Reliability Enhancement and Power Loss Minimisation in Distribution System

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CERTIFICATE OF RECOMMENDATION

This is to certify that this dissertation entitled "**Reliability Enhancement and Power Loss Minimisation in Distribution System**" has been carried out by **ANUP KUMAR RAJAK** with Roll No. **002210802008** under my guidance and supervision and be accepted in partial fulfilment of the requirement for the degree of Master of Electrical Engineering. In my opinion this thesis, is worthy of its acceptance.

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The foregoing thesis is hereby approved as a creditable study of **Master of Electrical Engineering** and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or, opinion expressed or conclusion herein but approve this thesis only for the purpose for which it is submitted.

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I certify that except where due acknowledgement has been made, the work is that of the candidate alone. This thesis is a presentation of my original research work and has not been submitted previously, in whole or in part, toqualify for any other academic award. Furthermore, the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program.

The work was done under the guidance of Prof. (Dr.) Sunita Halder nee Dey, Professor, Electrical Engineering Department of Jadavpur University, Kolkata.

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ABSTRACT

The study delves into the analysis of the IEEE 33 bus distribution system, integrating distributed generation (DG) into the network. It employs the particle swarm optimization (PSO) algorithm to determine the optimal placement and size of DG units aimed at minimizing overall system power loss, Energy not supplied (ENS) and enhancing voltage levels.

Utilizing MATLAB, the study conducts reliability assessments of the system using multiple indices including system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), customer average interruption duration index (CAIDI), average energy not supplied (AENS), and energy not supplied (ENS).

By applying PSO algorithm, the research aims to strategically position DG units and optimize their capacities to mitigate power losses, minimise the ENS and improve voltage stability within the distribution system. Subsequently, reliability studies assess the system's robustness and performance under various operational conditions. The integration of DG units, coupled with the application of PSO algorithm and reliability analysis, contributes to advancing distribution system planning and operation methodologies. This research facilitates the efficient utilization of distributed energy resources to enhance overall system performance and reliability, addressing contemporary challenges in power distribution systems.

The thesis provides empirical support for the effectiveness of integrating Distributed Generation (DG) into the system. Through extensive data analysis utilizing the PSO algorithm and reliability calculations, it demonstrates that incorporating DG leads to enhancements in overall power loss reduction, mitigation of voltage drop, and improvements in reliability indices.

Chapter 1

1.1 Introduction

Distribution systems play a crucial role in the power grid as they serve as the primary connection point between bulk power sources and end consumers. An organized and efficient distribution network is essential to meet the growing demand from residential, industrial, and commercial users. Analysing the load flow in radial distribution networks is vital for effective load management and transfer planning. Power utilities aim to optimize the configuration of distribution feeders to minimize real power losses and ensure balanced loads, thus improving energy efficiency and overall system performance. Understanding fundamental design principles is crucial for operating electric power systems effectively.

1.2 Background of the study:

In modern power distribution systems, ensuring reliability and minimizing power loss are critical objectives to meet the ever-growing demand for electricity while maintaining operational efficiency and cost-effectiveness. Reliability, defined as the ability of the system to provide uninterrupted power supply to consumers, is a paramount concern for utilities and consumers alike. Interruptions or outages in power supply can lead to significant economic losses, inconvenience, and even safety hazards for individuals and businesses. Therefore, enhancing the reliability of distribution systems is essential for ensuring the smooth functioning of society and the economy.

Additionally, minimizing power loss in distribution systems is equally important. Power losses occur due to resistance in transmission lines, transformers, and other distribution components, leading to energy wastage and reduced system efficiency. By minimizing power loss, utilities can optimize energy utilization, reduce operational costs, and mitigate environmental impacts associated with energy generation and distribution.

Despite the longstanding dominance of deterministic methods, there's a growing acknowledgment of the advantages offered by probabilistic approaches in capturing the stochastic behaviour of power systems. Challenges such as data limitations and resistance to probabilistic methods have hindered widespread adoption, but advancements in techniques and increased understanding have made probabilistic approaches more feasible. The development of reliability evaluation techniques tailored for power systems and emphasize the significance of various reliability indices, advocating for the adoption of probabilistic approaches to provide more objective assessments. [1].

This thesis explores the interplay between reliability enhancement and power loss minimization in distribution systems, with a particular focus on the integration of distributed generation (DG) technologies. Through empirical analysis and advanced optimization techniques such as the particle swarm optimization (PSO) algorithm, it investigates how the inclusion of DG can improve overall system performance, reduce power loss, enhance voltage stability, and elevate system reliability.

1.3 Organization of Thesis

The thesis is structured as follows:

- **Chapter 1** contains a brief detail of distribution system and reliability studies. It gives the idea about the importance of loss minimisation in the power system, the method to achieve the loss minimisation and reliability studies in the distribution system.
- **Chapter 2** details about advantages of power loss minimisation and reliability studies which leads to motivation of the thesis work. Different literatures and journals available are mentioned along with the work carried out.
- **Chapter 3** contains brief idea and algorithm about backward forward load flow technique, various steps involved in the calculation of load flow algorithm using backward forward sweep method.
- **Chapter 4** contains the brief idea about various reliability indices calculated in the thesis and the algorithm for calculation of reliability indices in the system.
- **Chapter 5** contains idea about particle swarm optimisation techniques (PSO) , its algorithm based technique for optimal location of DG and optimal DG size in the system.

- **Chapter 6** depicts the objective functions required for the problem statement and constraints involved.
- **Chapter 7** represents simulation results and discussions.
- **Chapter 8** presents the conclusion and further scope of work.
- **Appendices.**

Chapter 2

2.1 Motivation of Work

Power loss minimization techniques and reliability improvement studies measures in distribution systems offer several advantages:-

1. Cost savings: By reducing power losses, utilities can save on energy expenditure, leading to cost savings for both the utility and consumers. This is particularly important in the context of rising energy prices and the need for efficient resource utilization.

2. Improved efficiency: Minimizing power losses increases the overall efficiency of the distribution system. This means that more of the generated power reaches consumers without being wasted, resulting in a more effective use of resources.

3. Enhanced voltage stability: Power loss minimization techniques often involve voltage regulation measures, which help to maintain stable voltage levels throughout the distribution network. This contributes to improved equipment performance and reliability, reducing the likelihood of voltage-related issues such as equipment failures or voltage sags.

4. Reliability enhancement: Implementing reliability improvement measures such as distributed generation integration, fault detection, and isolation systems, and advanced automation technologies can enhance the overall reliability of the distribution system. This leads to fewer service interruptions, reduced downtime, and improved customer satisfaction.

5. Resilience to grid disturbances: Distribution systems with minimized power losses and enhanced reliability are better equipped to withstand and recover from grid disturbances such as faults, outages, and extreme weather events. This resilience ensures continuity of service and minimizes the impact of disruptions on consumers and critical infrastructure.

6. Integration of renewable energy sources: Power loss minimization techniques often involve the integration of renewable energy sources like solar and wind power into the distribution system. By optimizing the integration of these sources, utilities can reduce dependency on conventional fossil fuels, mitigate environmental impacts, and enhance system sustainability.

7. Compliance with regulatory standards: Many regulatory bodies require utilities to meet certain reliability standards and efficiency targets. Implementing power loss minimization techniques and reliability improvement measures helps utilities comply with these standards, avoiding penalties and ensuring regulatory compliance.

8. Future-proofing the grid: As distribution systems evolve to accommodate emerging technologies such as electric vehicles, energy storage systems, and smart grid technologies, minimizing power losses and enhancing reliability are essential for future-proofing the grid. These measures ensure that the distribution system remains resilient, efficient, and adaptable to changing energy demands and technological advancements.

9. Environmental concern: with minimisation of power loss and reliability in the system, the carbon footprint can be minimised which in long term can be essential to achieve the long term goal of India to become net carbon neutral by 2070.

2.2 Literature Review

Various researchers have developed various techniques to find out optimal DG placements in the IEEE bus system and to conduct reliability studies in the IEEE distribution system by calculating various reliability indices. Based on the various research paper, journals and literatures, it can be divided into following parts:-

1. DG placement in IEEE bus system to minimise the losses in the system

a) Acharya et.al [2] proposed an analytical method to place distributed generation units in the primary distribution system to minimize total power losses in the system. This approach, based on the exact loss formula, is used to examine the impact of DG size and location on network losses. The proposed methodology is tested and validated on three distribution test systems (IEEE 30, 33, 69 bus) of different sizes and complexities. Comparisons with exhaustive load flows and loss sensitivity methods highlight the effectiveness of the proposed approach. It is indicated by results that the traditional loss sensitivity factor approach may not always yield the best placement for loss reduction.

b) Ali Mohammed Jaleel et.al [3] introduces a novel approach for evaluating reliability and determining the optimal location and capacity of distributed generation (DG) units in IEEE 33 bus system. The method employs multi-objective functions to minimize power losses and enhance voltage profiles. Reliability analysis is conducted using the electrical transient analyser program (ETAP) in an IEEE 33-bus test system.

c) In the study by D. B. Prakash et. al [5], the optimal placement and sizing of distributed generation (DG) units to reduce power loss and improve voltage profiles in distribution networks are explored. The particle swarm optimization (PSO) algorithm is utilized to determine the best location and size for DG units. Analysis is conducted on both IEEE 33-bus and IEEE 69-bus radial distribution systems, considering two different cases for each system. Comparative results underscore the effectiveness of the approach.

d) The application of the particle swarm optimization technique for finding the optimal size and optimum location of DG in radial distribution networks for active power compensation by reducing real power losses and improving voltage profiles is proposed by Satish Kansal et al. [6]. Two different parameters are taken into account for calculating the optimal siting and sizing of DG. An analytical expression based on the exact loss formula is used for calculating the DG size, while the loss sensitivity factor is considered for calculating the optimal site of DG. The developed formulation is tested on the standard IEEE 33 system, and a comparative study of results is conducted with that of the exhaustive load flows.

e) The improved decomposition-based evolutionary algorithm (I-DBEA) is utilized by Amir Ali et.al [8] for the selection of the optimal number, capacity, and site of DG to minimize real power losses and voltage deviation, while maximizing the voltage stability index.

