they could be synchronous compensators such as gas turbines. Non-RES DGs is characterized by minimizing active and reactive losses whereas their main disadvantage is that they have a small effect on the total generation cost reduction and lead to an increase in global warming. Based on the capacity, DGs can be classified as small (less than 5kW), medium (5kW to 5 MW), and large (5MW to 50MW) distribution generators [11]. Figure 1.6 represents the classifications of DGs based on different factors.

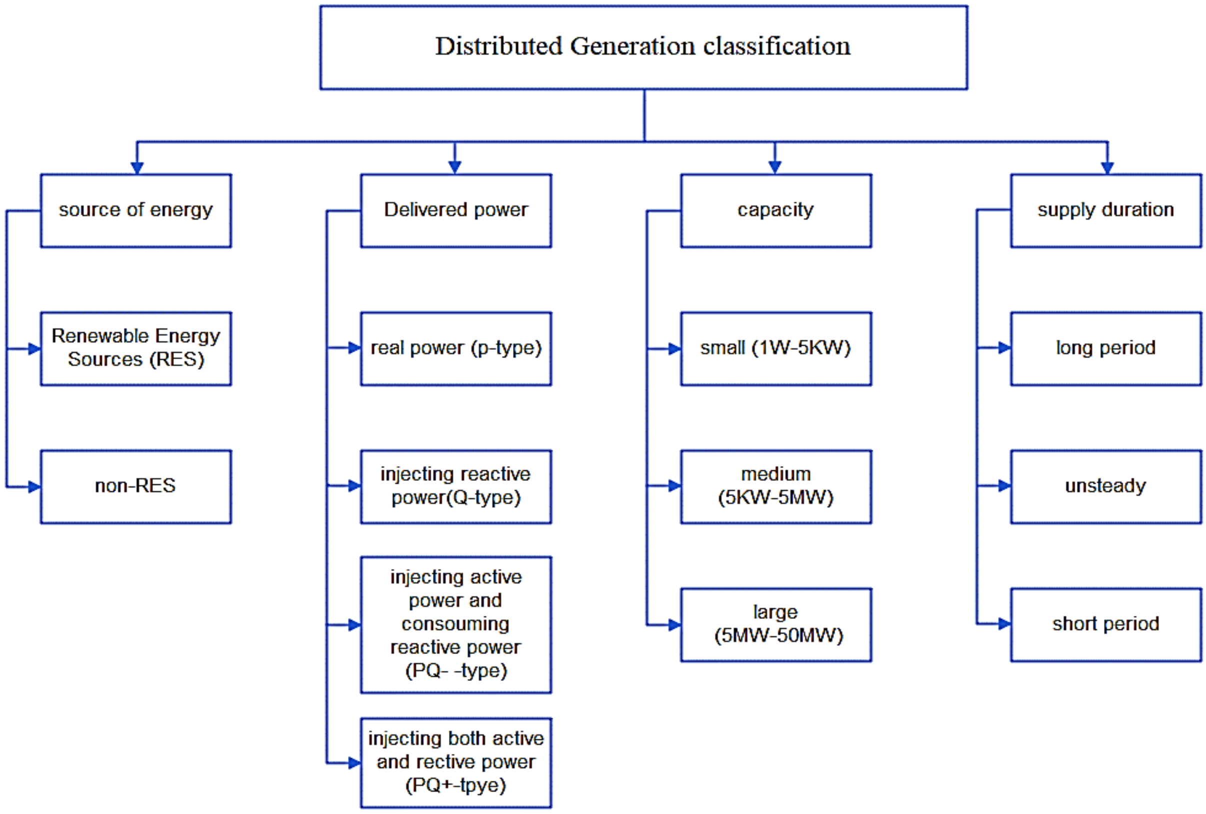


Figure 1.6 Classification of Distributed Generation.

1.3.3 Impacts of distributed generation on the distribution network:

Penetration of DG is a new challenge for traditional electric power systems, as it changes network power flows, modifying energy losses. This causes an impact on network operation and planning practices of distribution companies with both technical and economic implications [12]- [13].

1. The effect of Distributed generation on power flow :

In a radial feeder, depending on the technology, DG units can deliver a portion of the total real and/or reactive power to loads so that the feeder current reduces from the source to the location of DG units [10].

2. The effect of Distributed generation on system power losses :

DG units are capable of delving real and/or reactive power to the network based on the type of DGs used. This will cover a portion of the total power demand leading to reducing the losses in the network. Any loss reduction is beneficial to distribution utilities, which is generally the entity responsible to keep losses at low levels. Loss reduction is, therefore, the most important factor to be considered in the planning and operation of DG [14]– [15]. However, studies [16]–[17] have indicated that if DG units are improperly allocated and sized, the reverse power flow from larger DG units can lead to higher system losses. Hence, to minimize losses, it is important to find the best location and size.

3. the effect of Distributed generation on the investment cost:

When the distributed generation has access to the distributed network, if the installed area needs more power, distributed generation can supply electricity to reduce the investment cost of the network. However, if the electricity supply of the area is already sufficient, the distributed generation will not be completely utilized. This situation may waste cost and energy.

4. the effect of Distributed generation on network stability :

Voltage stability is the ability of a power system to return to normal or stable operation after a disturbance and to sustain acceptable voltage levels under normal operating conditions. On the other hand, Power system instability can be seen as a loss of synchronism. Voltage instability is caused by the mismatch between the reactive power generated and that consumed. Installing distributed generation can enhance the network's power quality. The voltage profile can be improved by properly allocating distributed generation, which means allowing voltages to be closer to the rated voltage to maximize system efficiency. When the load increases, installing distributed generation can supply power to the near loads, which makes the network more stable. However, the contribution of some distributed generations depends on the weather or environment. The sudden starts and stops of distributed generation may cause voltage fluctuations. Therefore, the system will be unstable.

5. The effect of DG on voltage profiles:

Many non-linear loads are connected to today's electric power networks. These include power electronic equipment, arc discharge devices, electronic control equipment by semiconductor devices, saturated magnetic devices, rotating machines, and residential loads with switch-mode power supplies such as computers. Harmonics can cause maloperation of control devices, additional losses in capacitors, transformers, transmission lines, and rotating machines, additional noise in motors, telephone interference, or causing parallel and series resonances [18]. With the DG access to the networks, power flow will be changed to bidirectional, thus, this power flow will cause voltage fluctuations. If the output power of DG can be adjusted following the load, the voltage fluctuations can be controlled. However, when the DG is intermittent or unstable, such as wind generation or solar generation, it is difficult to control the output power. This may also lead to affect the voltage fluctuation.

6. the effect of Distributed generation on the reliability of the system:

The placement of DG can affect the reliability of the system both positively and negatively depending on the distribution system and its characteristics [19]. Distributed generation can supply power to the near loads to increase reliability. However, if the penetration level of DG in the existing grid increases then this will cause a considerable effect on the performance parameter of the system. Besides, if the DG units work in autonomous mode, as a small-scale network, the consequences for power stability and quality are relied upon to be more sensational because of the unlucky deficiency of the grid support. DG diminishes losses and enhances voltage. With the right arrangement, distribution generation can likewise enhance consumer reliability and power quality [14]– [18].

1.3.4 DG allocation problem

ne of the most critical issues in distribution system planning is DGs allocation problem. This problem includes the determination of installation location, the capacity, and the technology of the DGs to be placed. In other words, DGs allocation problem aims to locate the appropriate type of DG with the optimal size at a suitable location on the network to achieve an objective function. Losses, power flow, voltage profile, and network reliability are all affected by Distributed generation. Therefore, the optimization of DG allocation is very important to improve the operational conditions of the distribution network. The objectives of the DG allocation problem can be minimization of distribution losses (active and/or reactive power), minimization of generation costs (DG installation, operation, and maintenance), system reliability improvement, or voltage profile improvement. Generally, the basic objectives of the DG allocation problem are loss reduction and voltage profile improvement.

1.3.5 Effect of size and location of DG on system loss

As it has been previously mentioned, the penetration of DGs into the distribution network affects system losses; improper sizing or locating of DG units causes higher losses compared to the case without DGs. However, an optimal allocation of DGs leads to reduce system losses. Figure 1.7 represents a three-dimension plot of power losses versus DG capacity for a 69-bus distribution and DG installation bus system [20].

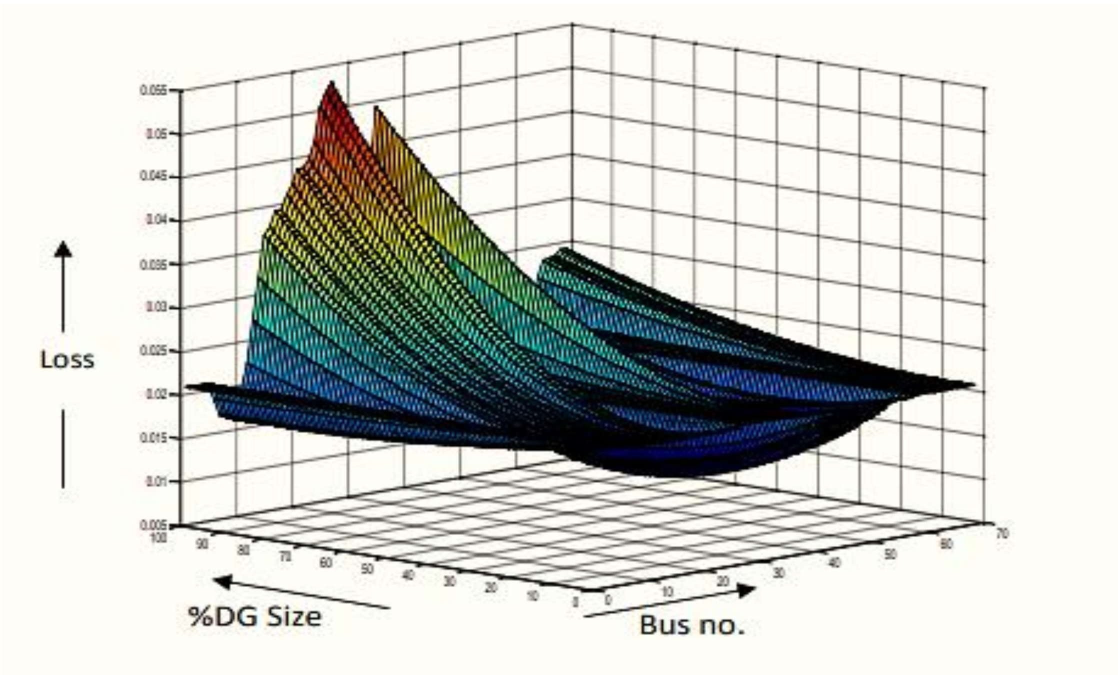


Figure 1.7 Effect of size and location of DG on system loss [20].

As revealed by the figure 1.7, first, as the size of the DG rises on a given bus, the loss drops until it reaches a minimum at a certain size (optimal size). Then, if the size of DG is further increased, the losses begin to rise and may exceed the losses in the basic system case (without DG). As can be seen in the same plot, the position of DG has also a crucial role in limiting losses. Changing the location of the DG leads to different loss values. For a specified DG size, there exists a bus number where the losses are at a minimum value. That is the optimal DG location for the scheduled size. Therefore, the penetration of DGs into a typical distribution system is constrained by DG capacity and its installation location. Leastwise, the size of DG should be kept at a minimum so that it does not increase electrical losses. Using high-capacity DG in inappropriate location may create excessive power flow through the lines, resulting in increased losses and probably protection failures. To overcome that, optimization techniques are used for DGs allocation problems.

1.3.6 Effect of DG on Voltage Stability and Methods of its determination

The impact of DG in the distribution system is to increasing the real power loading capacity of the system, which related to the voltage stability. Voltage stability is usually determined using P-V curves, Q-V curves, and stability indices such as the Index Vector Method (IVM), Voltage Stability Index (VSI) and Voltage Deviation Index (VDI) [21]. The voltage collapse initiates at the most sensitive bus and then it advances to other sensitive buses. The most sensitive bus will be one that exhibits one of the succeeding conditions [22]

1) Lowest reactive power margin.

2) Highest critical point.

3) Highest reactive power deficit.

4) Maximum percentage change in voltage.

The P-V curve method power is based on constant power factor while the real power at a bus is gradually increased. Then iterative power flow is performed until the point of voltage collapse (PoVC) is obtained. This is the critical point of the stability of the system. An overreach in load beyond the PoVC will results in a rapid voltage drop of the power system and, consequently, network collapse [23]. For the Q-V curve method, the variation of receiving end voltage with variation in load reactive power for different real power loads is represented in curves, the locus of the knee point in the curves is the critical stability point. The region to the right of the knee point is the stable region. The main disadvantages of these two methods are the requirement of repetitive load flow analysis and time-consuming [24]. As a result, new techniques are developed for voltage stability analysis that are faster. Especially for distribution systems that are broad and complex. These methods evaluate the stability of the system using stability indices.

The voltage stability index (VSI) gives the information for voltage stability of the radial distribution systems. The variation of this factor which indicating system voltage stability in presence and absence of DGs. VSI is used to identify the most sensitive bus to the voltage failure in the distribution networks. The VSI is defined as [25]

$$VSI(m2)=|V(m1)|^4-4\{P(m2)\,x(jj)-Q(m2)r(jj)\}^2-4\{P(m2)r(jj)+Q(m2)x(jj)\}|V(m1)|^2 \tag{1.1}$$

Where,
NB = total number of nodes.
jj = branch number.
VSI (m2) = voltage stability index of node m2 (m2 = 2, 3... NB).
r (jj) = resistance of branch jj.
x (jj) = reactance of branch jj.
V (m1) = voltage of node m1.
V (m2) = voltage of node m2.
P (m2) = real power load fed through node m2.
Q (m2) = reactive power load fed through node m2.

In order to attain the stable operation of the radial distribution system, the Voltage Stability Index (VSI) should be maximized. Buses with the lowest VSI values are more sensitive. The voltage collapse initiates at the most sensitive bus and then it advances to other sensitive buses [26].

1.4 Faults in distribution power system

1.4.1 Electrical Fault

A fault in an electric power system can be defined as any failure that interferes with the normal flow of current that causes the deviation of voltages and currents from nominal values. Under normal or safe operating conditions, the electric power system operates under normal voltage and current ratings. However, when a fault occurs in the network, voltage and current values deviates from their nominal ranges. In other words, electrical fault is any abnormal condition of the system. It can be caused by equipment failures such as transformers, rotating machines, bus bars, etc. In addition, human errors, and environmental conditions including lighting, wind, tree falling on lines may contribute in the appearance of electrical faults. Any fault in the power system result in over current, under voltage, unbalance of the phases, reversed power and high voltage surges. Therefore, the interruption of the electric service, equipment damages, severe economic losses and reduce system reliability.

1.4.2 Classification of power system faults

Faults in three-phase power systems are classified into two categories, open and short circuit faults. Furthermore, these faults can be symmetrical or unsymmetrical faults as illustrated by figure 1.8.

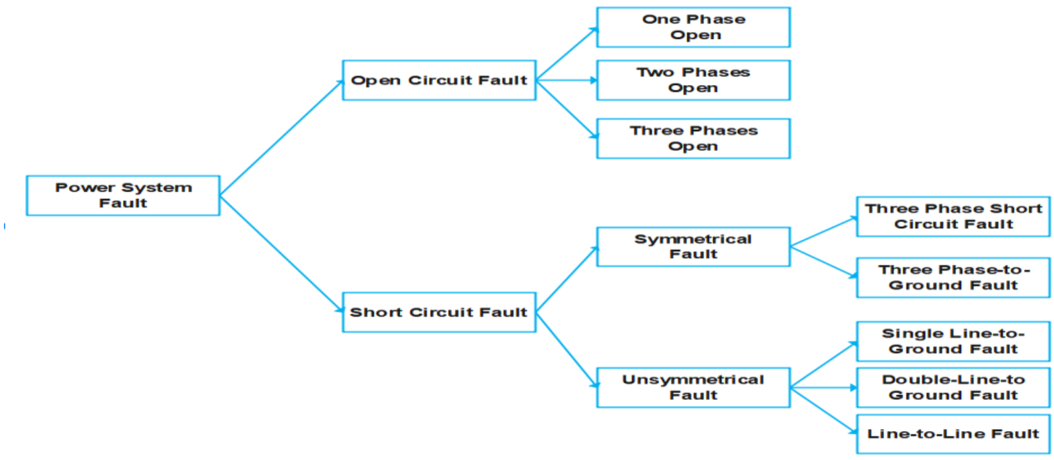


Figure 1.8 Classification of power system faults.

