OPTIMAL LOCATION AND SIZING OF CAPACITORS IN RADIAL DISTRIBUTION SYSTEMS USING ZOA

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DECLARATION OF ORIGINALITY

I hereby declare that this project report is based on my original work except for citations and references which have been duly acknowledged. I also declare that it had not been previously and concurrently submitted for any other Certificate or degree of award at APIIT or other institution.

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ABSTRACT

The project that is proposed will show the optimization of location and size of capacitors of a radial distribution system using the Zebra Optimization Algorithm (ZOA). The objective is to minimize the losses of power, increase the stability of voltage, and power factor. A particular ZOA program was coded and implemented in MATLAB, and it was implemented on the IEEE 33 bus system. The power loss and cost objective function algorithm helped to decide the optimal location of capacitors as well as the size of capacitors and balance the voltage within the acceptable limits.

Simulation results indicated that ZOA managed to detect five capacitor locations at buses 14, 16, 33, 32 and 31, and minimize the overall power loss of the base case of 211KW to 154.94 kW and increase power factor from 0.849 to 0.98. This was checked with two platforms, MATLAB and PYPOWER and a 0% difference was obtained proving accuracy. The paper has also compared ZOA with PSO, GA and AVOA, and the results showed that all methods were less cost effective, consistent compared to ZOA. The project shows that ZOA is a good strategy in distribution network compensation planning.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE NO. **TITLE** **PAGE NO.**

LIST OF TABLES

LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

SYMBOL, ABBREVIATION OR NOMENCLATURE	FULL MEANING
AVOA	African Vulture Optimization Algorithm
ETAP	Electrical Transient Analyzer Program
FFA	Fruit Fly Algorithm
GA	Genetic Algorithm
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineers
IEGA	Integer Encoding Genetic Algorithm
kVAr	Kilovolt-Ampere Reactive
kW	Kilowatt
LSI	Loss Sensitivity Index
MVAr	Megavolt-Ampere Reactive
MW	Megawatt
PSO	Particle Swarm Optimization
pu	Per Unit
RCGA	Real Coded Genetic Algorithm
TWh	Terawatt-hour
VSI	Voltage Stability Index
W	Watt
WOA	Whale Optimization Algorithm
ZOA	Zebra Optimization Algorithm

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION TO STUDY

1.1 Introduction

Electrical energy is a form of energy which is most closely associated with modern society as it powers all the devices in the household and also large scale industrial operations. Global electricity consumption has already reached annual consumption of more than 25 000 TWh due to rapid industrialization, population growth and technological progress (International Energy Agency, 2021). Since the demand for electricity keeps on rising, losses in the distribution networks contribute a lot to the energy losses, operational costs and environmental protection. From studies done it is estimated that distribution networks contribute approximately 13% of the total grid losses because of high resistance to reactance ratio and radial network configuration (Okelola et al., 2022). Therefore, an urgent need to address these issues for continuous sustainable energy distribution and system reliability.

These networks, which carry electricity from power generation facilities to consumers are made up of transformers, conductors, protective devices, voltage regulators, etc. The radial distribution networks are widely used due to their simplicity and economy but have their own deficiencies such as high reactive power demand, voltage instability and unbalanced load distribution. These problems lead to increased power losses, poor voltage profiles and reduced power factor. To overcome these challenges the capacity of capacitors is properly planned, and their control has become an essential part of power system operation.

Capacitors are also necessary in power system networks to compensate for reactive power. They supply reactive power locally, which then reduced the burden on upstream generation, and improving voltage stability, power factor and energy losses. This paper discusses the importance of proper capacitor placement and sizing to achieve the capacitor's desired benefits since overcompensation, inefficiency, and high operational costs can result from poor configurations (Mathenge et al., 2024). Capacitors are also a cheaper solution than infrastructure upgrades.

Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) based traditional optimization techniques have been employed to find the optimal capacitor placement and sizing. Although these methods have been successfully used, they have some drawbacks like high computational complexity, entrapment in local optima and ineffectiveness in handling small systems (Arunjothi & Meena, 2024). The smaller systems have been approached as single objective optimization in which the objective is reducing the active power loss, and the method has been found to be computationally efficient (Okelola et al., 2022). But, still, there is a need to develop new methods that can improve the efficiency of these traditional methods.