2. Objective function and optimisation techniques studies

a) Zaineb Chelly Dagdia et. al [12] explores knowledge discovery from data, emphasizing optimization problems solvable through evolutionary and bio-inspired computation algorithm. It provides an overview of various approaches, including genetic algorithms, evolutionary strategy, genetic programming, and swarm intelligence etc.

b) Ali Mohammed Jaleel et.al [3] introduces an approach that employs multi-objective functions to minimize power losses and enhance voltage profiles. Strategic placement and capacity decisions for DG units are made utilizing modified particle swarm optimization (MPSO) and MATLAB.

c) An integrated reliability evaluation method based on genetic algorithm to solve the optimisation problem is used by Zhengyang Xu et. al [7] In the case study, a real distribution system is used to validate the proposed methodology.

d) P. Dinakara Prasad Reddy et.al [9] has developed efficient approach for solving the load flow problem in distribution systems, specifically tailored to radial distribution networks. This method eliminates the need for time-consuming decomposition or bus admittance matrix, resulting in faster convergence with fewer iterations. Validation on standard IEEE test systems demonstrates superior performance compared to existing algorithms.

3. Reliability studies in distribution system

a) The reliability performance of the distribution system is analysed by P.Chandra Sekhar et. al [4] in terms of SAIFI, SAIDI, CAIDI, ASAI, ASUI, ENS, and AENS. An algorithm to calculate the reliability indices for a simple 9-bus radial distribution feeder with and without DG is developed. The improvement in the feeder's reliability is studied for different locations of DG with respect to the fault point. All the above analysis are carried out by developing tools in MATLAB.

b) P.U.Okorie et.al [19] discusses the various reliability indices SAIDI, SAIFI, CAIDI, ENS etc. frequently used in the distribution system and reiterated the significance of reliable distribution system.

c) Sullivan et. al [20] analysed the reliability of the distribution system based on customer reliability indices . They discussed customer survey and thereafter the calculation of ENS (energy not supplied). Customers cost based on number of interruptions and voltage variation has been analysed.

2.3 Research Gap

1. The inclusion of distributed generation with multi- objective function like minimisation of power losses along with minimisation in various reliability indices can be studied further.

2. Real time reliability analysis of the actual distribution system using powerful tools will be beneficial in future design of distribution system.

2.4 Objective of the thesis

The objective of the thesis is to explore the potential of integrating the distributed generation (DG) into the modern power distribution system so as to enhance the efficiency and reliability of the system. The study aims to strategically place the DG into the IEEE 33 bus test system so as to minimize the overall power loss and improve the voltage stability in the system by using the particle swarm optimization (PSO) algorithm.

The particular objective of the thesis are:-

1. To provide detailed reliability assessment using key indices like SAIDI, CAIDI, SAIFI, ENS, and AENS to evaluate system performance.
2. To demonstrate that DG integration with the help of optimization techniques can reduce power losses, stabilize voltage conditions and enhance system robustness.
3. Combining minimization of power loss and improvement of reliability indices as a multi-objective function with the help of optimization techniques by integrating distributed generation (DG) in the system.

Ultimately this thesis aims to improve distribution system planning by using optimization techniques and reliability assessments to build a more efficient and reliable system.

Chapter 3

Load Flow Distribution

3.1 Introduction

Load flow analysis ensures efficient and reliable distribution system operation by calculating voltage levels, power losses. It aids in planning and expansion, assessing component capacity, and ensuring reliability. Additionally, it facilitates fault analysis, contingency planning, and the integration of renewable energy sources, optimizing solar and wind power integration while maintaining system stability and quality.

3.2 Power Balance Equation

Injected power at i^{th} bus can be written as:-

$$S_i = P_i + jQ_i \qquad \text{... (3.1)}$$

Where , S_i is the apparent power in the i^{th} node of the system,

P_i and Q_i are the active power and reactive power in the i^{th} node of the system respectively.

Also, $S_i = V_i I_i^*$ ... (3.2)

$$I_i = \sum_{k=i}^{n} (Y_{ik} V_k) \qquad \text{... (3.3)}$$

I_i represents current injected into i^{th} node of the system.

From equation (3.2), it can be written,

$$S_i = V_i \sum_{k=i}^{n} (Y_{ik} V_k)^* \qquad \text{... (3.4)}$$

Equation (3.4) can be written as,

$$S_i = \sum_{k=i}^{n} V_i \, V_k \, |Y_{ik}| \, \angle(\delta_i - \delta_k + \gamma_{ik}) \qquad \text{... (3.5)}$$

Where, $V_i = |V_i|\angle(\delta_i)$; $V_k = |V_k|\angle(\delta_k)$; $Y_{ik} = |Y_{ik}|\angle(\gamma_{ik})$

From equation (3.5), real and reactive power injection at i^{th} bus be find out and given as ,

$$P_i = \sum_{k=i}^{n} V_i \, V_k \, |Y_{ik}| \cos(\delta_i - \delta_k + \gamma_{ik}) = P_{Gi} - P_{Di} \qquad \text{... (3.6)}$$

$$Q_i = \sum_{k=i}^{n} V_i \, V_k \, |Y_{ik}| \sin(\delta_i - \delta_k + \gamma_{ik}) = Q_{Gi} - Q_{Di} \qquad \text{... (3.7)}$$

Where $P_{Gi}$and Q_{Gi} is the real and reactive power generated at i^{th} bus respectively.

Where $P_{Di}$and $Q_{Di}$is the real and reactive power demand at i^{th} bus respectively

If there is no DG in the system, the equation can be given by:-

$$P_{Gi} = P_{Di} + P_L \qquad \text{... (3.8)}$$

$$Q_{Gi} = Q_{Di} + Q_L \qquad \text{... (3.9)}$$

Where P_{Di}, P_L, Q_{Di} and Q_L are the active and reactive power demand and power loss in the system respectively.

Now, considering DG as an active load source, the modified power equation becomes:-

$$P_i + P_{DGi} = P_{Di} + P_L \qquad \text{... (3.10)}$$

$$Q_i = Q_{Di} + Q_L \qquad \text{... (3.11)}$$

Therefore by using equation (3.6), (3.7), (3.10), and (3.11), final power balance equation will be :-

$$\sum_{k=i}^{n} V_i \, V_k \, |Y_{ik}| \cos(\delta_i - \delta_k + \gamma_{ik}) + P_{DGi} = P_{Di} + P_L \qquad \dots (3.12)$$

$$\sum_{k=i}^{n} V_i \, V_k \, |Y_{ik}| \sin(\delta_i - \delta_k + \gamma_{ik}) = Q_{Di} + Q_L \qquad \dots (3.13)$$

3.3 Backward-Forward Sweep method for load flow:-

The invention of digital computers made the load flow solution easy with the development of conventional methods like Gauss-Seidel method, Newton-Raphson method, Decoupled and Fast-Decoupled methods. However, reasons like high R/X ratio and radial structure of distribution systems make the conventional methods unsuitable for load flow solution in distribution systems and very often the solution diverges as these are designed for mesh structures [9]. Due to high X by R ratio there will be decoupled effect means P will be basically depending on angle of the voltage that is delta (δ) and Q will mainly depend upon voltage difference δV. And, Because of this decoupling effect Jacobean metrics of Newton-Raphson method will be diagonal dominating, and it help in fast convergence. Therefore, load flow methods which is used in the transmission line is neither efficient nor simple for distribution system [10].

3.4 Methodology for the Backward - forward sweep method are as follows:-

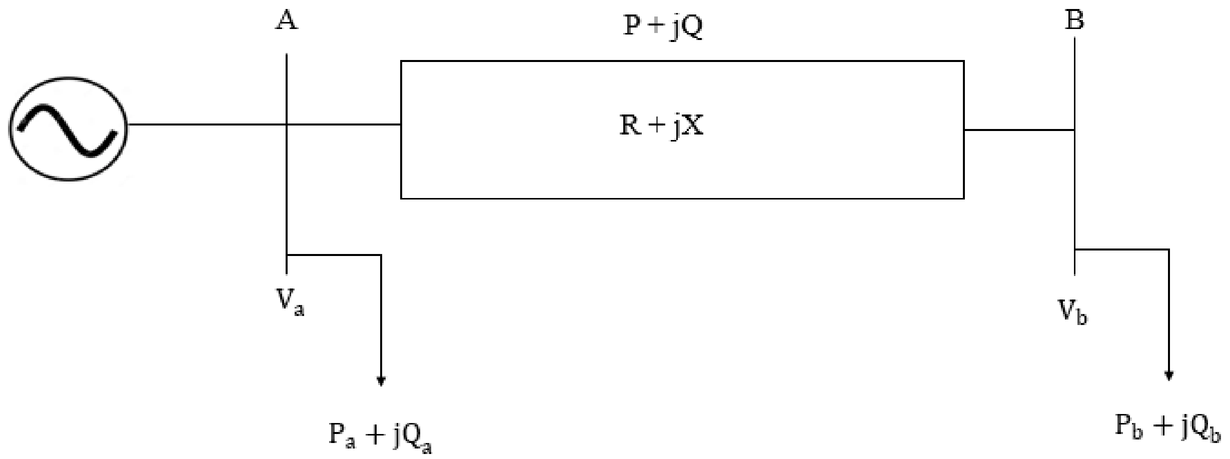


Figure 3.1 Sample distribution system [5]

From the above figure, current at bus 'A' is calculated by the equation below:

$$I_A = \left(\frac{P_a + jQ_a}{V_a}\right)^* \quad \text{... (3.14)}$$

Similarly current at bus 'B' is given by,

$$I_B = \left(\frac{P_b + jQ_b}{V_b}\right)^* \quad \text{... (3.15)}$$

Line current at line 'AB' by KCL, is given by,

$$I_{AB} = I_B \quad \text{... (3.16)}$$

Voltage at node 'B' is calculated as;

$$V_b = V_a - I_B(R + jX) \quad \text{... (3.17)}$$

Now, real and reactive power loss in the line is given by ,

$$P_{loss(A,B)} = I_{AB}^2\, R = I_B^2 R \quad \text{... (3.18)}$$

$$Q_{loss(A,B)} = I_{AB}^2 X = I_B^2 X \quad \text{... (3.19)}$$

Total active and reactive power loss of the system can be calculated by summing power losses in all the branches and it is expressed as given in equation (3.20):

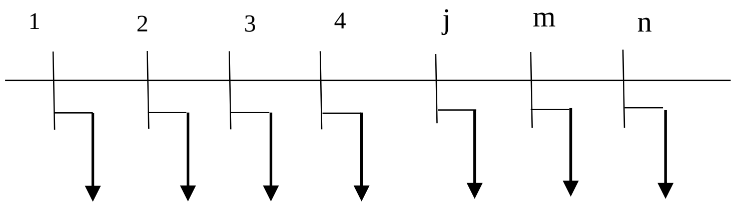
$$P_{totalloss} = \sum P_{loss(A,B)} \qquad \text{... (3.20)}$$

Active power loss minimization is considered as objective function and expressed as given in equation (3.21):

$$f = \min P_{loss} = \sum_{i=1}^{nb} I_i^2 R_i \qquad \text{... (3.21)}$$

Where nb = nos. of branches in the power system.