1.4.2.1 Open circuit faults

Figure 1.9 illustrates the open circuit faults for single, two and three phases (or conductors) open condition.

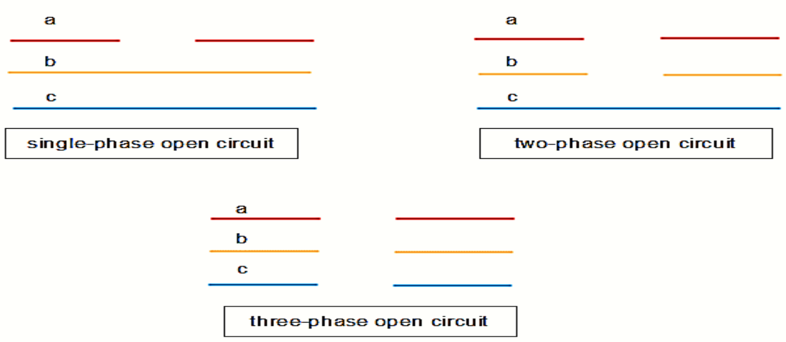


Figure 1.9 Open circuit faults.

The most common causes of these faults involve failure of circuit breaker in single phase or more, melting of a fuse or phase conductor, and combined failures of conductors, cables and overhead lines. Consider that an electric power system with a balanced load is under normal conditions before the occurrence of open circuit fault. If one of phase conductor is melted, the actual loading of the alternator is reduced and this cause the acceleration of the alternator, thus, its speed overreaches the synchronous speed, which causes over voltages in other transmission lines. Thus, single and two-phase open circuit faults result in abnormal operation of the system. In addition, it may causes death (to humans as well as animals) and damages in electric equipment.

1.4.2.2 Short circuit Faults

A short circuit fault can be defined as, an abnormal connection of extremely low impedance between two points with different voltages. It occurs because of insulation failure between phase conductors and the ground. These faults are the most common types that result in the flow of high current through transmission lines or equipment. If short circuit faults are not cleared within a short time, then it leads to equipment damage. Short circuit faults are also known as shunt faults.

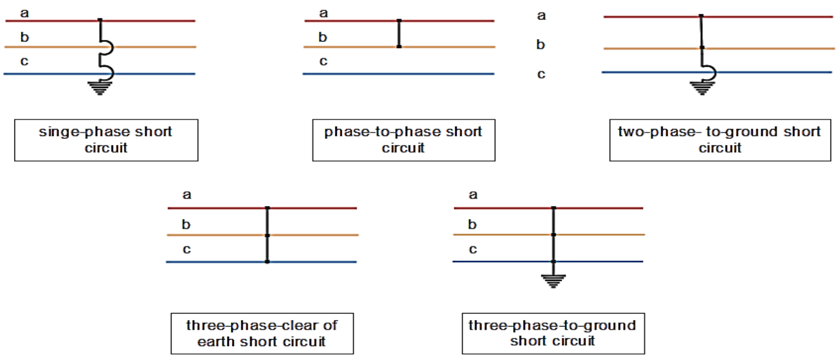


Figure 1.10 Short circuit faults.

Short circuit faults may be due to internal or external effects. Internal effects include breakdown of transmission lines or equipment, aging of insulation, deterioration of insulation in generators, transformers, and other electrical equipment, improper installations, and inadequate design. External effects include overloading of equipment, insulation failure due to lighting surges, and mechanical damage by the public. Arcing faults can lead to fire and explosion in equipment such as transformers and circuit breakers. In addition, the fault current causes the overheating of the equipment, which further leads to reducing the life span of their insulation. Moreover, short circuit faults can cause voltage fluctuations that create harmful effects on the service rendered by the power system.

1.4.3 Symmetrical and Unsymmetrical Faults

As discussed above, faults are mainly classified into open and short circuit faults and again these can be symmetrical or unsymmetrical faults.

1.4.3.1 Symmetrical Faults

A symmetrical fault gives rise to symmetrical fault currents that are phase-shifted by 120 degree from each other. Symmetrical fault is also called as balanced fault. This fault occurs when all the three phases are simultaneously short-circuited. These faults rarely occur in practice as compared with unsymmetrical faults. Three-phase faults and three-phase-to-ground faults are included in this category. The occurrence of symmetrical faults is in the range of 2 to 5% of the total system faults. However, if this type causes huge damage to the equipment even though the system remains in balanced condition.

1.4.3.2 Unsymmetrical Faults

The most common faults that occur in the power system network are unsymmetrical faults. This type of fault gives rise to unsymmetrical fault currents (having different magnitudes with unequal phase displacement). These faults are also called unbalanced faults as it causes unbalanced currents in the system. Both open circuit faults (single and two phases open condition) and short circuit faults (excluding three-phase faults) are included in this category. Single line-to-ground (LG) faults are the most common faults since that 70-80 percent of the faults that occur in power systems are of this type. This forms a short circuit path between the line and the ground. Although this type has the highest occurrence percentage, it is the least severe compared to the other types of faults. A line-to-line fault occur when a live conductor gets in contact with another live conductor. Heavy winds are the major cause of this fault during which swinging of overhead conductors may touch together. These are less severe faults and their occurrence range may be between 15-20%.In double-line-to-ground faults, two lines come into the contact with each other as well as with the ground. These are severe faults and the occurrence of these faults is about 10% when compared with total system faults.

Table 1-1 Faults type and percentage of occurrence

Fault	Percentage of occurrence	type
Single line-to-ground (L-G)	60-75%	Unsymmetrical
Line-to-line (L-L)	5-15%	Unsymmetrical
Double line-to-ground(L-L-G)	15-25%	Unsymmetrical
Three-phase	<5%	Symmetrical

1.4.4 System protection

When the fault occurs in any part of the system, it must be cleared in a very short period in order to avoid greater damage to equipment and the interruption of power to the customers. The fault clearing system uses various protection devices .Some of the protective devices directly connected to the circuits are called switchgear. They include instrument transformers, circuit breakers; disconnect switches, fuses and lightning arresters. These devices arc necessary to deenergize either for normal operation or on the occurrence of faults. The associated control equipment and protective relays are placed on switchgear in control houses [27]. Protective relays include impedance relays, directional relays, differential relays and pilot relays. The detection of the fault location has a critical role in electric protection since the fault must be cleared as fast as possible.

1.4.5 Fault analysis

In Power System, during Normal Operation, load flow analysis allows to plan for safe operation and future growth of the power system. On the other hand, for abnormal operation, Fault analysis is necessary to select, design and coordinate suitable switchgear equipment, electromechanical relays, circuit breakers, and other protection devices. For balanced faults (three-phase faults), Per-phase analyses can be used. However, for unbalanced faults (L-to-G, L-L, L-L-to-G faults) sequence networks analyses is used. In other words, for balanced faults the positive sequence network is used to compute circulating currents and voltages whereas unbalanced fault analysis is the extension of balanced fault analysis to the sequence networks (negative and zero sequences) but at the fault location.

1.4.5.1 Fault analysis using Z bus

Let Z_{bus}(n×n matrix), the impedance matrix formed using the per-phase equivalent network of a balanced three-phase system of n buses. For three-phase fault at bus k, the nodal impedance equations of the network in the Z_{bus} matrix form is given by

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ . \\ . \\ . \\ \Delta V_k \\ . \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ . \\ . \\ . \\ -V_f \\ . \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} Z_{11}\, Z_{12} \,.\,.\,.\,.\,.\, Z_{1n} \\ Z_{21}\, Z_{22} \,.\,.\,.\,.\,.\, Z_{2n} \\ Z_{31}\, Z_{32} \,.\,.\,.\,.\,.\, Z_{3n} \\ .\,.\,.\,.\,.\,.\,.\,.\,.\,.\,. \\ .\,.\,.\,.\,.\,.\,.\,.\,.\,.\,. \\ .\,.\,.\,.\,.\,.\,.\,.\,.\,.\,. \\ Z_{k1}\, Z_{k2} \,.\,.\,.\,.\,.\, Z_{kn} \\ .\,.\,.\,.\,.\,.\,.\,.\,.\,.\,. \\ Z_{n1}\, Z_{n2} \,.\,.\,.\,.\,.\, Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ . \\ . \\ . \\ -I_f'' \\ 0 \\ 0 \end{bmatrix} \tag{1.2}$$

Where,

V_f is the pre-fault voltage at bus k.

- I_f'' branch current injected into bus k by the fault (fault current).

ΔV_n is the voltage change at bus n due to current $-I_f''$.

Thus, the changes in bus voltages due to - I_f'' are given by

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ . \\ . \\ . \\ \Delta V_k \\ . \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ . \\ . \\ . \\ -V_f \\ . \\ \Delta V_n \end{bmatrix} = -I_f'' \begin{bmatrix} column\ k \\ of \\ Z_{bus} \end{bmatrix} = \begin{bmatrix} -Z_{1k} I_f'' \\ -Z_{2k} I_f'' \\ -Z_{3k} I_f'' \\ . \\ . \\ . \\ -Z_{kk} I_f'' \\ . \\ -Z_{nk} I_f'' \end{bmatrix} \tag{1.3}$$

From the row number k of equation (1.3) we have

$$I_f'' = \frac{V_f}{Z_{kk}} \tag{1.4}$$

Substituting the expression for I_f'' into equation (1.3) gives

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ . \\ . \\ . \\ \Delta V_k \\ . \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} \frac{-Z_{1k}}{Z_{kk}} V_f \\ \frac{-Z_{2k}}{Z_{kk}} V_f \\ \frac{-Z_{3k}}{Z_{kk}} V_f \\ . \\ . \\ . \\ -V_f \\ . \\ \frac{-Z_{nk}}{Z_{kk}} V_f \end{bmatrix} \tag{1.5}$$

Neglecting pre-fault load currents and assuming that all the buses of the network have pre-fault voltages equal to V_f.By applying the principle of superposition, these pre-fault voltages add to the voltage deviations given by the last equation to obtain the bus voltages after the occurrence of the fault.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ . \\ . \\ . \\ V_k \\ . \\ V_n \end{bmatrix} = \begin{bmatrix} V_f \\ V_f \\ V_f \\ . \\ . \\ . \\ V_f \\ . \\ V_f \end{bmatrix} + \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ . \\ . \\ . \\ \Delta V_k \\ . \\ \Delta V_n \end{bmatrix} = V_f \begin{bmatrix} 1 - \frac{Z_{1k}}{Z_{kk}} \\ 1 - \frac{Z_{2k}}{Z_{kk}} \\ 1 - \frac{Z_{3k}}{Z_{kk}} \\ . \\ . \\ . \\ 0 \\ . \\ 1 - \frac{Z_{nk}}{Z_{kk}} \end{bmatrix} \tag{1.6}$$

Thus, the voltages at all buses of the network can be calculated using the pre-fault voltage V_f of the fault bus and the elements in the column of Z_{bus} corresponding to the fault bus.

For three-phase fault at bus k with pre-fault voltage $V_{f,}$ the bus voltage at any bus j after the fault is given by

$$V_j = V_f - Z_{jk} I_f'' = V_f - \frac{Z_{jk}}{Z_{kk}} V_f \tag{1.7}$$

Where $Z_{jk}$and Z_{kk} are elements in column k of the system Z_{bus}. If the prefault voltage of bus j is not the same as the pre-fault voltage of fault bus k, then V_f on the left in Eq is replaced by the actual prefault voltage of bus j. Knowing the bus voltages during the fault, the sub-transient current from bus I to bus j in the line of impedance Z_b connecting those two buses,

$$I_{ij}'' = \frac{V_i - V_j}{Z_b} = -I_f'' \left(\frac{Z_{ik} - Z_{jk}}{Z_b}\right) = -\frac{V_f}{Z_b}\left(\frac{Z_{ik} - Z_{jk}}{Z_{kk}}\right) \tag{1.8}$$

This equation shows I_{ij}'' as the fraction of the fault current I_f'' appearing as a line flow from bus i to bus j in the faulted network. If bus j is directly connected to the faulted bus k by a line of series impedance Z_b , then the current contributed from bus j to the current in the fault at bus k is simply V_j/Z_b where V_j is given by Equation 1.7 [28].

1.4.5.2 Sequence networks analyses

The equivalent symmetrical sequence network is used for unbalanced faults analysis. Where the three-phase unbalanced power system is transformed into its equivalent sequence networks based on symmetrical components: Zero-sequence components, Positive –sequence components, and Negative –sequence components using symmetrical component transformation matrix C.

$$C = \frac{1}{3} . \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{1.9}$$

Where $a = e^{j\frac{2\pi}{3}}$

The sum of the three symmetrical components is equal to the original Power system. Unsymmetrical faults unbalance the power system but only at the fault location. This causes a coupling of the sequence networks. The sequence networks are coupled at the point of fault depending upon the fault type. Therefore, sequence networks are first established then used to compute the fault current I_{a012}.

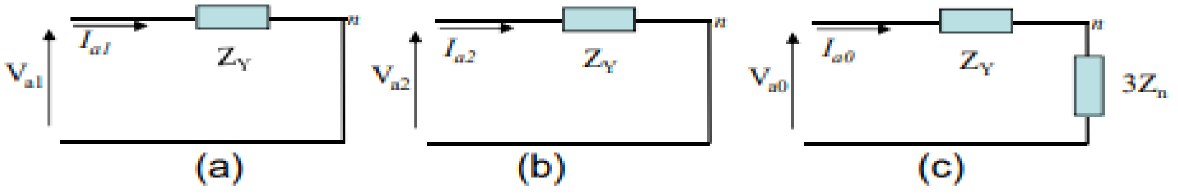


Figure 1.11 Thevenin equivalent sequence circuits of PS before fault

(a) positive, (b) negative and (c) zero sequence.

After calculating the fault current using symmetrical components, the actual fault current is obtained using the inverse symmetrical component transformation.

$$I_{abc} = C.I_{a012} \tag{1.10}$$

Where,

I_{abc} unbalanced current phasors.

C symmetrical component transformation matrix.

I_{a012} symmetrical components of the unbalanced current phasors.

Single Line-to-Ground fault

The sequence network connection for single line-to-ground fault at bus k with fault impedance Z_f is represented in figure 1.12

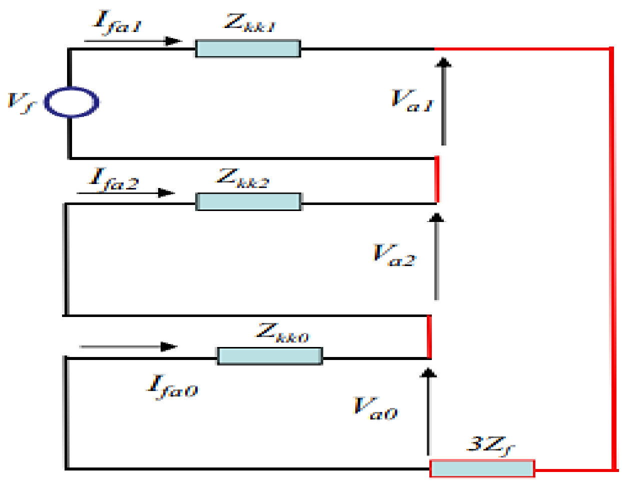


Figure 1.12 Sequence network connection for single line-to-ground

The sequences of fault current are given by equation (1.11) and equation (1.12).

$$I_{fa0} = \frac{V_k(0)}{Z_{kk1}+Z_{kk2}+Z_{kko}+3Z_f} \tag{1.11}$$

$$I_{fa2} = I_{fa1} = I_{fa0} \tag{1.12}$$

Line-to-Line fault

For line-to-line fault at bus k, assume that phases b and c were shorted through an impedance Z_f. The sequence network connection is given by figure 1.13.