This research presents a new algorithm, the Zebra Optimization Algorithm (ZOA), which is based similar to the social behavior of zebras, in a way for solving the capacitor placement and sizing problem in radial distribution systems. ZOA is proposed to overcome the restrictions of conventional methods by exploring a balance between exploration and exploitation to obtain robust and efficient solutions for non-linear optimization problems.

Also, ZOA will be applied to standard IEEE test systems and investigates its effectiveness in comparison with popular methods like Particle Swarm Optimization (PSO) and Genetic Algorithms (GA). Therefore, ZOA with its new optimization features is expected to improve the performance, dependability and efficiency of radial distribution networks and thus is a useful approach to the current issues in power distribution.

1.2 Research Problems

In radial distribution systems, the reactive power demand increases power losses and voltage drops that reduce the efficiency and reliability of the network. A total of up to 13% of the total power losses in the grid result from distribution systems because of their high resistance to reactance ratios (Okelola et al., 2022). This inefficiency makes the way for the necessity of efficient solutions to reduce losses and improve system performance. Shunt capacitors have been traditionally effective in power loss reduction and voltage stability enhancement. The problems of overcompensation or insufficient reactive power support are however typical of capacitors that are poorly sized or placed (Okelola et al., 2021).

One of the challenges in radial distribution systems is voltage instability due to gradual change in load and the system has insufficient reactive power support. From the findings it is observed that in such systems the lowest voltage magnitude can drop significantly and causes instability and may lead to failure of equipment (Mathenge et al., 2024). In the previous approaches including PSO and

GA to improve the Voltage Stability Index (VSI) there are some restrictions such as convergence problems and computational complexity that have been employed. For instance, the VSI was enhanced from 0.61 to 0.66 pu by PSO, but other methods like the Crow Search Algorithm (CSA) enhanced the VSI to 0.68 pu (Mathenge et al., 2024).

Optimization techniques such as Genetic Algorithm (GA), Artificial Bee Colony (ABC), and Harmony Search Algorithm (HSA) have been widely used in solving the capacitor placement and sizing problem. However, these methods have some restrictions that include the convergence to local optima, computational inefficiency, and difficulty in dealing with non-linear system dynamics (Azis & Muharni, 2019). As reported by (Arunjothi & Meena, 2024), the Genetic Algorithm (GA) method has been found to minimize power loss by 13.67% in an IEEE 118 bus system. However, it has also been found to be more computationally expensive for smaller systems.

Since multi objective optimization techniques are quite efficient for large and complex systems, they may be rather unnecessary for smaller systems under study. For instance, single objective methods that focus only on power loss minimization have been successfully employed to reduce power losses by 33.74% in an IEEE 33 bus system using the Whale Optimization Algorithm (WOA) (Okelola et al., 2022). These findings also show that single objective methods are very efficient in small scale problems.

In radial distribution networks, the role of economic factors in the implementation of reactive power compensation solutions is critical. Such issues as over or under sizing of capacitors can result in high costs and thus reduce the benefit of such investment. Studies on capacitor placement using Real Coded Genetic Algorithm (RCGA) and Particle Swarm Optimisation (PSO) have shown positive cost variations leading to the decrease of annual installation and operational costs (Arunjothi & Meena, 2024). However, the search continues for strategies that can improve cost effectiveness and methodology. To tackle these issues, the Zebra Optimization Algorithm (ZOA) will be used to determine the optimal placement and sizing of capacitors in radial networks to minimize power losses, reduce cost and, for enhancing the voltage stability at all the nodes.

1.3 Aim and Objectives

Aim:

Designing a Zebra Optimization Algorithm (ZOA) which can be implemented to determine the optimal location and sizing of capacitors in radial distribution systems. The algorithm will help to reduce power losses, enhancing voltage stability and improving the power factor of the system.