For multi-branch system, the general branch current can be calculated using backward-forward sweep given as:-



Initialisation of voltage for j[th] node,

$$V_j^0 = V_s\angle 0^o \quad \text{for j = 2, 3, 4.......m , n} \qquad \text{...(3.22)}$$

For k[th] iteration, load current at j[th] node,

$$I_j^k = \frac{(P_{Lj}+Q_{Lj})^*}{\left(V_j^{k-1}\right)^*} \quad \text{for j = 2, 3, 4..... n} \qquad \text{...(3.23)}$$

Branch current for '*mn*' can be calculated by using backward sweep given as,

$$I_{mn}^k = I_n^k + \sum sum\ of\ all\ current\ of\ branches\ emanated\ from\ bus\ 'n' \qquad \text{... (3.24)}$$

Using forward sweep, voltage at the bus can be calculated as ,

$$V_n^k = V_m^k - Z_{mn} I_{mn}^k \quad \text{for all n = 2,3,…..n} \qquad \text{…(3.25)}$$

Error can be calculated between two iteration and given as

$$e_j^k = \left| V_j^k - V_j^{k-1} \right| \quad \text{for j = 2,3………n} \qquad \text{…(3.26)}$$

Maximum error among all the iterations are,

$$e_{max}^k = \max(\, e_2^k, e_3^k, \dots \dots \dots e_n^k) \qquad \text{… (3.27)}$$

Convergence criteria can be given as,

$$e_{max}^k \le \text{€} \qquad \text{… (3.28)}$$

3.5 Backward- forward sweep load flow algorithm:-

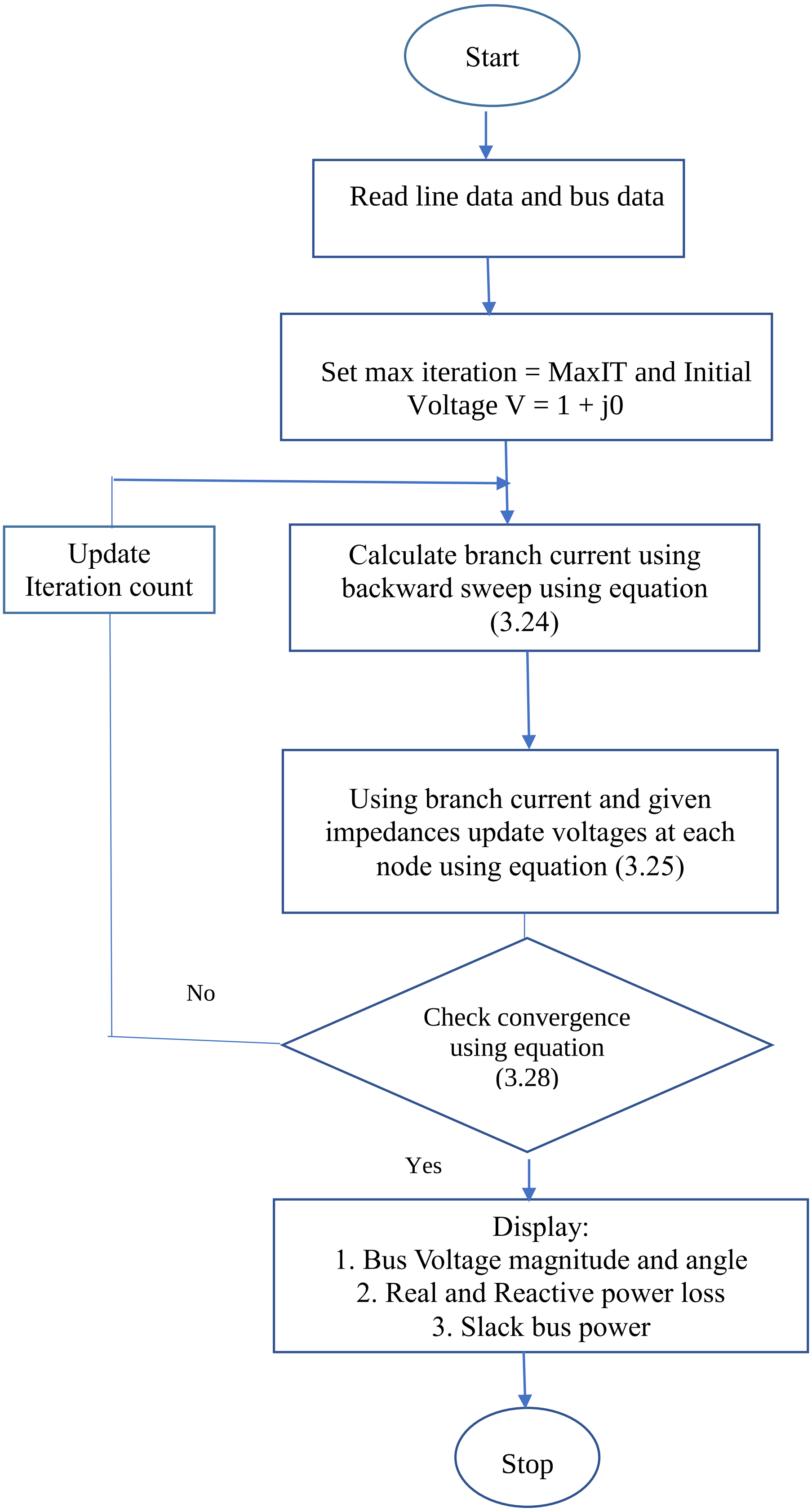


Figure 3.2 Backward-forward sweep load flow algorithm

Chapter 4

Reliability Studies for Distribution System

4.1 Introduction

In recent decades, distribution systems have been less prioritized in reliability modelling and evaluation compared to generating systems due to their lower capital intensity and localized outage effects. Generating systems, with higher stakes, have received greater emphasis on reliability. Despite this, customer failure statistics show that distribution systems significantly contribute to supply unavailability. This underscores the need for evaluating distribution system reliability, comparing reinforcement schemes, and optimizing reliability improvements within limited capital resources. [1]

4.2 Indices frequently used in the distribution system

There are various types of indices being used in the distribution system. Some indices are customer oriented, while some are energy oriented. Reliability indices evaluated traditionally include average failure rate, outage duration, and annual unavailability. These values are not deterministic but represent expected values derived from probability distributions, reflecting long-term averages. While fundamental, these indices may not fully capture system behaviour and response. Therefore, the indices are explained below in two sections, one is customer oriented and other is energy oriented. [1]

A. Customer Oriented Indices

i). System average interruption frequency index (SAIFI)

It is a reliability index used in the power industry to measure the average number of interruptions per customer served over a specific period, typically one year. SAIFI is an important metric for assessing the reliability of a distribution system, as it provides insight into the frequency of service interruptions experienced by customers. A lower SAIFI value indicates better system reliability, while a higher value suggests greater frequency of interruptions

$$SAIFI = \frac{Total\ no.of\ customer\ interruptions}{Total\ no.of\ customer\ served} = \frac{\sum \lambda_i N_i}{\sum N_i} \qquad \text{... (4.1)}$$

Where, $\lambda_i$is the failure rate and N_i is the number of customers at load point *i*.

ii) System average interruption duration index (SAIDI)

SAIDI stands for system average interruption duration index. It is a reliability index used in the power industry to measure the average duration of interruptions per customer served over a specific period, typically one year. This index provides insight into the average duration of outages experienced by customers, helping assess the reliability of a distribution system. A lower SAIDI value indicates better system reliability, as it implies shorter average outage durations for customers.

$$SAIDI = \frac{Sum\ of\ customer\ interruption\ duration}{Total\ no.of\ customers} = \frac{\sum U_i N_i}{\sum N_i} \qquad \text{... (4.2)}$$

Where U_i is the annual outage time and N_i is the number of customers at load point *i*.

iii) Customer average interruption duration index (CAIDI)

CAIDI stands for customer average interruption duration index. It is a reliability index used in the power industry to measure the average duration of interruptions experienced by customers who have experienced an outage during a specific period, typically one year. This index provides insight into the average time it takes for power to be restored to customers following an outage. A higher CAIDI value indicates shorter restoration times and better service reliability for customers.

$$CAIDI = \frac{Sum\ of\ customer\ interruption\ duration}{Total\ no.of\ customer\ interruption} = \frac{\sum U_i N_i}{\sum \lambda_i N_i} = \frac{SAIDI}{SAIFI} \qquad \text{... (4.3)}$$

Where, λ_i is the failure rate, $U_i$is the annual outage time and N_i is the number of customers of load point *i*.

B. Energy Oriented Indices

i) Energy not supplied (ENS)

ENS stands for energy not supplied. It is a reliability index used in the power industry to measure the amount of energy that customers do not receive due to interruptions or outages over a specific period, typically one year. This index provides insight into the total amount of energy lost due to interruptions, helping assess the reliability of a distribution system. A lower ENS value indicates better system reliability, as it implies less energy lost due to interruptions.

ENS = Total energy not supplied by the system = $\sum L_{ai}U_i$ ... (4.4)

Where $L_{ai}$the average load connected to point *i* and U_i is the annual outage time.

ii) AENS (Average energy not supplied)

AENS, which stands for average energy not supplied, is a reliability index utilized in the power industry to gauge the typical amount of energy that customers miss out on due to interruptions or outages over a specific timeframe, usually a year. This index offers insight into the average energy loss per customer resulting from interruptions, aiding in the assessment of distribution system reliability from an individual customer's standpoint. A lower AENS value signifies better system reliability, indicating a reduced average energy loss per customer due to interruptions.

$$AENS = \frac{Total\ energy\ not\ supplied}{Total\ no.of\ customer\ served} = \frac{\sum L_{ai}U_i}{\sum N_i} \quad ...(4.5)$$

Where $L_{ai}$the average load connected to point i , U_i is the annual outage time , N_i is the number of customers of load point *i*.

Chapter 5

Solution technique for the optimization problem

5.1 Introduction

Solution of an objective function needs to be solved with the use of a solution technique which is efficient, robust and accurate to find the results. The optimisation problem needs to be handled with large number of data. Handing the large number of data in efficient manner is therefore essential. Hence solution technique used for the solution of objective function is an evolutionary optimisation technique which are inspired by principle of nature.

There are various evolutionary optimisation techniques are available like genetic algorithm, particle swarm optimisation, cultural algorithm etc. In this thesis work, particle swarm optimisation techniques is used as the solution technique.