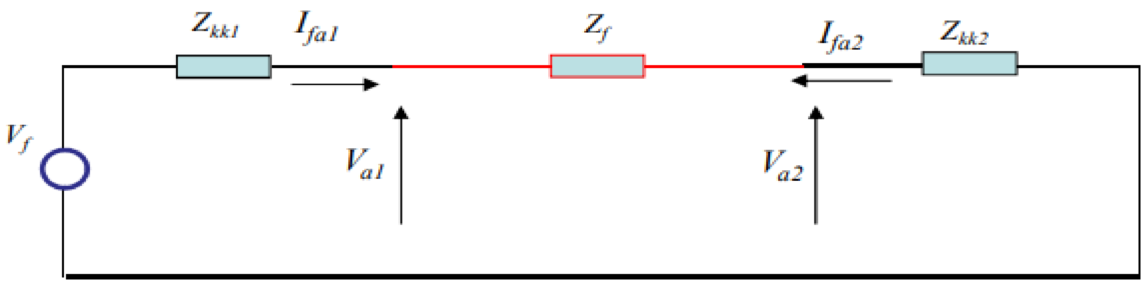


Figure 1.13 Sequence network connection for Line-to-Line fault

The sequences of fault current are given by equation (1.13) and equation (1.14).

$$I_{fa1} = \frac{V_k(0)}{Z_{kk1}+Z_{kk2}+Z_f} \tag{1.13}$$

$$I_{fa0} = 0 \text{ , } I_{fa1} = -I_{fa2} \tag{1.14}$$

Double Line-to-Ground fault

The Thevenin equivalent of sequence circuits connection for Double line-to-Ground fault at bus k with fault impedance Z_f is represented in figure 1.14. The positive-sequence in series with the parallel combination of negative- sequence and zero-sequence network.

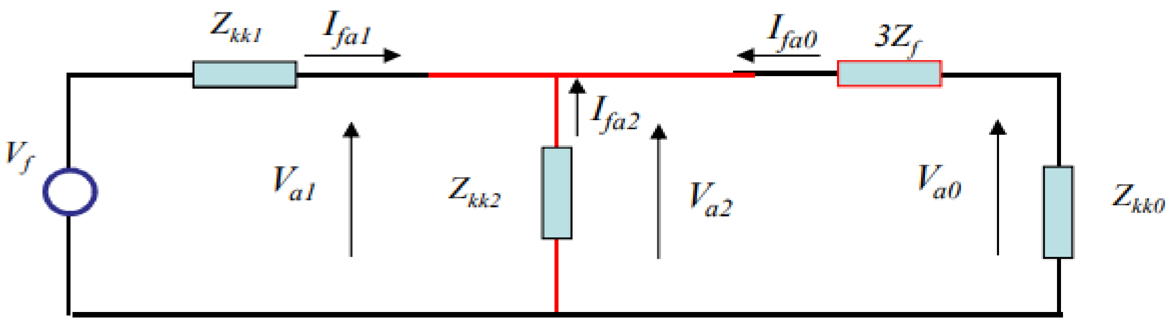


Figure 1.14 Sequence network connection for Double Line-to-Ground fault

The sequences of fault current are given by:

$$I_{fa1} = V_k(0)\left(\frac{\mathbf{1}}{Z_{kk1}+\frac{Z_{kk2}(Z_{kk0}+3Z_f)}{Z_{kk1}+Z_{kk0}+3Z_f}}\right) \tag{1.15}$$

$$I_{fa2} = -\frac{V_k(0)-Z_{kk1}\, I_{fa1}}{Z_{kk2}} \tag{1.16}$$

$$I_{fa0} = -\frac{V_k(0)-Z_{kk1}\, I_{fa1}}{Z_{kk0}+3Z_f} \tag{1.17}$$

1.4.6 Fault location detection

The detection of the fault location has a critical role in power system protection. The higher the accuracy of fault detection and determination of its location, the easier it is to control damages due to these faults and the faster the service is restored. Rapid restoration of service could reduce customer complaints, outage time, loss of revenue, and crew repair expense [29]. Different methods are presented for fault location in power distribution networks. These methods have two stages. In the first stage, the fault distance is determined and in the second stage, the fault section is estimated [30]. All the existing fault locator systems are based on impedance method, travelling wave, or knowledge-based methods that uses some optimization algorithms.

1. Impedance based locators:

Impedance based locators are used to locate the distance of fault from primary supply to the fault location by measuring current and voltages using one-end or two-end locators. These values are then fed to the mathematical equations for estimation of fault location. Implementation of these methods is very simple are cheap, but they have some problems such as sensitivity to fault resistance and multiple-solution [1, 4].

2. Travelling wave based locators:

Traveling wave-based fault location methods can be divided into two-terminal and one-terminal. With traveling wave analysis, however, one-terminal methods rely on the timing between reflections of voltage or current at impedance discontinuities – in this case, the fault – to find the distance between the sensor and the fault while two-terminal methods work based on the time delay between arrivals of information at the ends of the transmission line. The most important problem with the methods based on traveling waves is their requirement to use metering devices with extremely high sampling rate.

3. Knowledge based locators:

Knowledge based methods are used to reduce the time taken by impedance based locators by pre-calculating the set of data and matching it the current impedance. The area of knowledge based approaches falls under soft computing. Many artificial intelligence methods are used to compute the fault location, which includes different optimization algorithms. In soft computing the restrictions are looser and the possibilities to find complex correlations higher but the accuracy and certainty comes with a cost, which result in a trade of between precision and uncertainty.

1.5 Smart meter

Smart meters are smart sensors installed across the distribution system. Generally, smart meters are located in the low voltage side of the network to periodically record the quantity of the network for the vast majority of applications, such as energy management, demand response, prediction application, load forecasting, and fault location procedure. SMs can record the active and reactive power of each consumer, including industrial clients, and residential and commercial buildings [31]. In addition to electronic measurement, smart meters are employed to remotely communicate information for billing customers and operating their electric systems. These meters can take the reading and send the information in two-way communication. Smart meters were developed to meet the Advanced Meter Infrastructure, which is commonly known as AMI. It is capable of detecting power outages and monitoring voltage profiles for the control office. Of these types of devices, we can name digital protective relays, digital fault recorders, smart meters, and power quality meters.

Conclusion

The distribution system is the most critical part of any electrical system. Improving the characteristics of the distribution system, mainly the power losses, and the stability of the system is the most important issue in employing distribution system. In addition, fault detection is another challenge for researchers and new method based on the measurements of Smart meters are in research phase.

Chapter 2: Backward/Forward load flow method

Introduction

Power flow is an important process for determining power system parameters such as real power, reactive power, bus voltages, power angle, and line losses. It is a basic tool in the field of power system engineering, used both in planning and operational stages. Various methods for solving the load flow problem were developed such as Newton method and fast decoupled method. These known as classical methods. However, for solving load flow problem in distribution systems these methods may become difficult and inefficient. Therefore, researchers have developed new load flow methods for distribution system. One of these methods is the Backward/Forward load flow. This chapter outlines the power flow equations and Backward/Forward power flow method for distribution system and provides a brief discussion of Breadth First Search method and its applications.

Power flow problem

The power-flow problem is the computation of voltage magnitude and phase angle at each bus in a power system under balanced three-phase steady-state conditions. Therefore, real and reactive power flows can be determined in addition to power losses. The equivalent single-line diagram of the power system is adequate to obtain the input data for power flow. Input data consist of bus data, transmission line data, and transformer data. For each bus, four quantities are Associated: the real and reactive power, the voltage magnitude and the phase angle. Three types of buses are represented in the load flow calculation: load buses (PQ buses), voltage controlled buses (PV buses), and a slack bus. Where for each type of buses, two of the four quantities are specified and the two others are to be determined using load flow analysis.

2.1 Power flow equations

Consider Figure 2.1 that shows two buses of a distribution line.

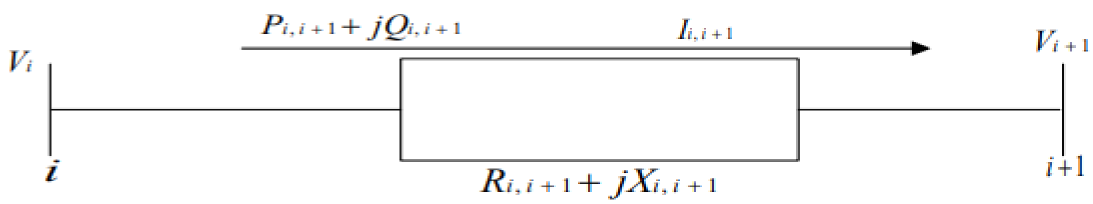


Figure 2.1 single line diagram of two buses in distribution network

The power flow equations in the branch $i, i+1$ are given by equation (2.1) and equation (2.2)

$$P_{i,i+1} = P_{i+1} - \left(R_{i,i+1} \frac{P_{i,i+1}^2 + Q_{i,i+1}^2}{|V_i|^2}\right) \tag{2.1}$$

$$Q_{i,i+1} = Q_{i+1} - \left(X_{i,i+1} \frac{P_{i,i+1}^2 + Q_{i,i+1}^2}{|V_i|^2}\right) \tag{2.2}$$

Where,

$P_{i,i+1}$ and $Q_{i,i+1}$ are real and reactive power at node $i+1$.

$V_i \angle\delta_i$ is the voltage at the node i.

$V_{i+1} \angle\delta_{i+1}$ is the voltage at the node $i+1$.

$R_{i,i+1}$ and $X_{i,i+1}$ are the resistance and the reactance of the line between node i and $i+1$ respectively.

The branch current is given by

$$I_{i,i+1} = \frac{V_i \angle\delta_i - V_{i+1} \angle\delta_{i+1}}{R_{i,i+1} + jX_{i,i+1}} \tag{2.3}$$

$$I_{i,i+1} = \frac{P_{i,i+1} - jQ_{i,i+1}}{V_i \angle -\delta_i} \tag{2.4}$$

By equating equation (2.3) and (2.4), equation (2.5) is obtained

$$V_i^2 - V_i V_{i+1} \angle\delta_{i+1} - \delta_i = \left(P_{i,i+1} - jQ_{i,i+1}\right)\left(R_{i,i+1} + jX_{i,i+1}\right) \tag{2.5}$$

Equating real and imaginary parts on both sides of equation (2.5), we obtain equations (2.6) and (2.7)

$$V_i^2 - V_i V_{i+1} \cos(\delta_{i+1} - \delta_i) = P_{i,i+1} R_{i,i+1} + Q_{i,i+1} X_{i,i+1} \tag{2.6}$$

$$V_i V_{i+1} \sin(\delta_{i+1} - \delta_i) = P_{i,i+1} X_{i,i+1} + Q_{i,i+1} R_{i,i+1} \tag{2.7}$$

Squaring and adding equations (2.6) and (2.7), we obtain equation (2.8):

$$V_{i+1}^2 = V_i^2 - 2\left(P_{i,i+1} R_{i,i+1} + Q_{i,i+1} X_{i,i+1}\right) + \frac{\left(P_{i,i+1} R_{i,i+1} + Q_{i,i+1} X_{i,i+1}\right)^2}{V_i^2} \tag{2.8}$$

Equations (2.1), (2.2), and (2.8) are the power flow equations.

For a power system with N buses the power flow equations for bus k are given by equation (2.9)

$$S_k^* = P_k - j.Q_k = V_k^*.\sum_{n=1}^{N} Y_{kn}.V_n \tag{2.9}$$

Where,

S_k, P_k, Q_k are the apparent, real and reactive powers at bus k respectively.

N is the bus number $n = 1 \dots \dots \dots N$

V_n is the voltage at bus n.

Y_{kn} is the element number kn of the system admittance matrix.

Knowing that,

$$V_n = V_n \,.\, e^{j\delta_n} \ , \ Y_{kn} = Y_{kn} . e^{j\Theta_{kn}} \tag{2.10}$$

Where,

δ_n and Θ_{kn} are phase and admittance angles respectively in rad.

V_n and Y_{kn} are voltage and admittance magnitudes respectively in p.u.

Therefore:

$$P_k - j.Q_k = V_k \,.\, e^{-j\delta_k} . \sum_{n=1}^{N} Y_{kn} . V_n \,.\, e^{j(\delta_n + \Theta_{kn})}, n = 1. \dots \dots \ N \tag{2.11}$$

Resolving into real and imaginary parts, the power flow equations are obtained:

$$P_k = \sum_{n=1}^{N} V_k \,.\, V_n . Y_{kn} \ \cos(\Theta_{kn} + \delta_n - \delta_k), k = 1 \dots \dots . . N \tag{2.12}$$

$$Q_k = -\sum_{n=1}^{N} V_k \,.\, V_n . Y_{kn} \ \sin(\Theta_{kn} + \delta_n - \delta_k), k = 1 \dots . . N \tag{2.13}$$

2.2 Load flow for distribution system

The review of power flow methods used to analyze distribution systems revealed that conventional power flow methods show convergence problem in solving such networks. These methods are inefficient even for the converged cases, in respect of storage requirements and number of iterations. Therefore, Special power flow methods have been developed over the years to fit the unique characteristics of distribution networks including high R/X ratio feeders, vast radial structure. These methods come under the category of Distribution System Load Flow (DSLF) methods. They provide efficient and simple load flow for radially configured networks than the traditional Gauss Seidel and Newton-Raphson methods. DSLF methods also include many modified versions of the traditional Newton method and its fast decoupled versions suitable for distribution system analysis. In recent years, the penetration of distributed generators into the distribution system has made the distribution network and the DSLF methods more complex than its earlier versions. In addition, The evolution of the present day three-phase unbalanced distribution load flow with multiple feeding sources, the tendency towards DG has gradually led the researchers to develop the so-called control functions, which perform online predefined tasks either in emergency or in normal conditions. These application programs require robust and efficient load flow solution methods incorporating a detailed modeling of the special features of distribution systems. Radial distribution systems are inherently unbalanced owing to factors such as the occurrence of asymmetrical line spacing, combinations of single, double and three-phase line sections and the imbalance of customer loads. Hence, solution methods based on the assumption of balanced loading are not applicable. The load flow methods proposed for the distribution systems considering the unbalance operation can be grouped into two basic categories. The first category includes Backward /Forward Sweep (B/FS) Ladder Network based methods and Implicit Zbus Gauss method, or modified versions. The other class is composed of methods, which require information on the derivatives of the network equations. Newton like methods involving formation of Jacobian matrix, and computation of power mismatches at the end of the feeder and laterals, and other fast decoupled methods, tailored specially for distribution systems, come under the second category [32].

2.3 Backward/Forward based distribution load flow method

This method has been represented in [3] , where it has been shown that, typically, only a few iterations were required for the solution of distribution networks using Backward/Forward sweep (B/FS) power flow solution technique. It is also revealed that in all the cases studied this power flow technique was significantly more efficient than the Newton-Raphson power flow algorithm while converging to the same solution. this method is simple since the Jacobian Matrix is not required, fast because the convergence of the solution is achieved rapidly, and robust. The general algorithm consists of two basic iterative steps, namely forward sweep and backward sweep. Forward sweep is mainly a voltage drop calculation from the sending end to the far end of a feeder. In addition, power flow and nodal voltages are updated in a forward direction. The backward sweep consists of starting the calculations from the far end of the feeder and moving back along the network to the sending end of the feeder. Each backward iteration is started with an estimation of the ending bus voltages. Then, a reverse trace is performed for determining the bus voltages across the network leading to a calculated value of the source voltage. New estimates for the ending bus voltages are determined based on the mismatch between the calculated and specified source voltages. Iterations are continued until the specified source voltage is obtained by calculation within a required accuracy.