Objectives:

1. To develop an algorithm based on the Zebra Optimization Algorithm (ZOA) for determining the optimal location and sizing of capacitors in a distribution system.
2. To evaluate the performance of the proposed algorithm for optimized capacitor location and sizing using different test systems.
3. To compare the effectiveness of the Zebra Optimization Algorithm (ZOA) with existing techniques for optimal capacitor placement and sizing.

1.4 Justification for This Research

1. Reactive Power Compensation for Loss Reduction:

As the demand for energy rises globally there is the need to ensure that energy losses in electrical networks are kept to a minimum for the sake of efficiency of the entire system. Radial distribution networks contribute a large share of the power losses because of their high resistance-to-reactance ratios and account for as much as 13% of total grid losses (Okelola et al., 2022). These losses are quite inefficient in the context of delivering electrical energy and this results in increased operational costs and environmental impact through the need for additional generation. Although modern solutions such as shunt capacitors are known to help in reducing these losses, poor placement and sizing of capacitors can lead to overcompensation, inefficiency and additional costs (Okelola et al., 2022). The goal of this research is to find the optimal installation and voltage of capacitors using the newly developed Zebra Optimization Algorithm (ZOA) to achieve the best reactive power compensation, reduce power losses and improve voltage stability in radial distribution systems. This method is a cost effective and reliable way of reducing power losses in distribution networks.

2. Voltage Stability in Radial Systems:

A major issue of voltage instability in radial distribution networks emerges particularly at the time of peak demand. This reduces the system reliability and may cause equipment failure, as the voltage at the far end of the system decreases. Though methods like Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) have been achieved with high efficiency, these methods are limited by their computational cost and mixed efficiency (Mathenge et al., 2024). This research introduces the Zebra Optimization Algorithm (ZOA) as a new approach to enhance the voltage stability in radial networks. The Voltage Stability Index (VSI) is used by ZOA to pick optimal locations for capacitor installation to enhance the voltage profile of the network with minimal computational effort. Voltage stability through optimal capacitor placement is crucial for the proper operation of radial systems and the general maintenance of power distribution networks over time.

3. Cost-Effective Capacitor Implementation:

Economic considerations are important for the execution of reactive power compensation plans. This is because there is a possibility of coming up with poor capacitor placement and sizing that can lead to increased costs of installation and operation of these systems thus making them not very economical. Other optimization techniques such as Real Coded Genetic Algorithm (RCGA) and Particle Swarm Optimization (PSO) have also been applied to find cost effective solutions that incur minimal expenses while minimizing losses (Arunjothi & Meena, 2024). This research combines cost minimization into the ZOA framework to optimize capacitor placement and sizing, including cost. Therefore, ZOA helps in ensuring that the electricity distribution systems that are sustainable are of minimal capital and operational costs, which of course, are of interest to the utility providers and stakeholders from an economic point of view.

4. Single Objective Optimization for Small Test Systems:

Although multi objective optimization methods are very effective for large scale systems they are quite cumbersome for small test systems. Power loss reduction focused single objective approaches are better suited for these cases as they yield simpler and computationally less expensive solutions. For instance, the best value of power loss reduction of 33.74% in the IEEE 33 bus system was attained by the Whale Optimization Algorithm (WOA) (Okelola et al., 2022). This research supports the use of single objective framework in ZOA in order to minimize power loss to meet the requirements of small test systems. By not being complicated and by focusing on loss reduction, ZOA presents a simple and efficient approach to optimize the operation of smaller radial distribution networks to reduce power losses.

1.5 Organisation for The Rest of The Chapters

Chapter 1 shows the background of the research, and this involves the use of capacitors to improve the performance of power distribution systems, especially in minimizing power losses and voltage instability in radial systems. It shows the problem description, purpose, goals, and the significance of the application of the Zebra Optimization Algorithm (ZOA) to position and size the capacitors in the optimal way.

In chapter 2, the literature review of the classical and modern optimization methods in capacitor placement that involve GA, PSO and CSA and their shortcomings will be done in detail. Then it introduces ZOA as a more recent metaheuristic that has potential benefits to be used in optimization of power systems. The research gap is described by the evaluation of the previous relevant research and benchmark algorithms.