5.2 Particle swarm optimisation

Particle swarm optimization was introduced by Eberhart and Kennedy in 1995 [13]. Like the simulated annealing technique, particle swarm is metaheuristic. The algorithm involves taking a set of candidate solutions (particles) with random initial position, and the particles are set to move around the space to search for the best solution. The directions and velocities associated with the particles are guided toward both the best known position for individual particle and the best known overall position. As the number of iterations increase, so will the convergence rate to the best known position for the entire population. [11]

It is a successful swarm intelligence model inspired by the collective behaviour of natural organisms like birds flocking and fish schooling. In PSO, individuals within a population (swarm) move through a search space based on their fitness, adjusting their velocity and position. Each particle remembers the best position it has visited, guiding its movement. PSO algorithm aggregate movements towards the best individual and neighbouring particles, harnessing social influence. This approach has led to efficient optimization algorithms applicable across various domains. [12]

5.3 The PSO algorithm [13] [16]:-

Velocity update of the swarms can be given as:-

$$V_i(t+1) = w.V_i(t) + C_1 * rand_1 * \left(pbest_i - X_i(t)\right) + C_2 * rand_2\left(gbest - X_i(t)\right) \quad \ldots (5.1)$$

Update in position of swarms can be given as:-

$$X_i(t+1) = X_i(t) + V_i(t+1) \quad \ldots (5.2)$$

where:

- $V_i(t)$ is the velocity of particle i at time t.
- $X_i(t)$ is the position of particle i at time t.
- $pbest_i$ is the best position found by particle i so far.
- $gbest$ is the best position found by any particle in the swarm.
- w is the inertia weight, controlling the impact of previous velocity.
- C_1 and C_2 are acceleration coefficients.
- $rand_1$ and $rand_2$ are random numbers between 0 and 1.

The values of w, C_1, and C_2 are typically chosen based on empirical studies and problem characteristics to balance exploration and exploitation in the search space. Additionally, mechanisms such as inertia weight adaptation and velocity clamping may be used to enhance the performance of the PSO algorithm.

5.4 Convergence Criteria

The convergence criteria in particle swarm optimization (PSO) are the conditions under which the algorithm terminates, indicating that a solution has been found or further optimization is unlikely to improve results. Common convergence criteria includes:-

1. Maximum iterations: stop after a set number of iterations.
2. Solution quality threshold: stop when the objective function value reaches within a desired a range.

3. Velocity threshold: stop when particle velocities become very small.
4. No significant improvement: stop if there's no improvement in the global best solution over several iterations.
5. Diversity-based: stop when particles converge closely together.
6. Time limit: stop after a predetermined time.

In this work, the maximum iterations criteria has been used as the convergence criteria.

5.5 PSO flow chart:-

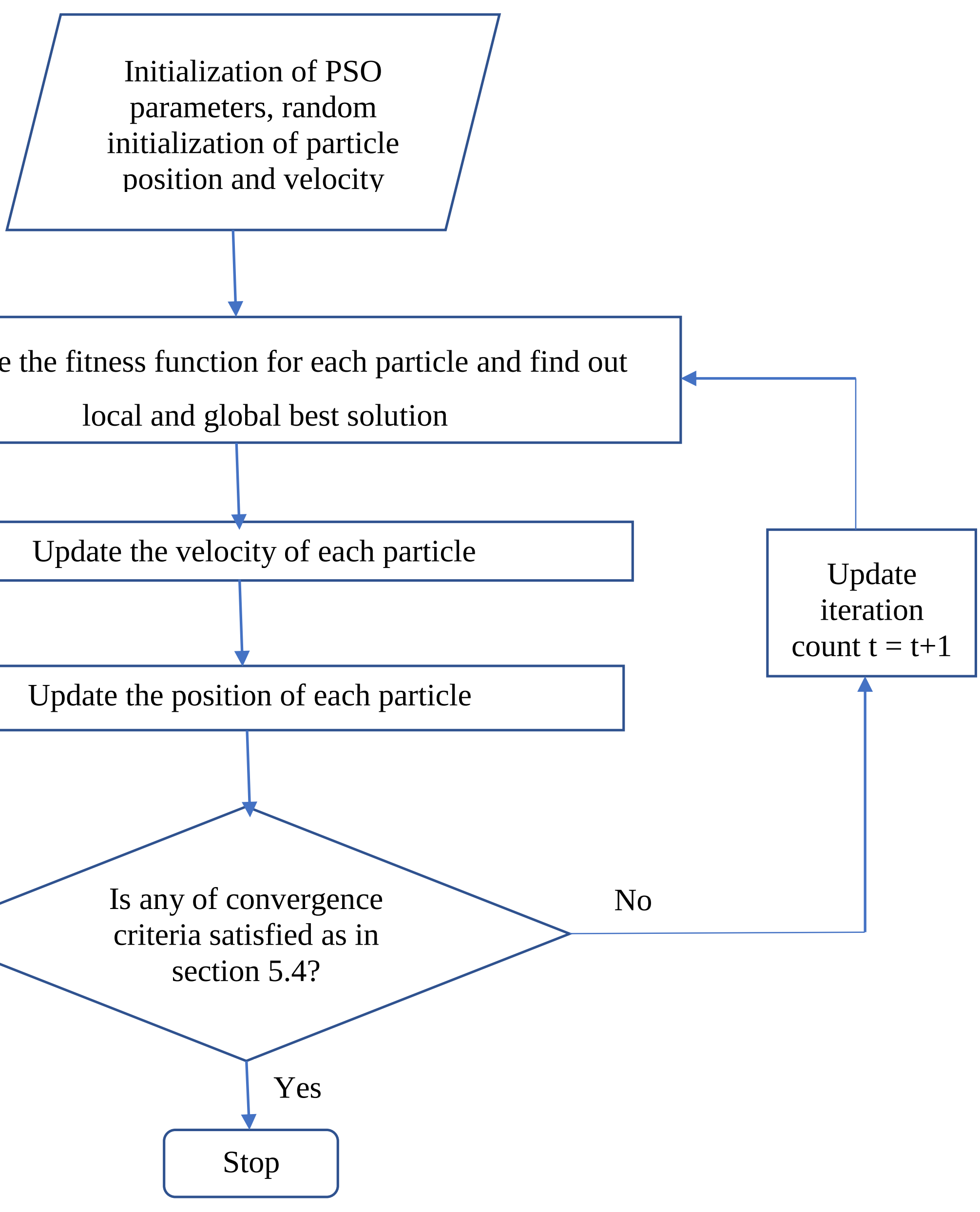


Figure 5.1 General PSO algorithm flow chart [18]

5.6 Analogy between PSO and bird flock

Analogy between particle swarm optimization (PSO) and bird flocking lies in their shared principles of collective behaviour, adaptation and emergent properties, making PSO a powerful optimization technique inspired by natural phenomena.

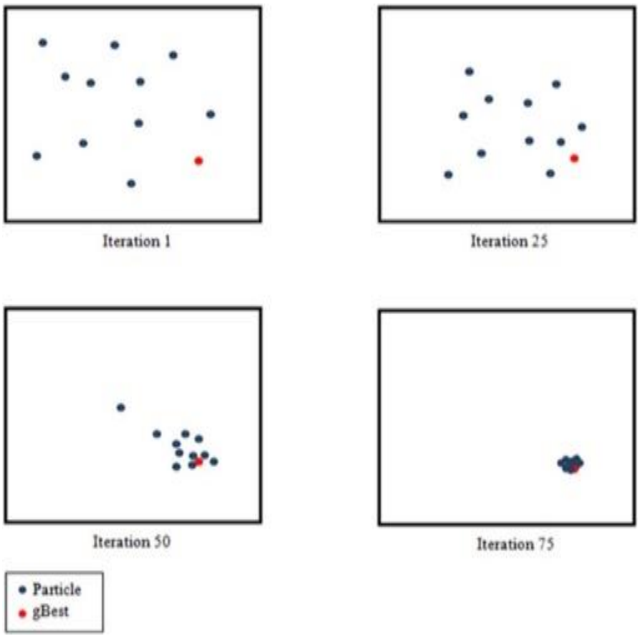


Figure 5.2 Bird flock **Figure 5.3 PSO movement towards global optima[17]**

Similarities in behaviour is explained in brief below:-

1. Individuals in a swarm: In PSO, particles represent individuals within a swarm. Similarly, in bird flocking, each bird in a flock represents an individual.
2. Search space exploration: Just as particles in PSO explore a search space to find optimal solutions, birds in a flock search for resources (such as food or shelter) within their environment.
3. Position update: The position update in PSO, which depends on the particle's velocity and previous position, is analogous to a bird's movement in response to its velocity and current location.

4. Social influence: PSO particles are influenced by both their personal best position (local best) and the best position found by any particle in the swarm (global best). Similarly, birds in a flock are influenced by the movement of nearby birds, leading to coordinated behaviour.

5. Adaptation to environment: Both PSO particles and birds adapt their movement based on environmental factors such as the presence of obstacles, availability of resources, and the movement of other individuals.

6. Emergent behaviour: PSO and bird flocking exhibit emergent behaviour, where complex collective patterns emerge from simple individual interactions. In PSO, this emergent behaviour leads to the convergence of the swarm towards optimal solutions, while in bird flocking, it leads to coordinated movements and formations.

5.7 Advantages and drawbacks of PSO over other evolutionary optimization techniques

1. Simplicity: PSO is relatively simple to implement and understand compared to other evolutionary algorithms such as genetic algorithms or differential evolution. It has fewer parameters to tune and is easier to customize for different optimization problems.

2. Efficiency: PSO often converges to the optimal solution quickly, especially for problems with smooth and continuous search spaces. Its simple update rules allow for efficient exploration and exploitation of the search space, leading to fast convergence.

3. Fewer parameters: PSO typically has fewer parameters to adjust compared to other evolutionary algorithms, making it easier to use for practitioners without deep knowledge of optimization techniques. This makes PSO a popular choice for optimization tasks where simplicity and ease of use are important considerations.

4. Global search capability: PSO has a strong global search capability, allowing it to effectively explore the entire search space and find globally optimal solutions. This makes PSO well-suited for optimization problems with multiple local optima or non-convex search spaces.

5. Memory less: PSO does not require maintaining a population of candidate solutions over multiple generations, unlike genetic algorithms or differential evolution. This memory less property reduces the computational overhead and memory requirements of PSO, making it more efficient for large-scale optimization problems.

6. Flexibility: PSO can be easily extended and customized to handle different types of optimization problems, including single-objective, multi-objective, constrained, and dynamic optimization problems. It can also be combined with other optimization techniques or problem-specific heuristics to enhance its performance.

7. Robustness: PSO is robust to noisy or uncertain objective functions and can handle optimization problems with discontinuous or non-smooth search spaces. Its stochastic nature allows PSO to escape local optima and explore the search space effectively.