The forward and backward sweep method has three variants determined by the quantity calculated during each iteration in the backward sweep. These include:

1. The current summation method, where the branch currents are evaluated.

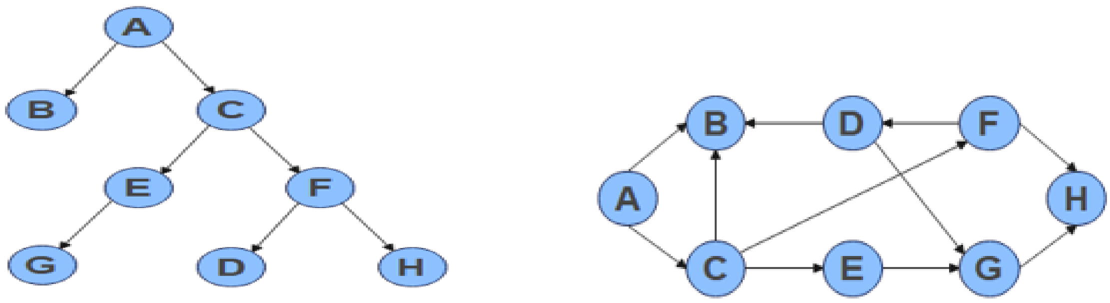
2. The power summation method, where the power flow in the branches is evaluated.

3. The admittance summation method where, node by node, the driving point admittances are evaluated.

In the algorithm provided by [3], regardless of the original topology of the system, the distribution network is first converted to a radial network. This can be done using breadth-first search (BFS) algorithm. Then, the Backward/Forward sweep load flow method is applied to the radial distribution network based on the direct application of the KVL and KCL.

2.4 Breadth First Search method (BFS)

In graph theory, breadth-first search (BFS) is a graph search algorithm. Starting by meshed network structure, the BFS algorithm transforms the structure of the network into tree structure (radial). The algorithm begins at the root node and explores all the neighboring nodes. Then for each of those nearest nodes, it explores their unexplored neighbor nodes, and so on. A simple example of BFS method is represented in figure 2.2.



(a)

Figure 2.2 (a) original network, (b) the resulted network after using BFS algorithm.

BFS is a uniformed search method that aims to expand and examine all nodes of a graph systematically in search of a solution. In other words, it exhaustively searches the entire graph without considering the goal until it finds it. It does not use a heuristic. This graph theory algorithm can be used to convert the original topology of the distribution system into radial topology [3].

2.5 Solution methodology

Given the voltage at the root node and assuming a flat profile for the initial voltages at all other nodes, the iterative solution algorithm consists of three steps:

2.5.1 Nodal current calculation

At iteration k, the nodal current injection, $I_i^{(k)}$, at a network node i is calculated as,

$$I_i^{(k)} = \left(S_i/V_i^{(k-1)}\right)^* - Y_i V_i^{(k-1)} \qquad i = 1,2, \dots \dots, n \tag{2.14}$$

Where,

$V_i^{(k-1)}$ is the voltage at node i calculated during the $(k-1)^{th}$ iteration

S_i is the specified power injection at node i

Y_i is the sum of all the shunt elements at the node i

2.5.2 Backward sweep

At iteration k, starting from the branches in the last layer and moving towards the branches connected to the root node, the current in branch L, $J_L^{(k)}$, is calculated as

$$J_L^{(k)} = -I_{i+1}^{(k)} + \textstyle\sum_1^n J_n \quad , L = b, b-1, \dots \dots, 1 \tag{2.15}$$

Where,

J_n are currents in branches emanating from node $i+1$

$I_{i+1}^{(k)}$ is the current injection at the node $i+1$

b is the number of branches

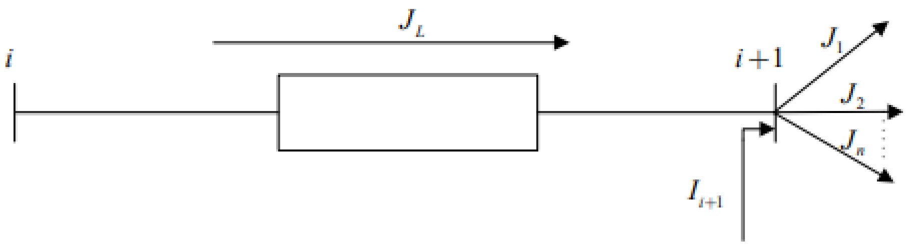


Figure 2.3 Branch and node currents in two-bus system

This is the direct application of the KCL.

2.5.3 Forward sweep

Nodal voltages are updated in a forward sweep starting from branches in the first layer toward those in the last. For each branch, L, the voltage at node L2 is calculated using the updated voltage at node L1 and the branch current calculated in the preceding backward sweep.

$$V_{i+1}^{(k)} = V_i^{(k)} - Z_L J_L^{(k)} , L = 1,2, \dots, b \tag{2.16}$$

Where, Z_L is the series impedance of branch L. This is the direct application of the KVL.

The three steps are repeated until convergence is achieved.

2.6 Convergence criterion

We used the maximum real and reactive power mismatches at the network nodes as our convergence criterion. As described in the solution method, the nodal current injections, at iteration k, are calculated using the scheduled nodal power injections and node voltages from the previous iteration. The node voltages at the same iteration are then calculated using these nodal current injections. Here, the power injection for node i at k^{th} iteration, $S_i^{(k)}$ is calculated as

$$S_i^{(k)} = V_i^{(k)}\left(I_i^{(k)}\right)^* - Y_i\left|V_i^{(k)}\right|^2 \tag{2.17}$$

The real and reactive power mismatches at bus i are then calculated as

$$\Delta \mathrm{P}_i^{(k)} = Re\left[S_i^{(k)} - S_i\right] \tag{2.18}$$

$$\Delta \mathrm{Q}_i^{(k)} = Im\left[S_i^{(k)} - S_i\right] \quad , i = 1,2, \dots \dots \dots \dots ., n \tag{2.19}$$

2.7 Algorithm for Backward/Forward Sweep load flow method

Step 1: Read power system data (the number of buses, the number of lines, slack bus, base kV, base kVA, bus data and line data).

Step 2: Starting from the root node, number the nodes and branches in the network by using Breadth First Search method and Branch Numbering Scheme respectively.

Step 3: Calculate the injected powers.

$$P_{inj}^{(i)} = P_{gen}^{(i)} - P_{load}^{(i)} \tag{2.20}$$

$$Q_{inj}^{(i)} = Q_{gen}^{(i)} - Q_{load}^{(i)} \quad , i = 1,2, \dots \dots , n \tag{2.21}$$

Step 4: Set iteration count, k=1.

Step 5: Set convergence $\epsilon = 0.001$, ΔPmax=0 and ΔQmax= 0.

Step 6: Calculate nodal current injection at network node 'i' as

$$I_i^{(k)} \; = \; \left(S_i / V_i^{(k-1)}\right)^* - Y_i V_i^{(k-1)} \quad , i = 1,2, \dots , n \tag{2.22}$$

Step 7: Backward sweep: Calculate current in the branch L as

$$J_L^{(k)} = -I_{i+1}^{(k)} + \textstyle\sum_1^n J_n \;\; , L = b, b-1 \,, \dots ., 1 \tag{2.23}$$

Step 8: Forward sweep: Calculate the voltage at node i+1

$$V_{i+1}^{(k)} = V_i^{(k)} - Z_L J_L^{(k)} \quad , L = 1,2, \dots ., b \tag{2.24}$$

Step 9: Calculate the power injection at node i as

$$S_i^{(k)} = V_i^{(k)}\left(I_i^{(k)}\right)^* - Y_i\left|V_i^{(k)}\right|^2 \tag{2.25}$$

Step 10: Calculate real and reactive power mismatches as

$$\Delta P_i^{(k)} = Re\left[S_i^{(k)} - S_i\right] \tag{2.26}$$

$$\Delta Q_i^{(k)} = Im\left[S_i^{(k)} - S_i\right] \qquad i = 1,2, \dots, n \tag{2.27}$$

Step 11: Check

$\Delta P_i^{(k)} > \Delta Pmax$, then set $\Delta Pmax$=$\Delta P_i^{(k)}$

$\Delta Q_i^{(k)} > \Delta Qmax$, then set $\Delta Qmax$= $\Delta Q_i^{(k)}$

Step 12: If $\Delta Pmax \ <= \ \epsilon$ and $\Delta Qmax \ <= \ \epsilon$, then go to step 14 Else go to step 13

Step 13: Set $k = k + 1$ and go to step 4.

Step 14: Print the number of iterations k and the power flow solution.

Step 15: Stop

2.8 Flowchart of Backward/Forward sweep method

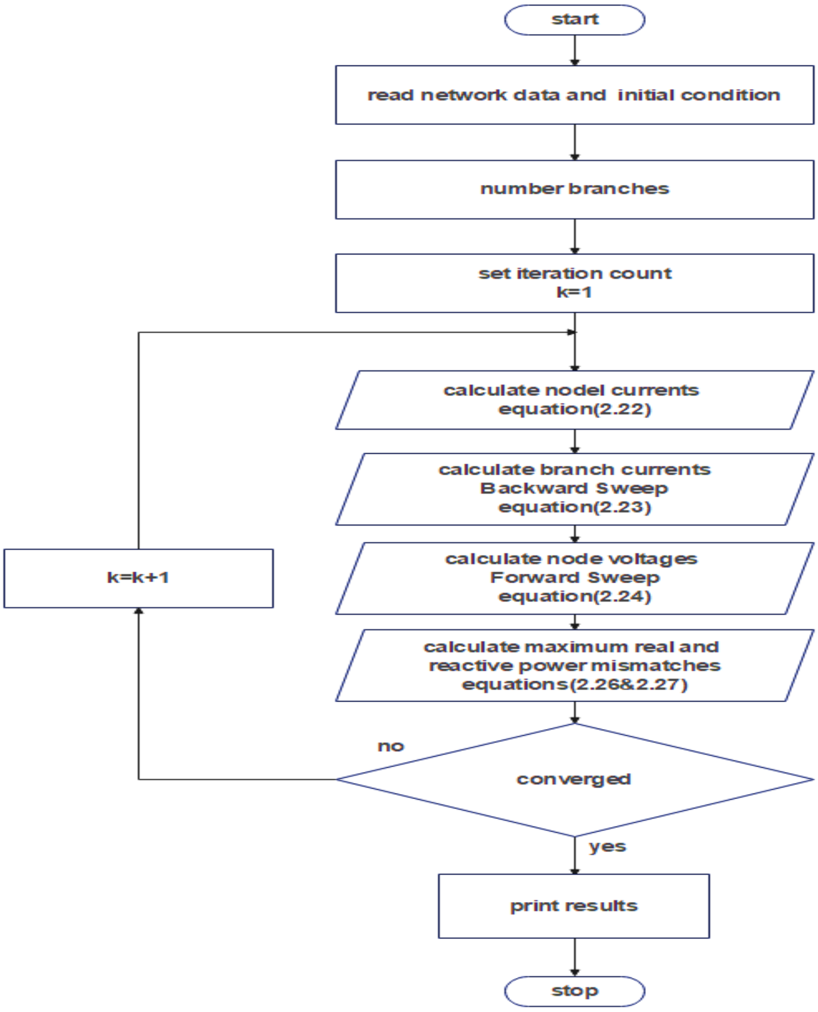


Figure 2.4 Flowchart of Backward/Forward load flow method.

Conclusion

Conventional power flow methods such as Newton Based methods and fast decoupled method require modification to adapt the unique characteristics of distribution, including high R/X ratio and unbalanced loads. However, Methods that are not based on Newton Raphson method and the calculation of the Jacobian matrix, such as the Forward and Backward Sweep method exploit the radial topological structure and the special characteristics of the distribution system and the computation time is short. Therefore, it can be concluded that these methods are more efficient than the conventional methods in solving load flow problem in distribution systems. Because of this, the Forward and Backward sweep method has been used in this work.

Chapter 3: Optimization methods.

Introduction

In different engineering activities like in research, sales, help, analysis, System design, and system development. Optimization algorithms are important tools to obtain best solutions for complex problems. Different numerical methods for optimization are used to design better systems. In distribution systems, distributed generation can influence the power losses and the voltage levels. In order to plan an optimal sizing and location of distributed generation, optimization algorithms are used. In addition, optimization can be used to allocate smart meters for fault detection.

3.1 Optimization

Optimization can be defined as the process of searching for a set of decision variables that results in maximizing or minimizing a target function subject to constraints. Decision variables or control variables are those on which the values of objective and constraints depend. A cost, error function, and loss function are problems related to minimization whereas, a profit or accuracy function is a problem related to maximization.

3.2 Optimization problem

Optimization problem consists of finding the best set of inputs for maximizing or minimizing a target function namely the objective function. The objective function could be subjected to specified conditions, which must be satisfied called constraints including equality and inequality constraints. Based on that, optimal problems are classified into two types: constrained optimization problems and unconstrained optimization problems. Moreover, depending on the nature of objective function, the optimization problem is classified as Linear programming (LP) problem or Nonlinear programming (NLP) problem. The process of solving optimization problem consists of a set of operations forming an optimization algorithm. The optimization algorithm iteratively executes in a search space, to find among them, the proper solutions and compares them accordingly until the problem converges and the best solution is found, this solution maybe the optimal solution for the problem or near to the optimal. The number of iterations and the convergence to the solution depend on the problem itself, for instance, if the objective function is linear or non-linear and if it includes constraints or not...etc. The convergence also depends on the optimization method used.

3.3 Optimization methods

Real-life problems can be modeled as optimization problems with a specific mathematical objective function. Multiple optimization methods were developed to solve optimization problems. Depending on the characteristics of the optimization problem mainly the objective function type, constraints, and the decision variables types a suitable method is selected. Optimization methods are classified into two main types: analytical methods and heuristic methods.

3.3.1 Analytical Methods

Also known as deterministic or exact methods. These are classical optimization methods that use classical mathematics theories such as calculus, algebra, and matrices to model systems and derive system variables' optimal values. These methods are particularly applicable when the objective functions are differentiable. Analytical methods include Simplex method, Gradient method, Newton's method, Interior-point method, and Sequential quadratic programming. The major advantage of these methods is the fast convergence to a unique solution. However, the solution depends on the nature of the objective function. In addition, this method is limited; the objective function and constraints should be continuous in the domain, the first and the second ordered derivatives should exist, and the derivatives should be continuous in the entire search space.

3.3.2 Stochastic methods

Stochastic methods refer to a collection of methods for minimizing or maximizing an objective function when randomness is present [33]. These algorithms are applicable for any optimization problem. However, finding the global optimal solution requires an infinite computation time, thus, it is typically impossible to reach the global optimal solution using stochastic methods but an approximation to it can be found. Hence, these methods are also known as approximate algorithms. Both heuristic and metaheuristic methods are classified in this category.

3.3.2.1 Heuristic Methods:

Heuristic methods are computer-oriented approaches that use artificial intelligence to search for optimal solutions to an optimization problem. Artificial intelligence methods have a simple mathematical structure. All the heuristic optimization algorithms are inspired by nature as a result they are called Nature-Inspired Algorithm. Search heuristics are particularly applicable when objective functions are highly nonlinear, and when the number of variables and constraints is large. In addition, search heuristics reduce development time and are robust since they are insensitive to missing data. Heuristic optimization techniques are independent of the nature of objective function and constraints, derivative free, very effective in solving large-scale optimization problems, and the only choice for solving very complex optimization problems.