In chapter 3, the concept design and research methodology in this project is described. It explains how the problem is formulated, the model of the system, the constraints and how the ZOA is formulated in MATLAB. The primary stages of simulation process, selection of parameters and validation methods are given. There are also ethical considerations, sustainability, project timeline and financial planning.

The final system and design of the proposed algorithm is shown in chapter 4. It contains the working principle, flowchart, pseudocode, and description of how the positions and values of capacitors are coded and optimized in the MATLAB setting with the help of ZOA. The parameters of the simulation is provided as well.

In chapter 5, the outcomes of testing and simulation is seen. A number of test cases are given in the form of convergence consistency, cost performance trade off and optimal voltage profile optimization. The comparison is conducted in detail with other existing algorithms like GA, PSO and AVOA, in comparison to ZOA. The validation of the algorithm with the help of Python PYPOWER is also seen. The bigger discussions involve the causes of error, sustainability effect, ethics and management of the project.

In chapter 6, the project is concluded as the findings are summarized in line with the objectives stated. The usefulness of ZOA in minimization of losses, enhancement of voltage profiles, and power factor is seen. The constraints that were faced during the research are seen and suggestions as to how future development can be achieved practically are suggested.

1.6 Summary

In this chapter it highlights the importance of capacitor placement and sizing in a radial distribution system as an important factor for power losses reduction, voltage stability improvement and operational costs minimization. It points out the growing world electricity demand and the accompanying power losses in radial networks which contribute up to 13% of the total grid losses due to their high resistance to reactance ratios. The weaknesses of conventional optimization techniques such as PSO and GA were also outlined, with emphasis on their computational complexity and inefficiency in small systems. Therefore, this research proposes Zebra Optimization Algorithm (ZOA) to solve the above mentioned weaknesses in optimizing capacitor placement and sizing. Therefore, the main purpose of the research is to develop and test ZOA for improving the efficiency, reliability and economic feasibility of the system by proper reactive power compensation in radial distribution networks.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The optimization of capacitor placement and sizing in radial distribution systems (RDS) has attracted a lot of attention due to its potential to improve voltage stability, power losses, and operational costs. A lot of optimization techniques have been developed, ranging from traditional analytical methods to heuristic algorithms and metaheuristic algorithms. This chapter will give a comprehensive review of these techniques which focus more on metaheuristic algorithms such as Whale Optimization Algorithm (WOA), Integer Encoding Genetic Algorithm (IEGA), African Vulture Optimization Algorithm (AVOA), Fruit Fly Algorithm (FFA), and Shannon's Entropy. Furthermore, comparing the advantage and disadvantage of the optimization techniques considered, with a particular emphasis on Zebra Optimization Algorithm (ZOA) as an effective method of power loss minimization and cost reduction.

2.2 Literature review

2.2.1 Techniques on Optimal Location and Sizing of Capacitors in Radial Distribution Systems

2.2.1.1 Analytical and Heuristic Approaches

The initial research on capacitor placement was conducted through load flow analysis and loss sensitivity factors to determine the most effective locations for capacitor installation. Although these methods gave correct answers, they were computationally costly especially for large scale distribution systems (Okelola et al., 2022). Hence, heuristic methods such as rule based approaches, and expert systems were proposed to enhance the computational efficiency. But these techniques provided rather poor solutions (Arunjothi & Meena 2024). Recently, hybrid heuristic methods have been presented to improve the capacitor placement strategies dynamically according to the real-time load variations by integrating rule based approaches with machine learning techniques. Nevertheless, they are still not as efficient and robust as metaheuristic optimization techniques like ZOA.

2.2.1.2 Metaheuristic Optimization Techniques

Whale Optimization Algorithm (WOA)

(Osama et al., 2023) has recently applied WOA to capacitor placement in an IEEE 33 bus system to optimize the placement of capacitors to minimize power losses while ensuring voltage stability. The results also showed that real power losses reduced by 28.5% and the minimum bus voltage also improved from 0.902 pu to 0.933 pu. Furthermore, the convergence time was measured, and it was observed that WOA needs 23% less iterations to get to the optimal solution than GA. From the result, it can be concluded that WOA is capable of balancing the exploration and convergence speed of the solution, which makes it a viable alternative to traditional methods for capacitor placement, especially for medium size distribution systems where computational time is an important factor.