Drawbacks of PSO:-

1. PSO has tendency to result in a fast and premature convergence in mid optimum points. [14]
2. Slow convergence in a refined search area (having weak local search ability). [15]

Chapter 6

Problem Statement

6.1 Objective

To determine the optimal location and size of distributed generation (DG) in the IEEE 33 bus system, Using particle swarm optimization (PSO) algorithm the effectiveness of the proposed method is to be verified by comparing power loss and voltage profiles with and without DG integration. A comparative study is to be presented to show the changes in power loss and voltage profile due to integration of DG.

6.2 Objective function

6.2.1 Single objective optimization:-

Active power loss minimisation is considered as objective function and it is expressed as:-

$$f = \min(P_{loss}) \quad \ldots (6.1)$$

Where f is the objective function and P_{loss} is the active power loss in the system.

6.2.2 Multi Objective optimization:-

A method has been studied using the PSO algorithm for minimisation of power loss along with the energy not supplied (ENS). In this method, a multi-objective function has been adopted to allow the optimisation of both parameters i.e. power loss and energy not supplied (ENS) at the same time. The objective function for multi-objective optimisation is given as:-

$$f_{mo} = w_1 \left(\frac{Ploss - P_{loss_{\min}}}{P_{loss_{\max}} - P_{loss_{\min}}} \right) + w_2 \left(\frac{ENS_{total} - ENS_{\min}}{ENS_{\max} - ENS_{\min}} \right) \quad \text{... (6.2)}$$

Where ENS_{total}= algebraic sum of ENS for the fault in all designated fuse locations.

- $P_{loss_{\min}}$ and $ENS_{\max}$ are the values of P_{loss} and ENS_{total} when P_{loss} is optimized alone.
- $P_{loss_{\max}}$ and $ENS_{\min}$ are the values of P_{loss} and ENS_{total} when ENS_{total} is optimized alone.
- w_1 and w_2 are the weightage factor.

In the equation 6.2, the two functions are taken into account, normalisation and weighting.

1. Normalisation
   - Power Loss normalisation

     $$\frac{P_{loss} - P_{lossmin}}{P_{lossmax} - P_{lossmin}}$$

     Above term normalises the power loss P_{loss} within the range defined by $P_{loss\,min}$ and $P_{lossmax}$. The resulting value will be between 0 and 1, where 0 represents minimum power loss and 1 represents maximum power loss.

   - Energy Not supplied (ENS) normalisation

     $$\frac{ENS_{total} - ENSmin}{ENS\max - ENSmin}$$

     Similarly, the above term normalises the total energy not supplied ENS_{total} within the range defined by ENS_{min} and ENS_{max}. The resulting value will also be between 0 and 1, where 0 represents the minimum ENS and 1 represents the maximum ENS.

2. Weighting

   w_1 and w_2 are weights assigned to the normalized power loss and ENS terms, respectively. These weights determine the relative importance of minimizing power loss versus minimizing ENS in the overall objective function.

6.3 Constraints considered

i.) The size of the distributed generation (DG) needs to be limited in the system to control voltage fluctuations, reduce the inclusion of harmonics, and manage costs.

$$\text{Min (DG Size)} \leq \text{DG Size} \leq \text{Max (DG Size)}$$

ii) Bus voltage limit needs to be taken care of while inserting the DG in the system, because voltage beyond certain limit may damage the components in the system.

$$0.90 \text{ pu} \leq V \text{ (in pu)} \leq 1.05 \text{ pu}$$

iii) DG location:- Considering the IEEE 33 Bus system , the DG location should be varied from node number 2 to node number 33.

6.4 Implementation of PSO in finding the optimal DG location and DG rating in IEEE 33 bus test system

Solving for optimal size & best location of DG, PSO based algorithm has been used and following steps are followed for implementation [5]:-

Step 1: Input system data such as line impedance, load and bus data.

Step 2: Run base case load flow program to get the base case power loss and reliability indices.

Step 3: Initialize population size.

Step 4: Initialize number of variables to be optimized.

Step 6: Generate random position and velocity for each particle.

Step 7: Calculate fitness value as objective function for each particle as defined in equation (6.1) for single objective function and equation (6.2) for multi-objective function for each DG location and size generated through step 6.

Step 8: Initialize current best position of each particle as '*pbest*'.

Step 9: Assign '*gbest*' as best amount '*pbest*' if new minimum is found and store it until new minimum is found. If a new minimum fitness value is found update the '*pbest'* corresponding to new position.

Step 10: Update velocity and position of each particle.

Step 11: If iteration count reaches maximum limit, go to Step 12 or else increase the counter by one and go to Step 7.

Step 12: Display the results. (Optimal DG location, Optimal DG rating)

Chapter 7

Results and Discussions

7.1 General

With the development of load flow technique, objective functions, constraints and solution techniques, the IEEE 33 bus system as given in figure 7.1 has been studied.

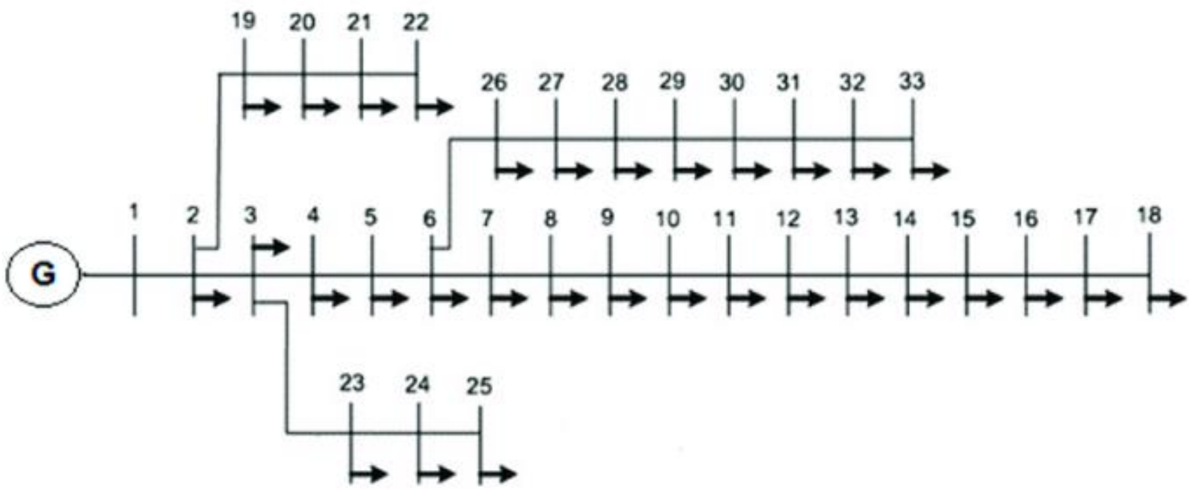


Figure 7.1 IEEE 33 Bus Single Line Diagram

Standard line and load data for the IEEE 33 bus system (in Appendix A) is being used for application of load flow techniques and solution techniques to get the results based on objective function as discussed in chapter 6 using MATLAB.

7.2 Load flow result for the system under base case condition

7.2.1 Bus voltage profile without the DG in IEEE 33 bus test system:-

Bus no.	Voltage (in pu) (angle in radian)	Bus no.	Voltage (in pu) (angle in radian)	Bus no.	Voltage (in pu) (angle in radian)
1	$1.00\angle 0$	12	$0.9177\angle -0.0192$	23	$0.9793\angle -0.0004$
2	$0.9970\angle 0.0001$	13	$0.9115\angle -0.026$	24	$0.9726\angle -0.00423$
3	$0.9829\angle 0.0007$	14	$0.9092\angle -0.034$	25	$0.9693\angle -0.0079$
4	$0.9754\angle 0.0014$	15	$0.9078\angle -0.012$	26	$0.9475\angle 0.0018$
5	$0.9680\angle 0.0021$	16	$0.9064\angle -0.0473$	27	$0.9450\angle 0.00285$
6	$0.9495\angle 0.0011$	17	$0.9044\angle -0.06095$	28	$0.9335\angle 0.0044$
7	$0.9460\angle -0.006$	18	$0.9038\angle -0.0737$	29	$0.9253\angle 0.0059$
8	$0.9323\angle -0.0127$	19	$0.9965\angle -0.001$	30	$0.9218\angle 0.0082$
9	$0.9260\angle -0.0168$	20	$0.9929\angle -0.00105$	31	$0.9176\angle 0.0013$
10	$0.9201\angle -0.0205$	21	$0.9922\angle -0.0147$	32	$0.9167\angle -0.0015$
11	$0.9192\angle -0.02$	22	$0.9916\angle -0.023$	33	$0.9164\angle -0.0048$

Table 7.1 Bus voltage without DG in the system

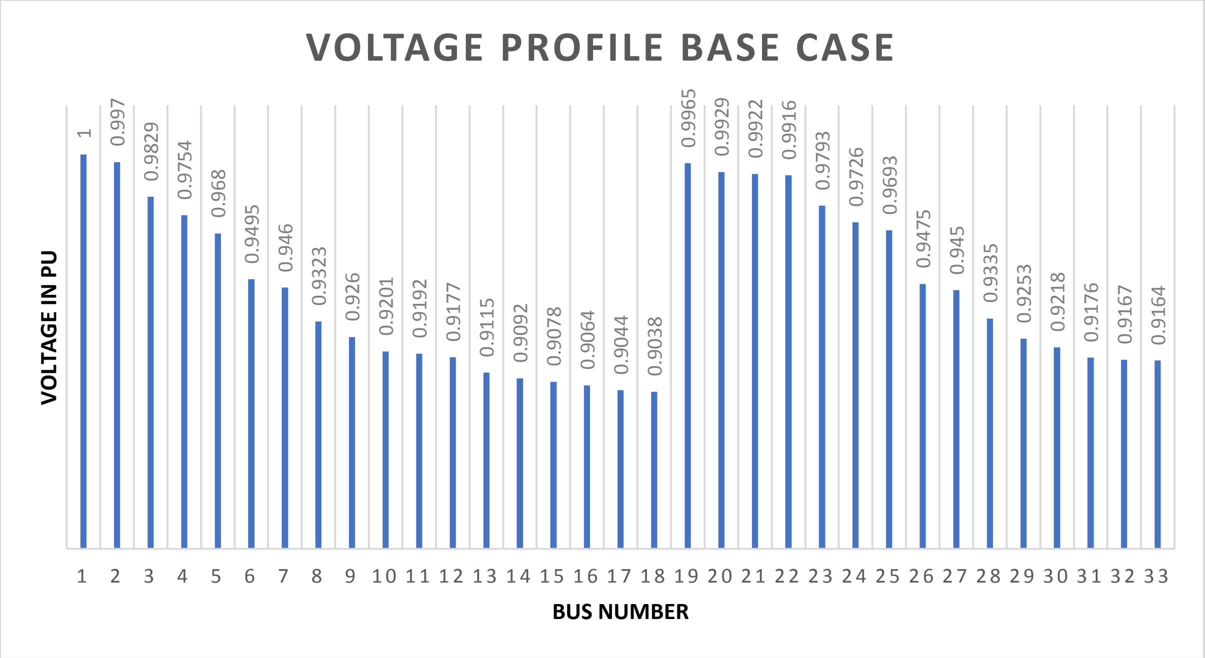


Figure 7.2 Bus voltage profile in base case without DG.