3.3.2.2 Metaheuristic methods

The name combines the Greek prefix "meta" ("beyond", here in the sense of "higher level") and "heuristic" (from ευρισκειν, heuriskein, "to find") [34]. A metaheuristic is a heuristic method for solving a very general class of computational problems by combining user-given black-box procedures, usually heuristics themselves, to obtaining a more efficient or more robust procedure. Heuristics are often problem-dependent, that is, a heuristic is defined for a given problem. Whereas, metaheuristics are problem-independent techniques that can be applied to a broad range of problems. The design of metaheuristic algorithms consists of two main criteria: the exploration of the search space and the exploitation of the best solution found. Metaheuristic algorithms are used in machine learning, data mining, system modeling, simulation, engineering designs, telecommunication…etc. Metaheuristic methods includes five types: Individual-based, Evolution-based, Swarm-based, Physics-based, and Human-based.

1. Individual-based:

Tabu Search (TS), Iterated Local Search (ILS) , and Simulated Annealing (SA).

2. Evolution-based:

Inspired from the evolutionary phenomena in nature using three main operators including selection, recombination, and mutation. Biogeography-based Optimization (BBO) algorithm, evolutionary membrane algorithm, human evolutionary model, Genetic algorithm, differential evolution, and Asexual Reproduction Optimization (ARO) are examples of evolutionary algorithms [35]

3. Swarm-based:

Inspired by the collective behavior of swarms in nature. Researcher have observed such behaviors of animals, plants, or humans, analyzed the driving force behind the phenomena, and then proposed various types of algorithms. Some of the most recent ones are Glowworm Swarm Optimization (GSO) Bees Algorithm (BA), Artificial Bee Colony (ABC) algorithm, Bat Algorithm (BA), Firefly Algorithm (FA), Cuckoo Search (CS) algorithm, Cuckoo Optimization Algorithm (COA), Grey Wolf Optimizer (GWO). Dolphin Echolocation (DE, Hunting Search (HS), and Fruit Fly Optimization Algorithm (FFOA) [36]

4. Physics-based:

Originates from physical laws in real-life and typically describes the communication of search solutions based on controlling rules ingrained in physical methods. The most recent algorithms in this category are Gravitational Search Algorithm (GSA), Chemical Reaction Optimization (CRO), Artificial Chemical Reaction Optimization Algorithm (ACROA), Charged System Search (CSS) algorithm, Ray Optimization (RO), Black Hole (BH) algorithm, Central Force Optimization (CFO), Kinetic Gas Molecules Optimization algorithm (KGMO), and Gases Brownian Motion Optimization (GBMO) [37].

5. Human-based:

Which motivated by human co-operations and human behavior in communities. One of the most used algorithms in this group are Teaching Learning-Based Algorithm (TLBA) Imperialist Competitive Algorithm (ICA), and Harmony Search (HS) [37].

3.4 Genetic Algorithm

3.4.1 Genetic Algorithm: A definition

Genetic algorithm is an evolutionary computation technique classified as a metaheuristic. It is used for solving both constrained and unconstrained optimization problems based on natural selection inspired by Charles Darwin’s theory of natural evolution, the process that drives biological evolution. The genetic algorithm was invented by John Holland in the 1960s and became popular through his book Adaptation in Natural and Artificial Systems in 1975 [38].The genetic algorithm repeatedly modifies a population of individual solutions. In every generation of the genetic algorithm, the genetic algorithm selects individuals from the current population. Where each individual is evaluated to give some measure of its fitness. The fitness of each individual is used to select the most fit individuals to be parents to generate more fit individuals for the next generation. Over successive generations, the population "evolves" toward an optimal solution. For solving any problem, the genetic algorithm follows the same simple process: encoding, selection, crossover and mutation. It is applicable for variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, non-differentiable, stochastic, or highly nonlinear. The genetic algorithm proposed by John Holland is the Simple Genetic Algorithm (SGA). However, the development of research on the genetic algorithm made the genetic algorithm an efficient optimization tool in many fields, such as engineering science, computer-automated design, management sciences and social sciences [39]. Compared to other optimization methods, genetic algorithm has many features; it is scalable since it can be easily combined with other algorithms such as Simulated Annealing Algorithm and Conjugate Gradient [40]. In addition, the genetic algorithm is highly adaptive, operate searching by using the optimization information, inherited the good gene chromosome to the next generation and eliminate the bad chromosome. Furthermore, it is easy to understand, as the theory is similar to biological inheritance.

3.4.2 The Components and Methodology of Genetic Algorithm

In general, a genetic algorithm has five basic components, as summarized by Michalewicz [41]:

1. A genetic representation of solutions to the problem.
2. A way to create an initial population of solutions.
3. An evaluation function rating solution in terms of their fitness.
4. Genetic operators that alter the genetic composition of children during reproduction.
5. Values for the parameters of genetic algorithm.

3.4.2.1 Encoding Issue

The solution must be encoded into chromosome to perform the genetic algorithm. Then Individuals are decoded into solutions. In Holland's work, encoding is carried out using binary string [42]. For many problems in the industrial engineering world, it is difficult to use this method. During the last 10 years, various encoding methods have been developed for particular problems to insure effective performance of genetic algorithms. Based on the type of symbol is used as the alleles of a gene, the encoding method can be classified as follows [43]:

- Binary encoding.
- Real number encoding.
- Integer or literal permutation encoding.
- General data structure encoding.

3.4.2.2 Population

The main goal of genetic algorithm is the find the best solution for the optimization problem among the set of all possible solutions. Each possible solution is called individual. A collection of individuals forms a population. An individual is characterized by a set of parameters (variables) known as Genes. Genes are joined into a string to form a Chromosome (solution). The two important aspects of population used in Genetic Algorithms are:

1. The initial population generation that is a set of many possible solutions.

2. The population size.

A simple genetic algorithm creates many chromosomes randomly under the constraint conditions. The number of chromosomes is the population size. Enlarging the population size can increase the search scope, leading to more accurate solutions, but the larger is the population size, the lager will be the time required by a GA to converge. The convergence time of GA is estimated by the function n*log(n) where “n” is the population size. Therefore, a suitable size of population should be selected. Practically, a population size of around 100 individuals is quite frequent. Depending on the complexity of the problem, a random initialization of population is carried. For instance, in binary coded chromosome, each bit is initialized to a random zero or one. The genetic algorithm will start from this generation, and select and inherit the high fitness individuals for the next generation. Genetic algorithm simulate natural evolution with the principle of survival of the fittest, and eventually get the optimal individual to satisfy the problem requirement. Ideally, in order to explore the whole search space, the first population should have a gene pool as large as possible. All the different possible alleles of each should be present in the population. To achieve this, the initial population is, in most of the cases, chosen randomly. Nevertheless, sometimes a kind of heuristic can be used to set the initial population. Thus, the mean fitness of the population is already high and it may help the genetic algorithm to find good solutions faster. Nevertheless, for doing this one should be sure that the gene pool is still large enough. Otherwise, if the population badly lacks diversity, the algorithm will just explore a small part of the search space and never find global optimal solutions [44].

3.4.2.3 Fitness function

Fitness is a value that measures the quality level of each individual. The value of fitness can influence the probability of being selected for the next generation. The fitness value is calculated using a function that is related to the objective function, and the value must be a non-negative number. High fitness value means high quality of the individual. The fitness function can affect the convergence speed of genetic algorithm.

3.4.2.4 Genetic operators

Typically, there are two types of search behaviors: random search and local search. The former explores the entire solution and is capable of achieving escape from a local optimum. The latter exploits the best solution and is capable of climbing upward to local optimum. GA is a general-propose search method where accumulated information is exploited by the selection mechanism and new regions of search space are explored using genetic operators. Genetic operators include crossover operator and mutation operator. The first one is used to perform a random search to explore the region beyond a local optimum whereas; the second one is used to perform a local search to find an improved solution. Thus, the two operators make the genetic search processes two types of search abilities [41].

A. Crossover

Crossover is the principal operator in GA. It is used to create new generation by changing the chromosomes of the parent generation to produce the next generation with a certain probability. It exchange a part of two or more chromosomes randomly to produce a new individual. Crossover can combine the good genes together in order to form a better solution and get closer to the optimal solution. There are many crossover techniques depending on different data structures. The most common technique is one-point crossover. One-point crossover means choosing one crossover point on both parents' chromosome strings and swap the data beyond that point between the two parents' chromosomes. The resulting strings are the children. For example, consider the following two six digits binary strings as strings, 101 110 and 111010. If the crossover occurs from the fourth digit, then this lead to children as shown below.

Parents A: 101 110 B: 111 010

Crossover point

Children A: 101 010 B: 111 101

Mutation operator:

The mutation operator is used to produce spontaneous random changes in various chromosomes. It changes one or more genes on a chromosome string to produce a new individual with a low probability. Mutation operator is used to prevent the loss of genes during the selection and crossover operations. An example is given below of mutation in six digits binary string, the mutation is performed on fourth digit is given below:

A: 100101

Mutation: 100001

3.4.2.5 Selection

Selection is the process of determining the number of times, or trials, a particular individual is chosen for reproduction and, thus, the number of offspring that an individual will produce. The selection of individuals can be viewed as two separate processes: determination of the number of trials an individual can expect to receive, and conversion of the expected number of trials into a discrete number of offspring. The first part is concerned with the transformation of raw fitness values into a real valued expectation of an individual's probability to reproduce and is dealt with in the previous subsection as fitness assignment. The second part is the probabilistic selection of individuals for reproduction based on the fitness of individuals relative to one another and is sometimes known as sampling [45]. The individuals with high fitness are selected and grouped into a new population according to the fitness value to keep the better individuals for the next generation, thereby; the selection directs the algorithm toward promising areas in the search space. The common methods of selection include truncation selection, tournament selection, stochastic universal sampling and roulette wheel selection [46].

3.4.3 Flowchart of Genetic Algorithm

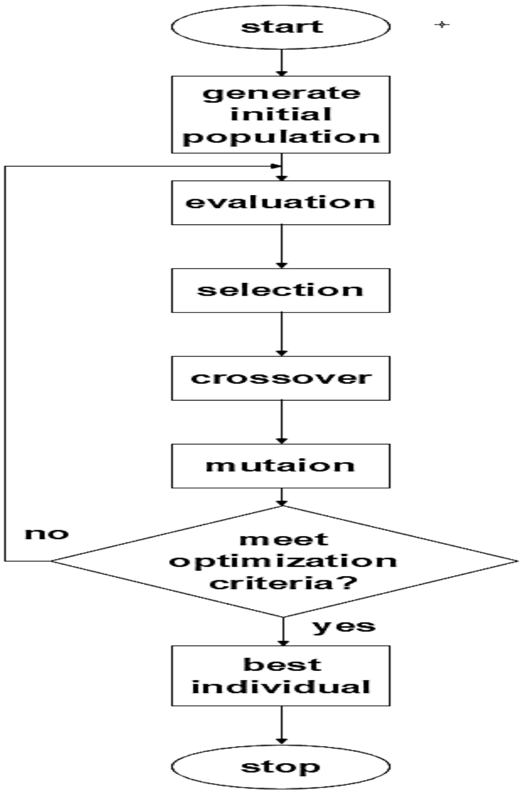


Figure 3.1 Flowchart of Genetic Algorithm

Conclusion

Analytical optimization techniques are problem dependent but fast and they give unique solution. In this work, an analytic optimization method will be used for optimal placement of DGs to reduce power losses. Where an exact loss formula is used as objective function. However, for optimal placement of smart meters, GA will be used since it is independent of the nature of the problem and very efficient in solving large scale and complex optimization problems.

Chapter 4: problem formulation, Results and Discussion.

Introduction

This chapter includes problem formulation, results, and discussion. The final goal of this work is to optimally allocate smart meters for fault detection in distribution system with DGs. Thus, the first step is the penetration of DG units into the radial distribution system. Analytic optimization method is used to allocate DGs for loss reduction. Since the penetration of DG units affects the stability of the system, the stability index is calculated for each bus to track the stability of the system. The second step is the optimal placement of smart meters to detect the fault location in the distribution system with DGs. For this part, GA is used.

Part one: optimal placement of DGs for loss reduction

4.1 Problem formulation

This section deals with the problem formulation for finding the optimal size and location of type 3 (DG capable of injecting both P and Q) for loss reduction in distribution network. The analytic optimization method is used.

4.1.1 Objective Function

The objective of the current DG placement problem is to minimize the power distribution losses in the network. In this work, the Exact Loss formula [47] as given by (4.1) has been used to evaluate the real power losses of the system.

The objective function is given by:

$$\begin{cases} Min\ P_L \\ P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \end{cases} \tag{4.1}$$

Where $\alpha_{ij} = \frac{r_{ij}}{V_iV_j} cos\,(\delta_i - \delta_j)$ $\beta_{ij} = \frac{r_{ij}}{V_iV_j} sin\,(\delta_i - \delta_j)$

$V_i \angle \delta_i$	is the complex voltage at the bus ith.
$r_{ij} + jx_{ij} = Z_{ij}$	is the ijth element of $[Zbus]$ impedance matrix.
P_i and P_j	are the active power injections at the ith and jth buses, respectively.
Q_i and Q_j	are the reactive power injections at the ith and jth buses, respectively.
N	is the number of buses.
P_L	is the power losses.

4.1.2 Assumptions and Constraints

1) The sizing and location of DG is considered at the peak load only.

2) Maximum active power limit of DG for different test systems is assumed to be equal to the total active load of the system.

3) The lower and upper voltage thresholds for DG with the optimal size, location and power factor are set at 0.95– 1.05 p.u.

4.1.3 Sizing at Various Location

An analytical expression for DG allocation in distribution networks is represented in [6]. Assuming $a = (sign)\tan(\cos^{-1}(PF_{DG}))$, the reactive power output of DG is expressed by (2)

$$Q_{DGi} = aP_{DGi} \tag{4.2}$$

where

$sign = +1$: DG injecting reactive power.

$sign = -1$: DG consuming reactive power.

$PFDG$ is the power factor of DG.

The active and reactive power injected at bus i, where the DG located, are given by (4.3) and (4.4) respectively.

$$P_i = P_{DGi} - P_{Di} \tag{4.3}$$

$$Q_i = Q_{DGi} - Q_{Di} = aP_{DGi} - Q_{Di} \tag{4.4}$$

From (1), (3), and (4), the active power loss can be rewritten as

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\begin{bmatrix}\alpha_{ij}\left[(P_{DGi} - P_{Di})P_j + (aP_{DGi} - Q_{Di})Q_j\right] \\ +\beta_{ij}[(aP_{DGi} - Q_{Di})P_j - (P_{DGi} - P_{Di})Q_j]\end{bmatrix} \tag{4.5}$$

The total active power loss of the system is minimum if the partial derivative of (4.5) with respect to the active power injection from DG at bus i becomes zero. After simplification and rearrangement, (4.5) can be written as

$$\frac{\partial P_L}{\partial P_{DGi}} = 2\sum_{j=1}^{N}[\alpha_{ij}(P_j + aQ_j) + \beta_{ij}(aP_j - Q_j)] = 0 \tag{4.6}$$

Equation (4.6) can be rewritten as

$$\alpha_{ii}(P_j + aQ_j) + \beta_{ii}(aP_i - Q_j) + \sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j) + a\sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j) = 0 \tag{4.7}$$

Let

$$\begin{cases} X_i = \sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j) \\ Y_i = \sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j) \end{cases} \tag{4.8}$$

From (4.3), (4.4), (4.7), and (4.8), (4.9) can be developed

$$\alpha_{ii}(P_{DGi} - P_{Di} + a^2 P_{DGi} - aQ_{Di}) + \beta_{ii} (Q_{Di} - aP_{Di}) + X_i + aY_i = 0 \quad (4.9)$$

From (9), the optimal size of DG at each bus i for minimizing loss can be written as

$$P_{DGi} = \frac{\alpha_{ii} (P_{Di} + aQ_{Di}) + \beta_{ii}(aP_{Di} - Q_{Di}) - X_i - aY_i}{a^2\alpha_{ii} + \alpha_{ii}} \quad (4.10)$$

The aforementioned equations give the optimum size of DG for each bus i, for the loss to be minimum. Any size of DG other than PDGi placed at bus i will lead to a higher loss. This loss, however, is a function of loss coefficients α and β. When DG is installed in the system, the values of loss coefficients will change, as it depends on voltage and angle. Updating the values of α and β again requires another load flow calculation.