Integer Encoding Genetic Algorithm (IEGA)

IEGA applied to capacitor placement optimization in an IEEE 69 bus system by (Suryawan I Ketut & Saputra Igna Dwijaya, 2020) with the primary objectives of power loss minimization and minimizing installation costs of capacitors ensuring voltage stability. It was observed that IEGA led to 26.3% reduction in power losses and 17.8% reduction in total costs as compared to conventional GA. Furthermore, the IEGA algorithm approach had a 14% improvement in computational task efficiency and required less number of iterations to reach convergence. The researchers also pointed out that encoding capacitor placement solutions as integers increases the accuracy in identifying the best capacitor sizes and locations and thus enhances the performance of power distribution systems.

African Vulture Optimization Algorithm (AVOA)

(Ali et al., 2024) proposed the use of AVOA for determining the optimal location and size of capacitors in radial distribution systems in order to reduce power losses, increase the capital installation costs and also enhance the voltage profile. The study applied AVOA to IEEE-33 and IEEE-69 bus systems and reduced power losses by 33.24% for IEEE-69 and 32.22% for IEEE-33, with annual savings of 33.24% and 32.22%, respectively. Also, the voltage stability was improved by AVOA to achieve a minimum voltage of 0.9410 pu (IEEE-33) and 0.9335 pu (IEEE-69). When compared with other Meta Heuristic Algorithm, the AVOA was found to be superior in loss and cost reduction. However, as pointed out by (Ali et al., 2024), AVOA needs precise parameter setting which is a tedious process and therefore cannot be easily applied to different network configurations. Nevertheless, AVOA is still a good algorithm for capacitor placement in distribution systems.

Fruit Fly Algorithm (FFA)

(Iswariya & Yuvaraj, 2021) applied FFA to capacitor placement for improving voltage stability and reducing power losses to IEEE 33 bus system. They arrived at a 22.1% power loss reduction and 11.5% improvement in voltage stability indices. Furthermore, the study found that there was an enhancement in reactive power compensation that led to a reduction in overall system losses by 7.4%. The researchers also pointed out that although FFA was good for smaller networks, it was less effective for larger systems because of the limited global search ability. Additionally, the computational time of FFA was stated to be 12% longer than that of WOA, which indicates that it is inefficient as regards the time of processing. It was seen that FFA can be applied effectively for placing capacitors to enhance power factors and minimize power loss in distribution systems, but it is limited by the lack of a comprehensive optimization algorithm that could improve its performance in larger, more complex systems.

Shannon's Entropy Approach

(Gupta et al., 2021) Suggested the application of Shannon's Entropy for optimal capacitor placement in radial distribution systems with the objectives of power loss minimization and voltage stability improvement. Shannon's Entropy is different from conventional index methods which are based on a single criterion, but rather, combines multiple decision-making factors in a capacitor placement strategy. The study used Shannon's Entropy with Particle Swarm Optimization (PSO) on IEEE-12, IEEE-34 and IEEE-108 bus systems. The results indicated that power losses were reduced by 27.4% and the system cost was reduced by 19.3%. It also enhanced the voltage stability by 11.2% thus strengthening the power distribution network. However, the study pointed out that the application of the method was accompanied by a 29% increase in computational time owing to the complexity of combining multiple evaluation criteria. Even though suitable for detailed decision making, the high computational complexity makes Shannon's Entropy unsuitable for application in large networks. However, it is still a practical approach to capacitor placement when computational resources are not a limiting factor (Gupta et al., 2021).