7.2.2 The total active and reactive power generation and total active and reactive power loss of IEEE 33 bus test system for base case condition are shown in table 7.2.

Total Active Power Generated (in kW)	**Total Reactive Power Generated (in kVAr)**	**Total Active Power loss (in kW)**	**Total Reactive Power loss (in kVAr)**
3715	2300	210.998	143.033

Table 7.2 Generation, load and power loss without DG.

From the table 7.1, 7.2 and figure 7.2, following observations are clear:-

Parameters	Bus number	Voltage magnitude (in pu)
Maximum voltage	19	0.9965
Minimum voltage	18	0.9038
Total active power loss (in kW)	210.998	

Table 7.3 Maximum, minimum value of voltages and active power loss in the system without DG.

From the figure no. 7.2, it can be deduced that maximum voltage is found in node no. 19 while the minimum voltage is found in node no. 18 which is obvious since it is the farthest most point from the generator end, hence maximum dip in the voltage is found in farthest most node i.e. at node number 18.

7.3 Inclusion of one DG in the system to minimise total active power loss using PSO

After finding the result for base case of load flow without the DG, Now the task is to find the optimal location and size of a DG so that total active power losses in the system could be minimised. In addition, voltage profile of the system will also be observed by including one DG in the system at the optimum location and comparative study would be done thereafter. The analysis has been done in MATLAB platform. With the help of PSO steps as described in article 6.4 , it is found that bus no 6 is the best location for single DG placement to minimise the total active power loss in the IEEE 33 bus test system. The DG size is found to be 2456 kW and DG location will be 6 as shown in table 7.4

Optimal Location of DG	Optimal DG rating in kW	Total Active Power loss (in kW)
6	2456	111.27

Table 7.4 Optimal location and rating of DG to minimise total active power loss

The voltage profile of the buses after inclusion of DG, of the desired rating at the desired location no. 6 as indicated in table no.7.4, has been improved and shown in table 7.5.

Bus no.	**Voltage (in pu) (angle in radian)**	**Bus no.**	**Voltage (in pu) (angle in radian)**	**Bus no.**	**Voltage (in pu) (angle in radian)**
1	$1.00\angle 0$	12	$0.95385\angle -0.004$	23	$0.9888\angle 0.0017$
2	$0.9985\angle 0.0004$	13	$0.9479\angle -0.0118$	24	$0.9822\angle -0.0020$
3	$0.9923\angle 0.002$	14	$0.9457\angle -0.019$	25	$0.9789\angle -0.005$
4	$0.9907\angle 0.005$	15	$0.9443\angle -0.026$	26	$0.9825\angle 0.014$
5	$0.9894\angle 0.007$	16	$0.9430\angle -0.030$	27	$0.9801\angle 0.0158$
6	$0.9844\angle 0.014$	17	$0.9410\angle -0.05$	28	$0.9690\angle 0.017$
7	$0.9810\angle 0.007$	18	$0.9404\angle -0.05$	29	$0.9611\angle 0.0187$
8	$0.9678\angle 0.001$	19	$0.9979\angle -0.0007$	30	$0.9577\angle 0.020$
9	$0.9617\angle -0.002$	20	$0.9944\angle -0.010$	31	$0.9537\angle 0.0147$
10	$0.9561\angle -0.006$	21	$0.9937\angle -0.014$	32	$0.9528\angle 0.011$
11	$0.95530\angle -0.005$	22	$0.9931\angle -0.023$	33	$0.9525\angle 0.008$

Table 7.5 Bus voltages with DG at optimal location.

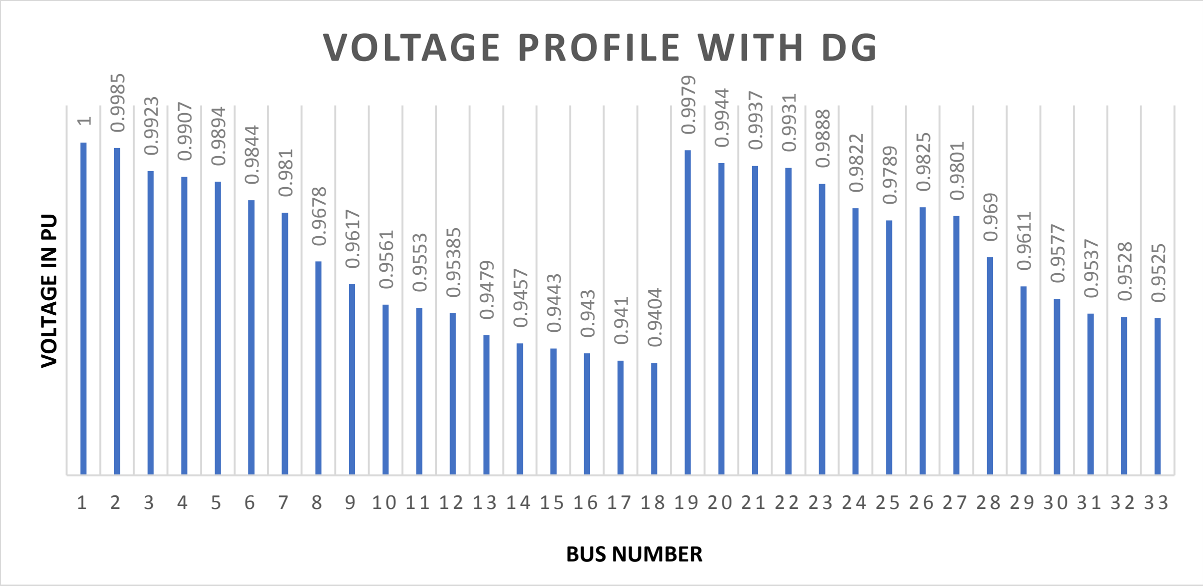


Figure 7.3 Bus voltage profile with one DG in the optimum location

From the table 7.5 and figure 7.3 following observations can be drawn:-

Parameter	Bus number	Voltage magnitude (in pu)
Maximum voltage	19	0.9979
Minimum voltage	18	0.9404

Table 7.6 Maximum and minimum value of voltages in the system with DG.

7.4 Comparative study of cases with and without DG in IEEE 33 Bus system

Cases	Power loss (in kW)	Min. voltage (in pu)
Without DG	210.998	0.9038
With DG	111.27	0.9405
% change in parameter with single DG placement	47.26% decrease	4.06% improved

Table 7.7 Effect of inclusion of DG in the system

Based on Table 7.7, a comparative study shows that the inclusion of DG in the system reduces active power loss by approximately 47.26%. This significant improvement enhances system efficiency and robustness, improving overall operation. Voltage is a critical parameter in any distribution system, as voltage dips can reduce system robustness and affect the performance of home appliances. Therefore, voltage improvement measures are crucial for planning engineers. By including one DG, a significant improvement of about 4.06% in the worst-case voltage has been achieved. Additionally, as seen in Figure 7.4 below, voltage improvements occur not only at the minimum voltage node but across almost every node in the system.

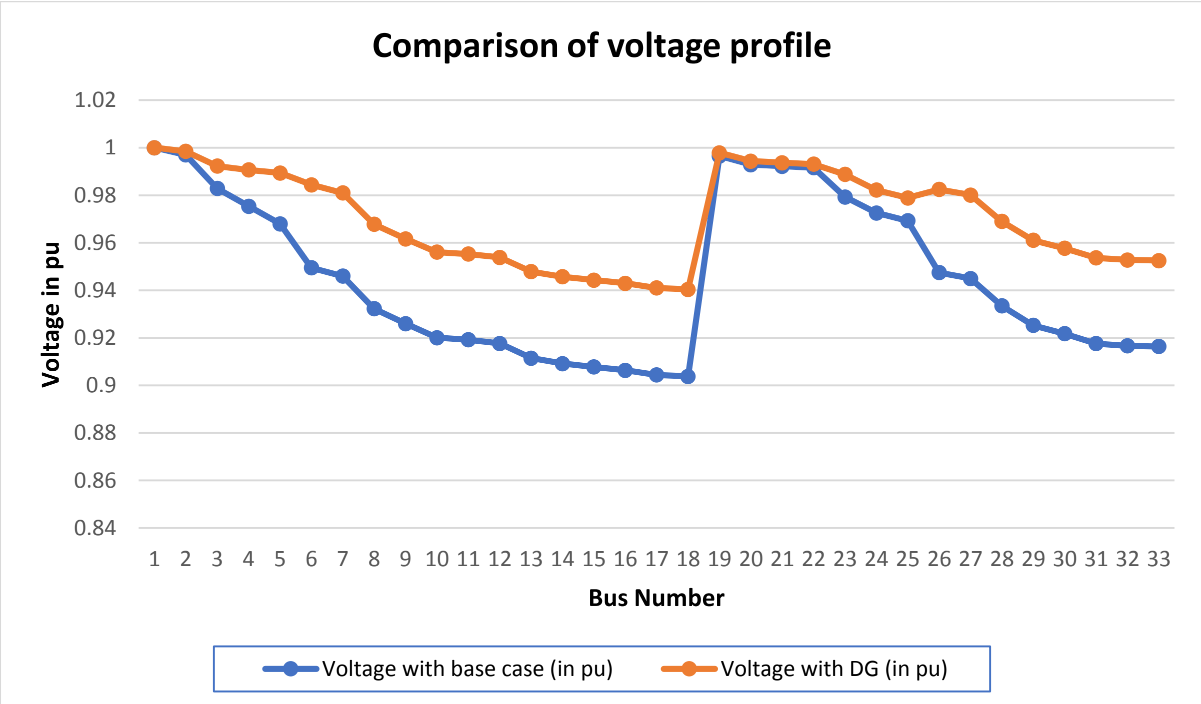


Figure 7.4 Bus voltage comparison without DG and with DG.

7.5 PSO algorithm convergence

The convergence curve over iteration number is shown in the figure 7.5.