4.1.4 Optimal size of DG

The power factor of DG depends on operating conditions and type of DG. When the power factor of DG is given, the optimal size of DG at each bus i for minimizing losses can be found in the following way.

1) Type 1 (DG capable of injecting P only): For Type 1 DG, power factor is at unity, i.e.,$PF_{DG} =$ 1, a = 0. From (4.10), the optimal size of DG at each bus i for minimizing losses can be given by reduced equation (11)

$$P_{DGi} = P_{Di} - \frac{1}{\alpha_{ii}}\left[\beta_{ii}Q_{Di} + \sum_{\substack{j=1 \\ j\neq i}}^{N}(\alpha_{ij} P_j - \beta_{ij}Q_j)\right] \quad (4.11)$$

2) Type 2 (DG capable of injecting Q only): Assuming $PF_{DG} = 0$ and a = ∞, from (4.2) to (4.10), the optimal size of DG at each bus i for minimizing losses is given by reduced equation (4.12)

$$Q_{DGi} = Q_{Di} + \frac{1}{\alpha_{ii}}\left[\beta_{ii}P_{Di} - \sum_{\substack{j=1 \\ j\neq i}}^{N}(\alpha_{ij} Q_j - \beta_{ij}P_j)\right] \quad (4.12)$$

3) Type 3 (DG capable of injecting both P and Q): Assuming 0 <PF_{DG}< 1, sign = +1 and “a” is a constant, the optimal size of DG at each bus i for the minimum loss is given by (4.10) and (4.4), respectively.

4) Type 4 (DG capable of injecting P but consuming Q): Assuming 0 < PFDG < 1, sign = −1 and “a” is a constant, the optimal size of DG at each bus i for the minimum loss is given by (4.10) and (4.4), respectively.

4.1.5 Optimal Power Factor

Consider a simple distribution system with two buses, a source, a load and DG connected through a transmission line as shown in figure 4.1.

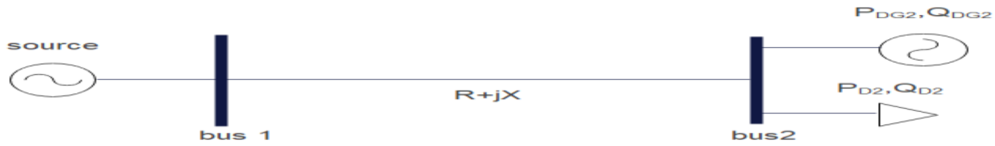


Figure 4.1 Simple distribution system with single DG

The power factor of the single load (PF_{D2}) is given by (4.13)

$$PF_{D2} = \frac{P_{D2}}{\sqrt{P_{D2}^2+Q_{D2}^2}} \tag{4.13}$$

The minimum loss occur when power factor of DG is equal to the power factor of load as given by (4.14).

$$PF_{D2} = PF_{DG2} = \frac{P_{DG2}}{\sqrt{P_{DG2}^2+Q_{DG2}^2}} \tag{4.14}$$

In practice, a complex distribution system includes a few sources, many buses, many lines and loads. The power factors of loads are different. If each load is supplied by each local DG, at which the power factor of each DG is equal to that of each load, there is no current in the lines. The total line power loss is zero. The transmission lines are also unnecessary. However, that is unrealistic since the capital investment cost for DG is too high. Therefore, the number of installed DGs should be limited. To find the optimal power factor of DG for a radial complex distribution system, fast approach is used. In this method, the power factor of combined total load of the system can be expressed by (4.13). In this condition, the total active and reactive power of the load demand are expressed as

$$P_D = \sum_{i=1}^{N} P_{Di} \tag{4.15}$$

$$Q_D = \sum_{i=1}^{N} Q_{Di} \tag{4.16}$$

The “possible minimum” total loss can be achieved if the power factor of DG (PFDG) is quickly selected to be equal to that of the total load (PFD). That can be expressed by (4.17).

$$PF_{DG} = PF_D \tag{4.17}$$

4.2 Computational Procedure

Step 1: Run load flow for the base case.

Step 2: Find the base case loss using (4.1).

Step 3: Calculate power factor of DG using (4.17).

Step 4: Find the optimal size of DG for each bus using (4.4) and (4.10).

Step 5: Place DG with the optimal size obtained in step 4 at each bus, one at a time. Calculate the approximate loss for each case using (4.1) with the values α and β of base case.

Step 6: Locate the optimal bus at which the total loss is minimum corresponding with the optimal size at that bus.

Step 7: Run load flow with the optimal size at the optimal location obtained in step 6. Calculate the exact loss using (4.1) and the values α and β after DG placement.

We have developed a code in MATLAB to optimally allocate and size DGs.

4.2.1 Load Flow Analysis

To calculate the initial network parameters, a load flow was done. The load flow technique used was the backward/forward sweep load flow method. Using equation (1.1), the voltage stability indices (VSI) for the network were calculated at each bus in addition to the load flow.

4.3 Case study

The network under study is the medium-voltage 33 bus distribution network [48]. The network is a 12.66 KV network and the total load connected to it is 3715 kW and 2300 kVAR.

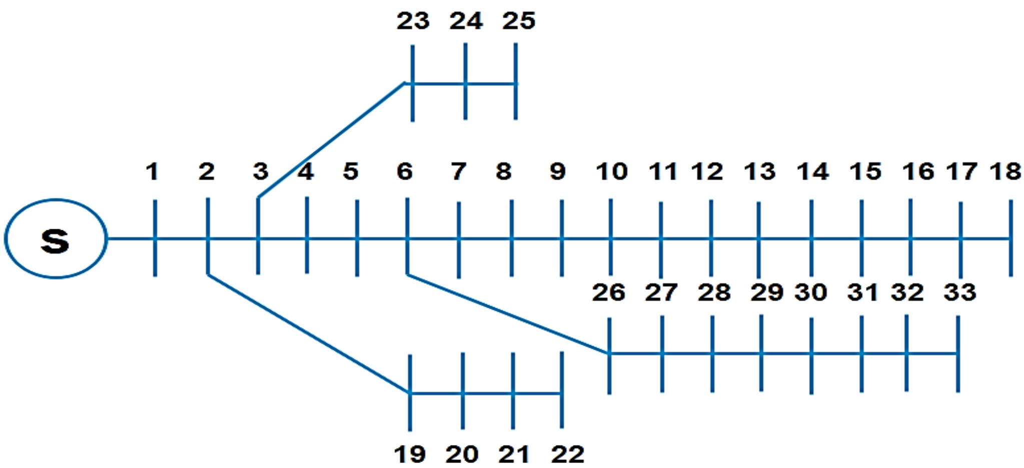


Figure 4.2 The medium-voltage 33 bus distribution network.

4.4 Results and discussion

4.4.1 Forward Backward load flow for the base case

Table 4-1 Load flow results and VSI for IEEE-33 Bus Network for the base case

Bus number	V bus (p.u)	STABILITYINDEX (p.u)	Angle (rad)	Pd KW	Qd KVAR	SDGi KVA
1	1.0000	1.0000	0.0000	0.000	0.000	4050.965
2	0.9970	0.9994	0.0019	100.000	60.000	4593.913
3	0.9829	0.9847	0.0093	90.000	40.000	4109.735
4	0.9755	0.9318	0.0105	120.000	80.000	3617.655
5	0.9681	0.9039	0.0143	60.000	30.000	3340.146
6	0.9496	0.8747	-0.0160	60.000	20.000	3018.883
7	0.9462	0.8129	0.1953	200.000	100.000	2863.416
8	0.9326	0.7998	0.3473	200.000	100.000	2038.628
9	0.9263	0.7559	0.4215	60.000	20.000	1764.767
10	0.9204	0.7358	0.4857	60.000	20.000	1570.155
11	0.9195	0.7176	0.4801	45.000	30.000	1539.017
12	0.9180	0.7149	0.4716	60.000	35.000	1481.890
13	0.9119	0.7101	0.5631	60.000	35.000	1295.211
14	0.9096	0.6915	0.6379	120.000	80.000	1237.753
15	0.9082	0.6846	0.6743	60.000	10.000	1174.712
16	0.9068	0.6804	0.6975	60.000	20.000	1102.029
17	0.9048	0.6764	0.7709	60.000	20.000	992.505
18	0.9042	0.6703	0.7806	90.000	40.000	937.531
19	0.9965	0.9387	0.0128	90.000	40.000	1900.703
20	0.9929	0.9860	0.0802	90.000	40.000	523.670
21	0.9922	0.9720	0.0996	90.000	40.000	461.068
22	0.9916	0.9693	0.1200	90.000	40.000	371.135
23	0.9794	0.9154	0.0405	90.000	50.000	2759.568
24	0.9727	0.9196	0.1289	420.000	200.000	1895.318
25	0.9694	0.8951	0.1726	420.000	200.000	1436.250
26	0.9477	0.8184	-0.0.524	60.000	25.000	2867.687
27	0.9452	0.8065	-0.1043	60.000	25.000	2688.021

28	0.9338	0.7970	-0.1855	60.000	20.000	2234.711
29	0.9256	0.7598	-0.2603	120.000	70.000	2018.870
30	0.9221	0.7339	-0.3568	200.000	600.000	1906.353
31	0.9179	0.7226	-0.2834	150.000	70.000	1664.214
32	0.9170	0.7098	-0.2633	210.00	100.000	1595.364
33	0.9167	0.7069	-0.2565	60.000	40.000	1516.594

Using equation (4.15), the total real demand of the system is 3715.000 KW

Using equation (4.15), total reactive demand of the system is 2300.000 KVAR

Optimal placement of the first DG is at bus 6

Optimal size of DG1: P_{DG1}= 2475.484 KW

Q_{DG1}=1727.899 KVAR

4.4.2 Forward Backward load flow after placing the first DG

Table 4-2 Load flow results and VSI for IEEE-33 Bus Network after the placement of DG1

Bus number	V bus (p.u)	STABILITYINDEX (p.u)	Angle (rad)	Pd KW	Qd KVAR	SDGi KVA
1	1.0000	1.0000	0.0000	0.000	0.000	1476.218
2	0.9991	1.0075	0.0000	100.000	60.000	1719.173
3	0.9959	1.0362	0.0002	90.000	40.000	1289.993
4	0.9964	1.0133	0.0002	120.000	80.000	826.014
5	0.9974	1.0168	0.0003	60.000	30.000	572.764
6	1.0002	1.0690	-0.0003	60.000	20.000	3027.419
7	0.9969	1.006	0.0034	200.000	100.000	376.354
8	0.9841	0.9862	0.0061	200.000	100.000	622.235
9	0.9781	0.9374	0.0074	60.000	20.000	643.085
10	0.9726	0.9150	0.0085	60.000	20.000	645.643
11	0.9718	0.8947	0.0084	45.000	30.000	644.165
12	0.9703	0.8917	0.0082	60.000	35.000	638.570
13	0.9645	0.8863	0.0098	60.000	35.000	608.335

14	0.9624	0.8655	0.0111	120.000	80.000	595.221
15	0.9611	0.8579	0.0118	60.000	10.000	573.992
16	0.9598	0.8531	0.0122	60.000	20.000	546.842
17	0.9579	0.8486	0.0135	60.000	20.000	501.584
18	0.9573	0.8418	0.0136	90.000	40.000	476.733
19	0.9985	0.9889	0.0002	90.000	40.000	866.673
20	0.9950	0.9941	0.0014	90.000	40.000	373.697
21	0.9943	0.9801	0.0017	90.000	40.000	339.479
22	0.9936	0.9773	0.0021	90.000	40.000	279.542
23	0.9923	0.9962	0.0007	90.000	50.000	1173.066
24	0.9857	0.9693	0.0022	420.000	200.000	1051.002
25	0.9825	0.9441	0.0030	420.000	200.000	861.186
26	0.9984	1.0066	-0.0009	60.000	25.000	394.850
27	0.9960	0.9934	-0.0018	60.000	25.000	487.561
28	0.9852	0.9829	-0.0032	60.000	20.000	683.768
29	0.9774	0.9415	-0.0045	120.000	70.000	756.818
30	0.9741	0.9126	-0.0062	200.000	600.000	777.007
31	0.9701	0.9001	-0.0049	150.000	70.000	723.187
32	0.9692	0.8857	-0.0046	210.000	100.000	701.683
33	0.9690	0.8825	-0.0045	60.000	40.000	669.113

Optimal placement of the second DG is at bus 15

Optimal size of DG2: P_{DG2}= 470.674 KW

Q_{DG2}=328.532 KVAR

4.4.3 Forward Backward load flow after placing the second DG

Table 4-3 Load flow results and VSI for IEEE-33 Bus Network after installing the second DG

Bus number	**V bus (p.u)**	**STABILITYINDEX (p.u)**	**Angle (rad)**	**Pd KW**	**Qd KVAR**	**SDGi KVA**
1	1.0000	1.0000	0.0000	0.000	0.000	3336.965
2	0.9975	1.0011	-0.0002	100.000	60.000	3712.148

3	0.9856	0.9953	-0.0014	90.000	40.000	3248.679
4	0.9798	0.9484	-0.0023	120.000	80.000	2768.483
5	0.9742	0.9267	-0.0033	60.000	30.000	2502.158
6	0.9602	0.9128	-0.0022	60.000	20.000	2205.843
7	0.9587	0.8566	0.0001	200.000	100.000	2056.145
8	0.9535	0.8721	0.0026	200.000	100.000	1250.263
9	0.9522	0.8431	0.0038	60.000	20.000	983.704
10	0.9514	0.8388	0.0048	60.000	20.000	795.058
11	0.9513	0.8220	0.0050	45.000	30.000	764.695
12	0.9513	0.8240	0.0052	60.000	35.000	708.858
13	0.9525	0.8433	0.0063	60.000	35.000	527.448
14	0.9535	0.8340	0.0065	120.000	80.000	471.985
15	0.9551	0.8368	0.0067	60.000	10.000	1199.666
16	0.9538	0.8320	0.0071	60.000	20.000	394.871
17	0.9518	0.8275	0.0084	60.000	20.000	366.672
18	0.9513	0.8208	0.0085	90.000	40.000	350.022
19	0.9969	0.9490	-0.0000	90.000	40.000	1583.506
20	0.9934	0.9877	0.0012	90.000	40.000	477.636
21	0.9927	0.9737	0.0015	90.000	40.000	423.740
22	0.9920	0.9709	0.0019	90.000	40.000	343.011
23	0.9821	0.9319	-0.0008	90.000	50.000	2274.988
24	0.9754	0.9299	0.0007	420.000	200.000	1637.233
25	0.9721	0.9052	0.0015	420.000	20.000	1260.398
26	0.9583	0.8622	-0.0029	60.000	25.000	2126.643
27	0.9558	0.8431	-0.0039	60.000	25.000	2029.077
28	0.9445	0.8334	-0.0055	60.000	20.000	1770.987
29	0.9364	0.7954	-0.0069	120.000	70.000	1641.985
30	0.9329	0.7689	-0.0088	200.000	600.000	1569.502
31	0.9288	0.7573	-0.0074	150.000	70.000	1328.598
32	0.9279	0.7442	-0.0070	210.000	100.000	1328.598
33	0.9279	0.7413	-0.0069	60.000	40.000	1263.604