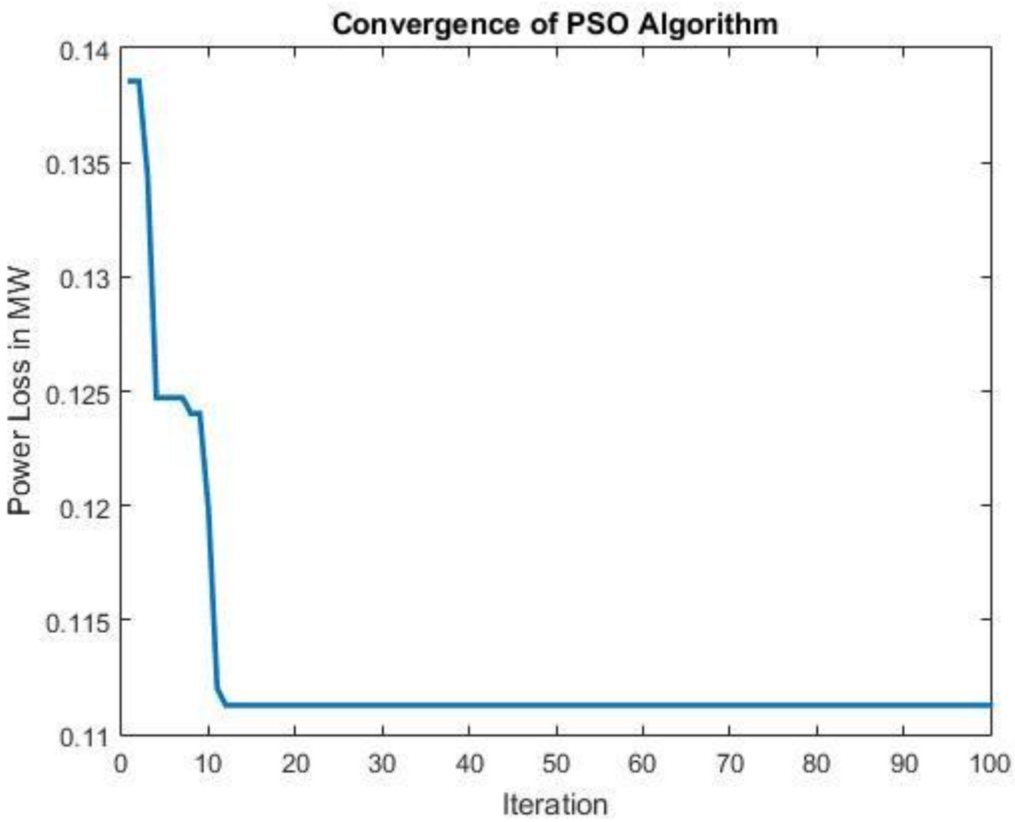


Figure 7.5 Convergence of PSO algorithm.

It can be seen from the curve that during initial number of iterations i.e. from 1-10, there is fast convergence of the PSO to reach out the optimum point. After 10^{th} iteration, the variation in the power loss is somewhat minimal.

7.6 Reliability Studies in the IEEE 33 Bus system

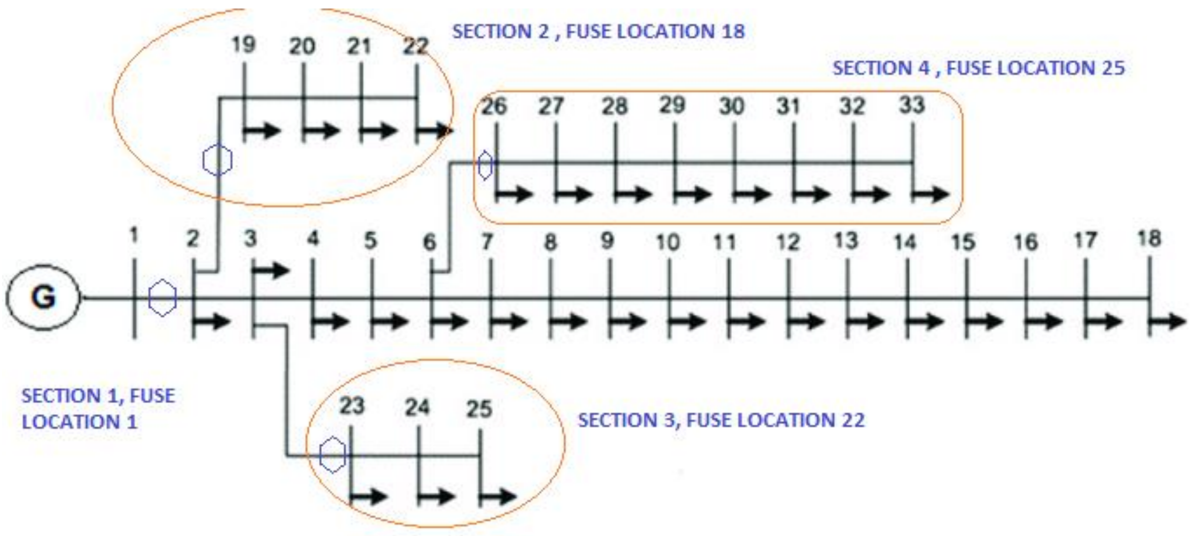


Figure 7.6 IEEE 33 Bus system with fuse installed and sections divided

In the figure 7.6, IEEE 33 bus test system has been divided in 4 sections with fuse location at key tie set locations 1, 18, 22 and 25 respectively. The division of section will give the idea about reliability of the system at the time of fault in the sections by calculating reliability indices of the system in case of different fuse locations and then a comparative study will be done on the basis of the indices. Data for mean time to repair, load connected in each nodes, probability of occurrence of fault per year has been prepared and given in appendix B. It should be noted that there is no inclusion of DG in the mentioned cases. The reliability indices has been calculated with fault in each sections without DG and the results are given in the table 7.8

Fault in section	Fuse location	Customer based indices			Energy based indices	
		System average interruption duration index (SAIDI)	System average interruption frequency index (SAIFI)	Customer average interruption duration index (CAIDI)	Energy not supplied (ENS) (kWh)	Average energy not supplied (AENS) (kWh)
1	1	3.3498	12.7262	0.2632	36757.80	43.244
2	18	0.3562	0.8333	0.4275	4118.40	4.845
3	22	0.2155	1.2950	0.1664	5697.30	6.703
4	25	0.7424	2.6108	0.2843	10323.20	12.145

Table No. 7.8 Reliability calculation for fault in each section with fuses without DG

7.7 Comparative study of reliability indices

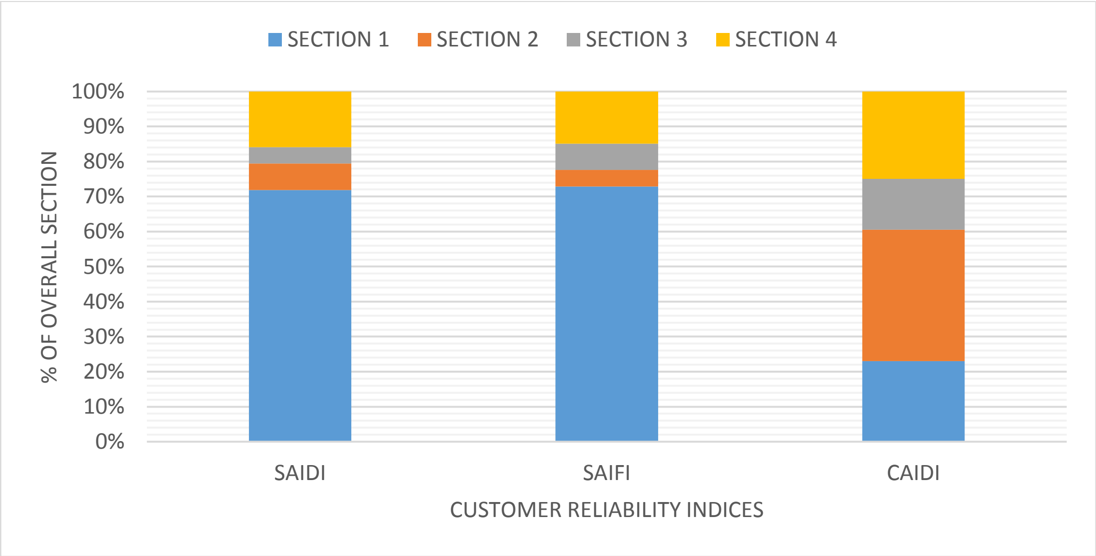


Figure 7.7 Customer based reliability indices for fault in various sections

Figure 7.7 shows the customer based reliability indices for fault in section 1 to 4 considering only one fault at a time. It can be seen from the graph that SAIDI is highest for fault in section 1, since number of customer duration interruptions during the fault in section 1 is highly affected. It is least in section 2 for the same reason as the number of customer interruption duration is least for section 2 as per appendix B.

Similarly we can see that for SAIFI, the section 1 is having highest value as the frequency of interruption is also high in this case when the fault was in section 1. And the same was least for section 2.

CAIDI is the ratio of SAIDI and SAIFI, hence it just reflects the value of both these indices.

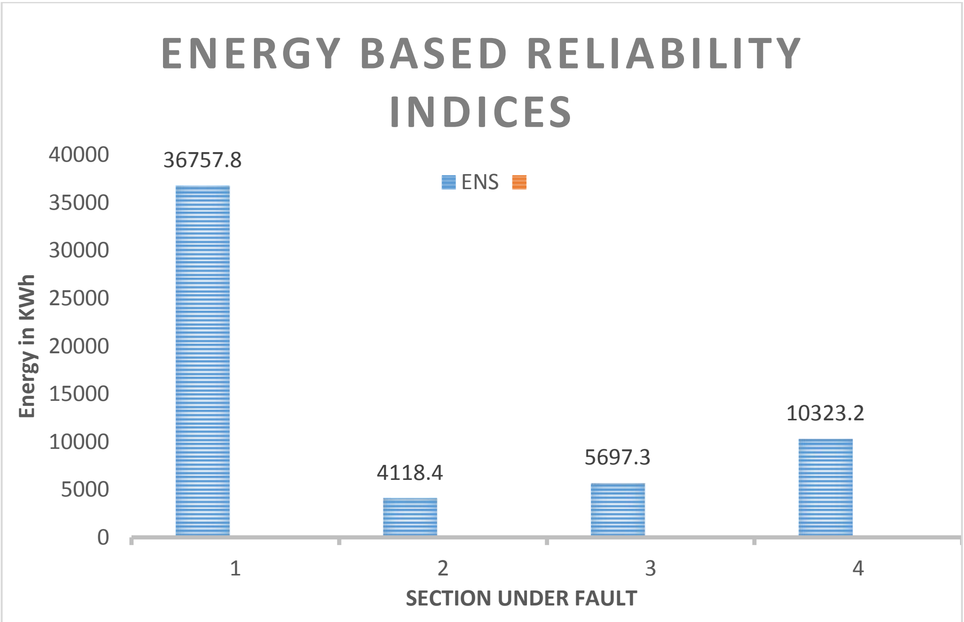


Figure 7.8 Energy not supplied (ENS) for fault in various sections

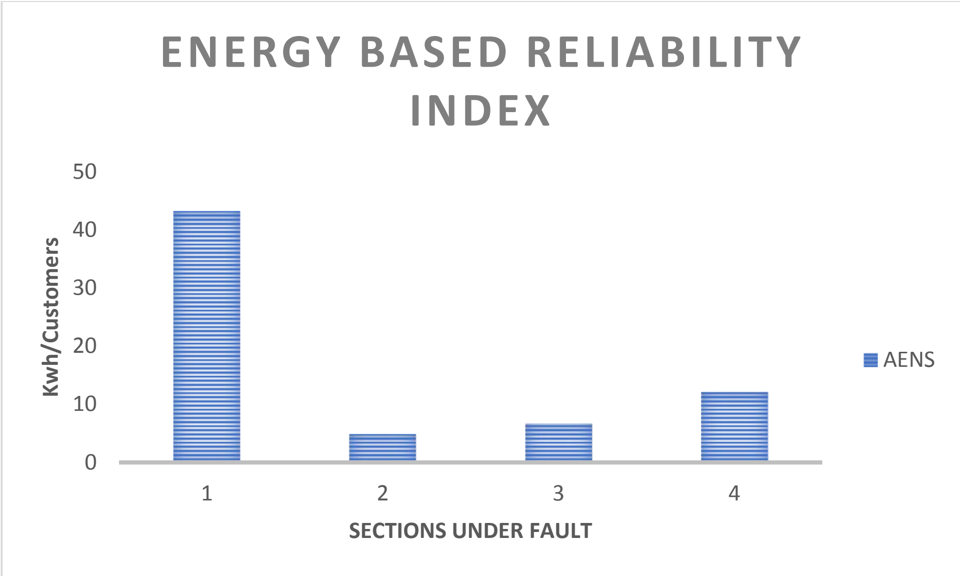


Figure 7.9 Average energy not supplied (AENS) for fault in various sections

Figure 7.8 and 7.9 show the variation of energy based reliability indices i.e. ENS and AENS for different faulty sections. It can be seen that maximum ENS occurred for fault in the section 1. Since when the fault is in section 1, maximum nos. of customers will get affected hence maximum amount of energy will be obstructed in this case, hence ENS is maximum in this case. Section 2 has least ENS, since the loading in this section is minimal.

From the above discussion, it can be seen that reliability indices calculations depends on the various factors in the distribution system like number of customers connected, annual failure rate, number of interruptions , load connected etc.

7.8 Optimum DG size considering power loss and ENS_{total}

In reference to the multi-objective function defined in section 6.2.2, a study has been conducted to minimize both power loss and ENS_{total} using the PSO algorithm. Three cases were examined:

First case: Only power loss is minimized.

Second case: Only ENS_{total} is minimized.

Third case: Both power loss and ENS_{total} are minimized simultaneously.

In the third case, the weighting factors for both normalized power loss and normalized ENS_{total} in the multi-objective function given in equation 6.2 are equal (w_1 and w_2 = 0.5).The cases are as follows:

Case	DG location	DG size (in kW)	P_{loss} (in kW)	ENS_{total} (in kWh)
P_{loss} is optimized alone	6	2456	111.27	56896.7
ENS_{total} is optimized alone	27	262.33	189.54	9815
P_{loss} and ENS_{total} both are optimized simultaneously	26	2417.59	112.95	9815.70

Table No. 7.9 Location of DG, P_{loss} and ENS_{total} for different cases of optimisation

Table 7.9 shows the variation in DG size, DG location, ENS_{total}, and power loss in the system. When ENS_{total} is optimized alone, power loss is highest at 189.54 kW, but ENS_{total} is minimized. Conversely, optimizing power loss alone results in the lowest power loss at 111.27 kW, but ENS_{total} is found to be maximum. The third case, where both ENS_{total} and power loss are minimized simultaneously, achieves near-optimal values for both metrics, making it the most acceptable scenario for minimizing both ENS_{total} and power loss.

Case	Customer based indices			Energy based indices		P_{loss} (in kW)
	SAIDI	SAIFI	CAIDI	ENS (in kWh)	AENS (in kWh)	
1. Base case without DG	4.67	17.47	0.27	10323.20	12.145	210.99
2. P_{loss} is optimized alone	4.66	17.47	0.27	20138.90	23.69	111.27
3. ENS_{total} is optimised alone	4.60	17.43	0.26	9815.70	11.55	189.54
4. P_{loss} and ENS_{total} both optimised simultaneously	4.61	17.44	0.26	9815.70	11.55	112.95

Table No. 7.10 Reliability indices for different cases considered in the multi-objective function.

Table 7.10 shows the effect of including DG installation on reliability indices and power loss in the system. The first case, without DG, has the highest power loss at 210.99 kW. Cases 2 to 4 inclusion of DG, reduces total active power loss. Customer-based reliability indices, such as SAIDI and SAIFI, improve in cases 2 to 4 compared to the base case. Specifically, SAIDI and SAIFI are nearly the same in cases 3 and 4, but higher in case 2, which is undesirable for reliability. Although case 3 has the minimum reliability indices, it also has the highest power loss. The optimal case, balancing reliability and power loss, is case 4, where both power loss and ENS_{total} are minimized.

Chapter 8

CONCLUSION

8.1 Contributions to the work

Firstly, a literature survey related to the research area has been conducted and different solution techniques has been explored.

In conclusion, this thesis underscores the pivotal role of distributed generation (DG) integration in modernizing power distribution systems, offering a sustainable pathway towards enhanced efficiency and reliability. By harnessing the power of the particle swarm optimization (PSO) algorithm, this study strategically positions DG units within the IEEE 33 bus distribution system, effectively minimizing power losses and bolstering voltage stability.

Moreover, through comprehensive reliability assessments utilizing indices such as SAIDI, SAIFI, CAIDI, AENS, and ENS, this research provides a nuanced understanding of system performance under diverse operational scenarios. The findings demonstrate that the incorporation of DG units, guided by the PSO algorithm, not only reduces overall power loss and voltage drop but also elevates reliability indices, signifying a marked improvement in system robustness.

By elucidating the symbiotic relationship between DG integration, optimization methodologies, and reliability analysis, this study advances the discourse on distribution system planning and operation strategies. It underscores the imperative of embracing distributed energy resources as pivotal components of a resilient and sustainable energy infrastructure.

In the face of evolving challenges in power distribution, including the need for resilience against disruptions and the imperative of reducing carbon emissions, the insights gleaned from this research offer actionable pathways forward. By leveraging advanced optimization techniques and reliability assessments, stakeholders can proactively steer distribution system planning towards a more efficient, reliable, and environmentally conscious future.

Combined study of both power loss and improvement in reliability indices with the help of PSO algorithm as a multi-objective problem gives broad approach to power system designers to consider both the parameters as combined fitness function, which then gives the optimum performance to the system.

In essence, this thesis serves as a testament to the transformative potential of integrating distributed generation, reliability studies and advanced optimization techniques in revolutionizing power distribution paradigms, paving the way for a more resilient, sustainable, and adaptive energy landscape.

8.2 Scopes of the future work

i) The inclusion of distributed generation with multi- objective function like minimisation of power losses along with minimisation in various reliability indices can be studied further.

ii) Real time reliability analysis of the actual distribution system using powerful tools will be beneficial in future design of distribution system.

iii) Different weightage factor to difference reliability indices can be given and analysed for further minimization of the parameters.

Appendices

Appendix A

Load Data of IEEE 33 Bus system

Bus No	P (in kW)	Q(in kVAr)
1	0	0
2	100	60
3	90	40
4	120	80
5	60	30
6	60	20
7	200	100
8	200	100
9	60	20
10	60	20
11	45	30
12	60	35
13	60	35
14	120	80
15	60	10
16	60	20
17	60	20
18	90	40
19	90	40
20	90	40
21	90	40
22	90	40
23	90	50
24	420	200
25	420	200
26	60	25
27	60	25
28	60	20
29	120	70
30	200	600
31	150	70
32	210	100
33	60	40

<u>Line data of IEEE 33 Bus System</u>

Line No.	From Bus	To Bus	R (in Ω)	X (in Ω)
1	1	2	0.0922	0.0470
2	2	3	0.4930	0.2511
3	3	4	0.3660	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	1.7144	1.2351
8	8	9	1.03	0.74
9	9	10	1.044	0.740
10	10	11	0.1966	0.0650
11	11	12	0.3744	0.1238
12	12	13	1.4680	1.155
13	13	14	0.5416	0.7129
14	14	15	0.5910	0.5260
15	15	16	0.7463	0.5450
16	16	17	1.2890	1.7210
17	17	18	0.7320	0.5740
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3554
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3083
23	23	24	0.898	0.7091
24	24	25	0.8960	0.7011
25	6	26	0.2030	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0590	0.9337
28	28	29	0.8042	0.7006
29	29	30	0.5075	0.2585
30	30	31	0.9744	0.9630
31	31	32	0.3105	0.3619
32	32	33	0.3410	0.5302

Appendix B

Modified consumer data for reliability study [3]

Bus No	kW	kVA	Nos. of Consumers	Lambda (Fault/year)	MTTR (in hr)
1	0	0	0	0.432	20.23
2	100	117	41	0.431	16.23
3	90	98	34	0.232	14.45
4	120	144	50	0.321	11.04
5	60	67	23	0.301	11.44
6	60	63	1	0	0
7	200	224	4	0.301	11.44
8	200	224	4	0.301	11.44
9	60	63	1	0.301	11.44
10	60	63	0	0.301	11.44
11	45	54	58	0.301	11.44
12	60	69	74	0.301	11.44
13	60	69	28	0.314	11.17
14	120	144	58	0.301	11.44
15	60	61	24	0.208	11.17
16	60	63	2	0.301	11.44
17	60	63	21	0.301	1.75
18	90	98	33	0.301	11.44
19	90	98	32	0.301	11.44
20	90	98	32	0.301	11.44
21	90	98	10	0.301	11.44
22	90	98	10	0.301	11.44
23	420	103	10	0.208	1.75
24	420	465	45	0.208	1.75
25	60	465	45	0.301	11.44
26	60	65	6	0.301	11.44
27	60	65	7	0.301	11.44
28	120	63	6	0.301	11.44
29	200	139	14	0.301	11.44
30	90	632	64	0.301	11.44
31	150	166	17	0.327	10.96
32	210	233	44	0.327	10.96
33	60	72	14	0.327	10.96

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