Optimal placement of the third DG is at bus 30

Optimal size of DG1: P_{DG3}= 1286.992 KW

Q_{DG3}=898.326 KVAR

4.4.4 Forward Backward load flow after placing the third DG

Table 4-4 Load flow results and VSI for IEEE-33 Bus Network after installing the third DG

Bus number	V bus (p.u)	STABILITYINDEX (p.u)	Angle (rad)	Pd KW	Qd KVAR
1	1.0000	1.0000	0.0000	0.000	0.000
2	0.9981	1.0038	-0.0001	100.000	60.000
3	0.9899	1.0123	-0.0006	90.000	40.000
4	0.9868	0.9753	-0.0010	120.000	80.000
5	0.9839	0.9638	-0.0015	60.000	30.000
6	0.9771	0.9764	-0.0009	60.000	20.000
7	0.9737	0.9111	-0.0030	200.000	100.000
8	0.9605	0.8973	0.0058	200.000	100.000
9	0.9544	0.8507	0.0071	60.000	20.000
10	0.9487	0.8294	0.0083	60.000	20.000
11	0.9479	0.8102	0.0082	45.000	30.000
12	0.9464	0.8073	0.0080	60.000	35.000
13	0.9405	0.8022	0.0097	60.000	35.000
14	0.9369	0.7824	0.0111	120.000	80.000
15	0.9369	0.7751	0.0117	60.000	10.000
16	0.9356	0.7706	0.0122	60.000	20.000
17	0.9337	0.7663	0.0135	60.000	20.000
18	0.9331	0.7599	0.0137	90.000	40.000
19	0.9976	0.9656	0.0001	90.000	40.000
20	0.9940	0.9904	0.0013	90.000	40.000
21	0.9933	0.9764	0.0016	90.000	40.000
22	0.9927	0.9736	0.0020	90.000	40.000
23	0.9864	0.9585	-0.0000	90.000	50.000
24	0.9798	0.9463	0.0015	420.000	200.000
25	0.9765	0.9214	0.0023	420.000	20.000
26	0.9775	0.9168	-0.0012	60.000	25.000
27	0.9782	0.9248	-0.0016	60.000	25.000

28	0.9815	0.9686	-0.0045	60.000	20.000
29	0.9844	0.9682	-0.0068	120.000	70.000
30	0.9867	0.9604	-0.0076	200.000	600.000
31	0.9828	0.9475	-0.0064	150.000	70.000
32	0.9819	0.9328	-0.0060	210.000	100.000
33	0.9816	0.9295	-0.0059	60.000	40.000

4.4.5 Optimal placement of DG for loss reduction

The power losses before and after assignment of DG units and percentage loss reduction in 33 bus distribution system is provided in table 4-5. The maximum number of DG units connected in this system is three. For the base case, the total power losses are about 210.069 KW. The results of the optimal placement of DGs algorithm show that when DGs are placed in the system there is a significant decrease in active power losses. When a single DG of type three with total size of 2475.484 KVA is connected at bus 6, there is reduction of 64.57% of total loss. When two DG units of ratings 2475.484 KVA and 573.992 KVA respectively, are placed at bus number 6 and 15 respectively, the losses reduced to 75.28%. When three DG units are connected at bus number 6, 15 and 30 of rating 2475.484 KVA, 2475.484 KVA and 573.992 KVA respectively, the losses reduce to 80.63%. Therefore, it can be concluded from table 4-5 that the optimal placement and sizing of DGs for the 33-bus distribution system using analytic method reduces the active power losses from 210.069 KW to 40.675 KW, which is 80.63% loss reduction.

Table 4-5 Results of optimization of location, size and power factor of DG units for loss reduction in 33-Bus distribution system

Case	DG power factors	Installed DG schedule	DG Size (KVA)	P loss (KW)	Loss reduction (%)
No DG				210.069	00.00
1 DG	0.82 lagging	Bus 6	2475.484	74.423	64.57
2 DGs	0.82 lagging	Bus 6 Bus 15	2475.484 573.992	51.922	75.28
3 DGs	0.82 lagging	Bus 6 Bus 15 Bus 30	2475.484 573.992 1569.502	40.675	80.63

Table 4-6 represents the minimum and maximum voltages and the bus associated to after placement of DG units. The results shows that the penetration of DG units into the network improve the voltage profile of the system in general.

Table 4-6 Voltage profile of 33 bus distribution system with and without DG units.

Cases	**Minimum voltage (p.u)**	**@ Bus**	**Maximum voltage (p.u)**	**@ Bus**
No DG	0.9042	18	1.0000	1
1 DG	0.9573	18	1.0002	6
2 DG units	0.9276	33	1.0000	1
3 DG units	0.9331	18	1.0000	1

To monitor the stability of the system after the placement of DG units, the VSI is calculated for each bus after each placement of DG. The minimum of the VSI for each case is represented in table 4-7. The results shows that the stability of the system is improved since the VSI is maximized for sensitive bus (bus with the minimum voltage stability index). For the base case, the minimum VSI is 0.6703 in p.u at bus number 18. With three DGs, the VSI increases to 0.7599 p.u. It can be concluded that the penetration of three DG units into the 33-bus network results in an improvement of the system stability.

Table 4-7 Minimum stability index for 33 bus distribution system with and without DG units

Case	**Minimum voltage stability index (p.u)**	**@ bus**
No DG	0.6703	18
1 DG unit	0.8418	18
2 DG units	0.7413	33
3 DG units	0.7599	18

Part two: optimal placement of smart meters for fault detection.

4.5 Problem formulation

4.5.1 Fault location methods based on smart meters

The fault locating algorithm proposed in this work is based on the on the monitoring capability of feeder meters and short circuit theory. The main idea is to employ the voltage drop information that could be measured using smart meters for calculating the fault location index, which indicates the bus closest to the fault point. For any fault in the system, the meters are polled to provide the voltage RMS value prior and during the fault occurrence [49].

Using the voltage magnitude measured by the feeder meters, the voltage deviation (ΔV) is calculated as follows:

$$\Delta V_i^{(abc)} = V_i^{(abc)p} - V_i^{(abc)f} \tag{4.18}$$

In which, the subscript i refers to the feeder meter installed in the Bus number i. $V_i^{(abc)p}$ and $V_i^{(abc)f}$ are respectively the voltages measured before and during the fault and the superscripts a, b, c show voltage deviation in phases a, b, c. If a fault occurs in bus k, the fault current in each phase can be estimated by the following equation using the voltage deviation measured by the meter i:

$$I_{fault,ik}^{(abc)} = (Z_{ik})^{-1}.\Delta V_i^{(abc)} \tag{4.19}$$

In which, $Z_{ik}$is the element on row number i and column number k in the impedance matrix and the fault current calculated by measuring the voltage of meter i, considering the fault in Bus number k. Therefore, with N meters in a network, there are N estimated fault currents based on the assumption that the bus under fault is bus k. If the fault really occurred at bus k, all the estimated currents must have practically the same value, which is close to the real value. On the other hand, if the fault occurs on any other BUS, the fault will be present on the fault current that is estimated based on the measurements of each meter i. In addition, the fault calculated by different meters might be different from each other. Based on the aforementioned explanation, a fault-location index δk can be used to identify the actual bus under fault. This index is given by the sum of the differences between the N estimated fault current values taking into consideration that bus k is under fault and their average value. Considering that bus k has a fault, using the equation (3):

$$\delta_k = \sum_{ph}^{a,b,c} \sum_{i=1}^{N} \left| I_{fault,ik}^{ph} - I_{fault}^{ph} \right| \tag{4.20}$$

In which $I_{fault,ik}^{ph}$ is the fault current calculated for phase ph by measuring the voltage by feeder meter in bus i and I_{fault}^{ph} is the average of all the calculated fault currents by voltage measurement of all the meters for bus k. As it was previously mentioned, if the bus understudy has a fault, all the estimated currents are practically similar. Therefore, the bus related to the smallest fault index is selected as the bus with the fault.

4.5.2 Fault location flowchart

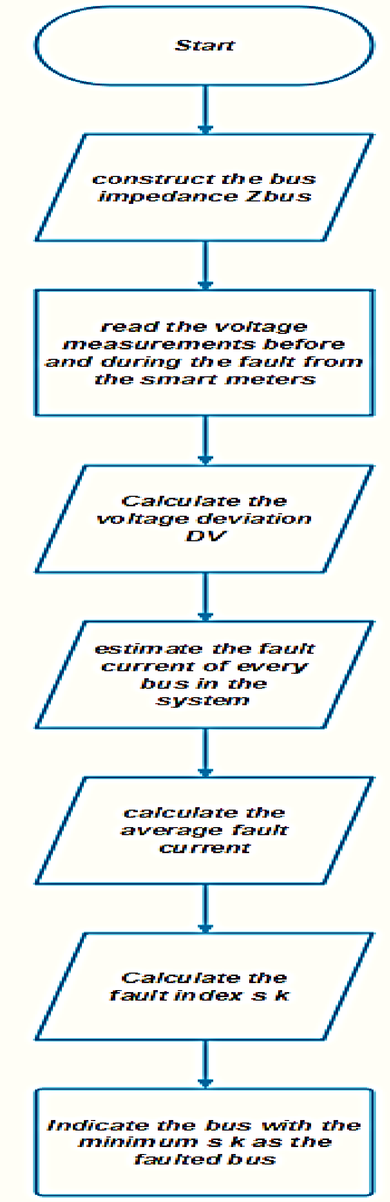


Figure 4.3 Fault location flowchart

4.5.3 Optimal placement of smart meters for fault detection

The method used for the optimal placement of smart meters is a combination of genetic optimization algorithm and fault locating algorithm. The fault location algorithm is employed by the genetic algorithm to evaluate the fitness of each particle generated by the genetic algorithm. A cost function is allocated for each particle based on the number of smart meters and the installation points. In this method, the network information, the connected loads and the installation points of smart meters are inputs to the fault locating algorithm. The output of this algorithm is a suggested fault location. Then this output is compared with the real fault location that was simulated for the calculation of $\Delta V_i^{(abc)}$. Based on that, the costs of locations suggested for installation of meters is evaluated for each particle. This process is repeated for each fault occurrence in each network bus and the total cost of each particle consists of total fault locating costs in each network bus plus the number of meters used in the suggested particle.

Performance steps for the suggested method are as the following:

1 - Receiving the network information (impedance of lines, connected loads)

2 - Receiving the particle or suggested locations for installation of meters and calculating the number of meters used in the particle; NOM (Number of Meter)

3 - Fault occurrence in all the network buses and applying the fault locating algorithm

4 - Comparing the response of the fault-locating algorithm (pf) with the real fault location (rf). If the response doesn't match the real location, then $cost(i,j)$ =1; otherwise, $cost(i,j)$ =1

5 - Total particle cost is calculated by the following equation:

$$T\ cost(j) = NOM + \sum_{i=1}^{M} cost(i,j)$$

4.6 Case study

The network under study is the medium-voltage 33 bus distribution network [48] with DG units installed at optimal locations based on the results of part one. Bus data, line data and the results of table 4-5 have been used to develop a Simulink model of the network. Network loads and the three DG units (installed in buses 6, 15 and 30) are considered as constant PQ model.

4.7 Simulation results and discussion

In order to analyze the performance of the fault locating method with the optimal number of meters, first we apply the optimal placement algorithm on the sample network and determine the installation points of meters. After determining the optimal number and location of meters, the fault location method will be tested. The network understudy has been simulated in MATLAB-Simulink software and the meters have been simulated in buses with meters. The faults apply to all the system buses in order to execute the optimal placement algorithm is a three-phase fault to the ground. The measurements of smart meters will be analyzed in MATLAB.

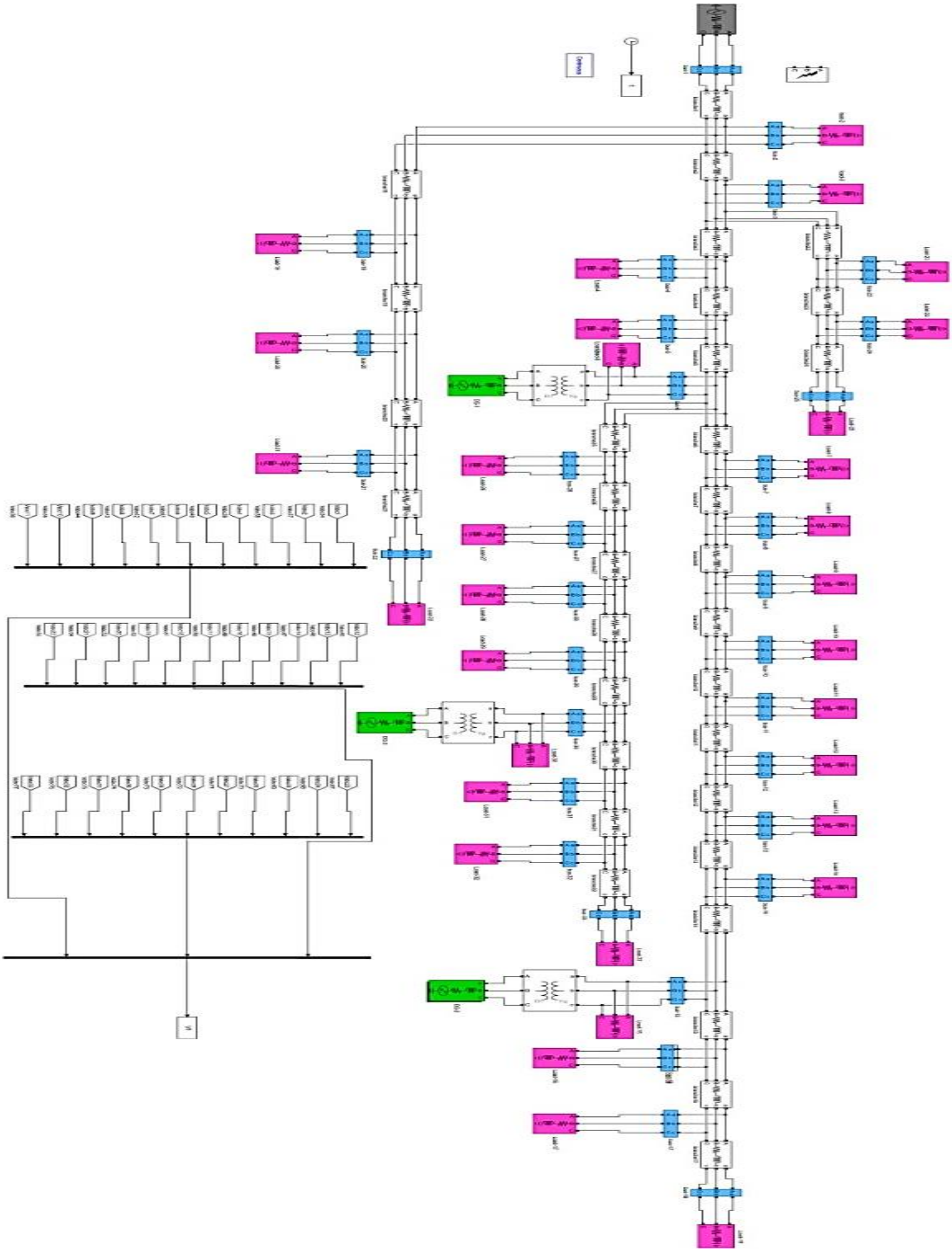


Figure 4.4 Simulink model of IEEE 33-bus radial distribution system.

4.7.1 Results of GA

Three-phase fault was simulated in the 33 network buses. The results were saved as RMS values to be used by the fault detection algorithm and the GA to evaluate the optimal placement of smart meters. The initial parameters of the GA used in the simulation are represented in table 4-8. The results of the optimization are represented in table 4-9.

Table 4-8 The initial parameters of the GA.

Initial population	60
Maximum number of iterations	100
NOM	06
Upper bounds	33
Lower bounds	01

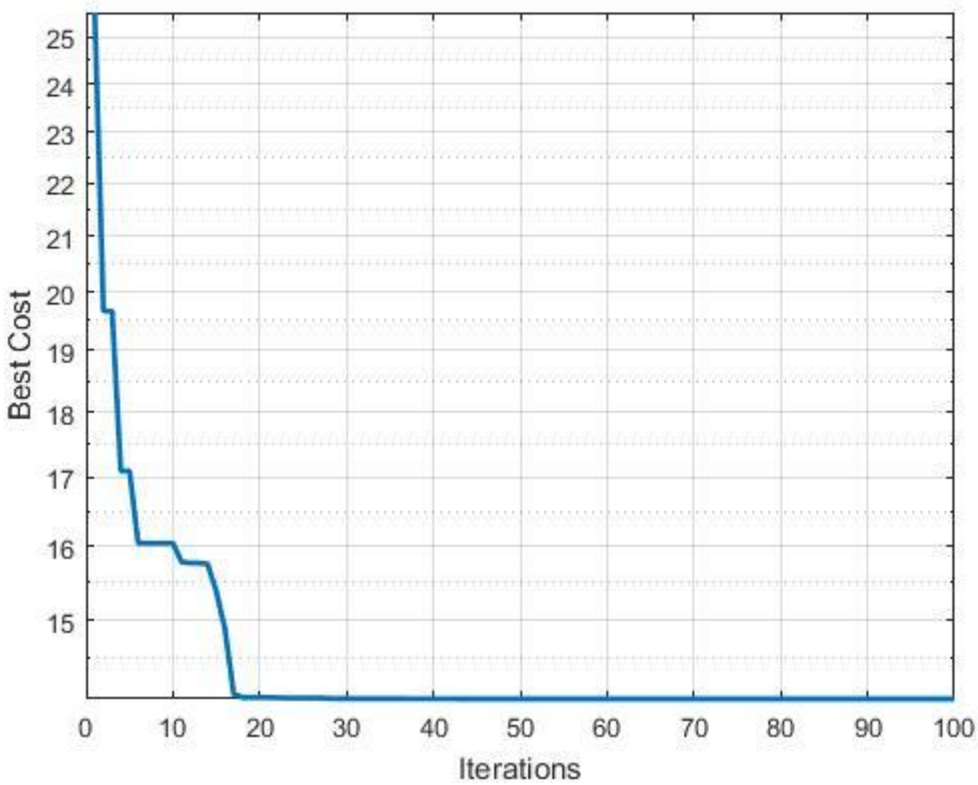


Figure 4.5 Fitness function (cost function).

Figure 4.5 represents the fitness function values for 100 iteration. The best value is 14. This means that the maximum number of faults that may allocated wrong is eight since NOM=6.

Table 4-9 The results of the optimization using the GA.

The number of smart meters	06
The optimal locations	05-04-10-02-33-14
The best cost function	14

The results show that with six smart meters placed at buses :05,04,10,02,33,14, the best costfunction is found to be equal to 14. We got different results by changing the maximum number of iterations and the initial population. However, the results represented above are the best among them.

4.7.2 The results of the fault detection method using optimal placement of smart meters

To evaluate the performance of the fault detection algorithm, it will be tested in different locations in the network with optimal number of smart meters. Only the measurement of smart meters located at buses: 05, 04, 10, 02, 33, 14 are used for the fault locating algorithm. Three-phase fault is applied in each bus (one at a time) of the network buses and for each fault, then a fault index is calculated for all the network buses using the measurements obtained by the simulation of that fault. The bus with the minimum fault index is the estimated fault location. The results are represented in table 4-10.

Table 4-10 The results of the fault detection algorithm using optimal placement of smart meters.

Location of fault	01	02	03	04	05	06	07	08	09	10	11
Suggested location	01	02	33	04	01	01	07	08	07	10	11
Error	-	-	%	-	%	%	-	-	%	-	-
Location of fault	12	13	14	15	16	17	18	19	20	21	22
Suggested location	12	13	16	15	16	17	18	14	20	21	22
Error	-	-	%	-	-	-	-	%	-	-	-
Location of fault	23	24	25	26	27	28	29	30	31	32	33
Suggested location	23	24	27	26	24	28	29	30	31	32	33
Error	-	-	%	-	%	-	-	-	-	-	-

According to Table 4-10, it can be seen that the fault location method with the optimal number of meters in the presence of DG has shown good efficiency, it only estimated eight buses wrong. However, since only 6 smart meters are used instead of 33 smart meters, we can say that the results are satisfactory.

General Conclusion:

We address the problem of optimally allocating smart meters for fault detection in medium distribution system with DGs. The first step to achieve the main goal was the placement of DG units in the simple radial network. The optimal size and location of the DGs have been determined by minimizing the power losses using analytical optimization method. Then, a combination of GA and fault detection algorithm was used for optimal placement of smart meters for fault detection in the presence of DGs. The methods were tested in IEEE 33-bus distribution system.

Initially, we have presented a general definition of power system network, distributed generation and the main impacts of the penetration of DG into distribution system. In addition, type of faults in power system, fault analysis and fault locating methods were described. Furthermore, the main features of smart meters are highlighted.

Moreover, a special load flow method for distribution systems is represented namely, The Backward/Forward method. This method is used in this work and it showed an excellent performance concerning the speed and the number of iterations to converge to the solution.

Then we proceeded to look at optimization techniques. Based on the problem, we choose the analytical method for optimal placement of DG units and the genetic algorithm for the placement of smart meters.

Finally, we formulated our main problem in two parts. Each part has an independent objective function to be optimized. The first part deals with the optimal placement and sizing of DG units for loss reduction. In this stage the Backward/Forward load flow method is employed. In addition, voltage stability index method is used to insure stable system after DGs placement. Whereas, the second part deals with the optimal placement of smart meters. the results of both parts were satisfying.

Further improvements can be adapted to our subject:

- Optimize the type of the DGs instead of using a specified type and combine different types to improve the reliability of the system.
- Improve the fault location algorithm to detect all types of fault.

References

[1] T. Ackermann, G. Andersson and L. Soder, “Distributed generation: A definition,” *Electric. Power System. Resouces,* vol. 57, no. 3, pp. 195-204, 2001.

[2] Edvard, "The structure of electric power systems(Generation, Distribution and transmission of energy)," *energy and power / Transmission and Distribution,* 09 October 2017.

[3] S. S and M. K, “Backward/Forward Sweep Based Distribution Load Flow Method,” *International Electrical Engineering Journal (IEEJ),* vol. 5, no. 9, pp. 1539-1544, 2014.

[4] C.-M. Augusto, F. John, J. Marcos, Padilha-Feltrin Antonio and R. Rubén, "Mixed-integer linear programming approach for optimal type, size and allocation of distributed generation in radial systems," *Electr Power Syst Res,* vol. 97, pp. 133-143, 2013.

[5] A.M.Emad, A. Al-Attar and M.Yasunori, “Hybrid GMSA for Optimal Placement and Sizing of Distributed Generation and Shunt Capacitors,” *Engineering Science and Technology Review,* vol. 11, no. 1, pp. 55-65, 2018.

[6] D.Q.Hung, N.Mithulananthan and R.C.Bansal, “Analytical expressions for DG allocation in primary distribution networks,” *IEEE Trans. Energy Convers,* vol. 25, no. 3, pp. 814-820, september 2010.

[7] T.Ackermann, G. Andersson and L.Soder, “Distributed generation: A definition,” *Elect. Power Syst. Res,* vol. 57, no. 3, april 2001.

[8] D.singh and R.K.Misra, “Effect of load models in distributed generation planning,” *IEEE Trans. Power Syst,* vol. 22, no. 4, pp. 2204-2212, november 2007.

[9] M.N.Marwali, J.W.Jung and A.Keyhani, “Stability analysis of load sharing control for distributed generation systems,” *IEEE Trans. Energy Convers,* vol. 22, no. 3, pp. 737-745, september 2007.

[10] D.Q.Hung et N.Mithulananthan, «Multiple distributed generator placement in primary distribution networks for loss reduction,» *IEEE Transactions on industrial electronics,* vol. 60, n° %14, pp. 1700-1708, 2013.

[11] P.Prakash and D.Khtod, “optimal sizing and siting techniques for distributed generation in distribution systems: A review,” *Renewable & Sustainable Energy Reviews,* 1 may 2016.

[12] T.Ackerman and V.Knyazkin, “Interaction between distributed generation and the distribution network: Operation aspects,” *Proceedings of the second international symposium on distributed generation power system market aspects,* October 2002.

[13] T.Hoff, H.J.Wenger and B.K.Farmer, “The value of grid-support photovoltaic in providing distribution system voltage support,” Clean power research conference, Napa, CA, 1995.,” in *Clean power research*, Napa, California, 1995.

[14] D.Singh and K.S.Verma, “Multi-objective Optimization for DG Planning with Load Models,” *IEEE Transactions on Power system,* vol. 24, no. 1, pp. 427-436, 2009.

[15] L.F.Ochoa, A.Padilhafeltrin and G.P.Harrison, “Evaluating distributed time-varying generation through a multiobjective index,” *IEEE Trans. Power Del,* vol. 23, no. 2, pp. 1132-1138, april 2008.

[16] N.Acharya, P.Mahat et N.Mithulananthan, «An analytical approach for DG allocation in primary distribution network,» *Int. J. Elect. Power Energy Syst,* vol. 28, n° %110, pp. 669-678, december 2006.

[17] Y.M.Atwa, E.F.El-Saadany, M.M.A.Salama and R.Seethapathy, “Optimal renewable resources mix for distribution system energy loss minimization,” *IEEE Trans. Power Syst,* vol. 25, no. 1, pp. 360-370, February 2010.

[18] G.V.K.Murthy, Dr.S.Sivanagaraju, Dr.S.Satyanarayana et B. Rao, «Reliability Improvement of Radial Distribution System with Distributed Generation,» *International Journal of Engineering Science and Technology (IJEST),* vol. 4, n° %19, pp. 4003-4011, 2012.

[19] A.Singh, N.Singhpal, V.S.Bhadoria, V.Shrivastava and A.K.Sihag, *Optimal Placement of DG for Reliability Improvement in Distribution System,* February 2016.

[20] N.Acharya, P.Mahat and N.Mithulananthan, “An analytical approach for DG allocation in primary distribution network,” *Elect. Power and Energy Syst,* vol. 28, no. 10, pp. 669-678, December 2006.

[21] M. Benalia, T. Madjid and T. Benaissa, “Optimal DG Unit Placement and Sizing in Radial Distribution Network for Power Loss Minimization and Voltage Stability Enhancement,” *Polytechnica Electrical Engineering and Computer Science ,* vol. 64, no. 2, pp. 157-169, 2020.

[22] S. Prakash, V. Rangta, N.S.Jayalakshmi and V. K. Jadoun, “Optimal Location of DGs in a Distribution System for Maintaining Voltage Profile and Loss Reduction Using Genetic Algorithm,” in *International Conference on Power Electronics & IoT Applications in Renewable Energy and its Control (PARC)*, GLA University, Mathura, UP, India, 2020.

[23] I.Gupta and V.Gupta, “Unbalanced Radial Distribution System Load Flow and Voltage Profile Enhancement in the presence of Distributed Generators,” *International Journal of Engineering Research & Technology (IJERT),* vol. 4, no. 5, pp. 1565-1571, 2015.

[24] C.A.Belhadj and M.A.Abido, “An optimized fast voltage stability indicator,” *PowerTech,* pp. 79-83, 1999.

[25] M.Chakravorty and D.Das, "Voltage stability analysis of radial distribution networks," *Electrical Power and Energy Systems,* vol. 23, pp. 129-135, 2001.

[26] P.Satyasheel, R.Vinay and N.S.Jayalakshmi, “Optimal Location of DGs in a Distribution System for Maintaining Voltage Profile and Loss Reduction Using Genetic Algorithm,” in *International Conference on Power Electronics & IoT Applications in Renewable Energy and its Control (PARC)* , GLA University, Mathura, UP, India, 2020.

[27] H. Saadat, Power System Analysis, New York: McGraw-Hill.2002.

[28] j. john and D. William, Power System Analysis, New York St.Louis San Francisco Auckland Bogata: McGraw-Hill. 1999

[29] M. K. M et P. B, «Fault location,» *Wiley Encyclopedia of Electrical and Electronics Terminology,* vol. 7, pp. 276-285, 1999.

[30] R.Dashti and J.Sadeh, "Fault Indicator Allocation in Power Distribution Network for Improving Reliability and Fault Section Estimation," *The International Conference on Advanced Power System Automation and Protection,* 2011.

[31] H.Mirshekali, R.Dashti, K.Handrup and H.Shaker, "Real Fault Location in a Distribution Network Using Smart Feeder Meter Data," *Energies,* 02 June 2021.

[32] Sivkumar.Mishra and Debapriya.Das, "Distribution System Load Flow Methods: A Review," April 2008.

[33] L. A. Hannah, "Stochastic Optimization," 4 April 2014.

[34] M. N. Alam, Writer, *Optimization Techniques Using MATLAB.* [Performance]. researchgate, 2021.

[35] L.L.Wee, W.Antoni, D. Ishak and H.Habibollah, "A Biogeography Based Optimization Algorithm Hybridized with Tabu Search for the Quadratic Assignment Problem," *Computational Intelligence and Neuroscience,* p. 12, 2016.

[36] A. Nadhir, N.M.Samia and A. Adham, "A Comprehensive Review of Swarm," *Plos One,* vol. 3, pp. 15-25, 2015.

[37] A.Laith, D.Ali, M.Seyedali, A.E.Mohamed and G.Amir, "The Arithmetic Optimization Algorithm," *Elsevier B.V,* 2021.

[38] M. Melanie, *An Introduction to Genetic Algorithms,* Massachusetts Institute of Technology, 1998.

[39] R. Olympia, Real-World Applications of Genetic Algorithms, 2012.

[40] S. Malcolm and D. Guy, "Genetic Algorithm in seismic waveform inversion," Institute of Theoretical Geophysics, Department of Eath Sciences, Downing Dt, Cambridge , 1991.

[41] Z.Michalewicz, Genetic Algorithm + Data structure = Evolution Programs, vol. 3, New York: Springer-Verlag, 1996.

[42] J.Holland, *Adaptation in Natural and Artificial systems,* Press,Cambridge: MIT, 1992.

[43] G.Mitsuo and C.Runwei, *Genetic Algorithms and Engineering Optimization,* John Wiley and Sons.Inc, 2000.

[44] S. S.N and D. S.N, "Terminologies and Operators of GA," in *Introduction to Genetic Algorithms*, New York, Springer-Verlag, 2008, pp. 41-42.

[45] A.Chipperfield, P.Fleming, H.Pohlheim and C.Fonseca, Genetic Algorithm toolbox for use with matlab, vol. 1, university of Sheffield, automatic control and systems engineering. 2002.

[46] J.V.Ranito, V.Muanda and L.M.Pmenqt, “Genetic Algorithms in Optimal Multistage Distribution Netwotk Planning,” *IEEE Transactions on Power Systems,* vol. 9, no. 4, November 1994.

[47] D.P.Kothari and J.S.Dhillon, Power System Optimization, New Delhi: Prentice Hall, 2006.

[48] M. Kashem, V.Ganapathy, G. Jasmon and M.I.Buhari, “Networks, A Novel Method for Loss Minimization in Distribution,” in *Int. Conf. Elect. Utility Deregulation Restruct. Power Technol*, 2000.

[49] F.C.Trindade, W.Freitas and J.C.Vieira, “Fault location in distribution systems based on smart eeder meters,” *IEEE transactions on Power Delivery,* vol. 29, no. 1, pp. 251-260, February 2014.