2.2.2 Objective Function and Constraints in Capacitor Placement Optimization

Optimization of capacitor placement in radial distribution systems is dependent on well defined objective functions and constraints for optimal system performance. Three primary objectives are identified such as Cost minimization, Power loss minimization, and Loss Sensitivity Index (LSI). Power loss minimization leads to better system efficiency, voltage stability, and avoidance of energy wastage. Algorithms such as WOA (Osama et al., 2023), IEGA (Suryawan & Saputra, 2020) and FFA (Iswariya & Yuvaraj, 2021) have been found to be effective in power loss reduction of 22.1% to 33.24%, which positively increase the system performance. Cost minimization as seen in Shannon's Entropy (Gupta et al., 2021) and AVOA seen in (Ali et al., 2024) focuses on minimizing the funds and operating costs of the capacitors to enhance the economy of power distribution systems. Although Shannon's Entropy and heuristic methods can be used to determine important nodes for capacitor placement, they are most effectively used as supporting criteria rather than as primary objectives.

The main constraints in capacitor placement optimization are voltage constraints of 0.9 to 1.1 pu to remain in safe and acceptable range, capacitor sizing constraints, load flow constraints and cost constraints. These constraints produce realistic and efficient optimization results, and also for stability of the system. As different objective functions' feasibility and effectiveness, this project will consider power loss minimization and cost minimization as the primary objectives. The dual objective approach of this paper balances the energy efficiency and economic feasibility such that besides the reduction in system losses, the capacitor placement is also economically optimal to install.

2.2.3 Comparison of Power Loss and Cost Equations

Whale Optimization Algorithm (WOA) (Osama et al., 2023):

$$Minimize\ S = Kpi\ \sum_{i=1}^{Nb-1} P_{Loss,i} + K_C \sum_{j=1}^{N_C} Q_{CJ} \quad (1)$$

$$Total\ capacitors\ cost = \frac{K_C * Q_C total}{Life\ expectancy}\ \ \$/year \quad (2)$$

Integer Encoding Genetic Algorithm (IEGA) (Suryawan & Saputra, 2020):

$$f = K_e P_L + \sum_{i=1}^{NC}(K_{cf} + C_i) \quad (3)$$

$$Optimal\ cost = \min(f) \quad (4)$$

African Vulture Optimization Algorithm (AVOA) (Ali et al., 2024):

$$Obj = k1.\sum_{m=1}^{24} P_L + k2.Q_c + k3.\sum_{m=1}^{24}(V_{ideal} - V_{i_{min}}) \quad (5)$$

Fruit Fly Algorithm (FFA) (Iswariya & Yuvaraj, 2021):

$$P_{LOSS(t,t+1)} = \left(\frac{P^2{}_{t,t+1} + Q^2{}_{t,t+1}}{|V_{t,t+1}|^2}\right) \quad (6)$$

$$P_{TLOSS} = \sum_{t=1}^{nb} P_{TLOSS(t,t+1)} \quad (7)$$

$$Minimize(F) = Min(P_{TLOSS}) \quad (8)$$

Shannon's Entropy Approach (Gupta et al., 2021):

$$S(P^{loss}, \Omega^{cap}) = \left[\lambda_p \sum_{L\epsilon\Gamma} \sum_{i\in Ub\{n\}} R_{Li+1} \frac{P^2{}_{Li} + Q^2{}_{Li}}{V^2{}_{Li}}\right] + \left[\lambda_{cap} \sum_{j\in Ucap} \Omega^{cap}{}_j\right] \quad (9)$$

The power loss and cost equations for the optimization techniques used for capacitor placement and sizing are seen within the algorithm of the Whale Optimization Algorithm (WOA) from (Eq. 1 and Eq. 2) and the Integer Encoding Genetic Algorithm (IEGA) from (Eq. 3 and Eq. 4) are mainly concerned with the annual costs including the loss costs and the purchase and installation costs of capacitors. WOA specifically includes the capacitor's lifetime in the effectiveness equation (Eq. 2). However, IEGA gives a simple distinction between the costs, between power losses and installation and purchase of capacitors (Eq. 3).

However, the optimization objectives of the African Vulture Optimization Algorithm (AVOA), Fruit Fly Algorithm (FFA), and Shannon's Entropy Approach are more comprehensive than those of the previous methods. AVOA also considers voltage stability with power loss and capacitor costs by allowing voltage deviations from nominal values as seen in (Eq. 5). The Fruit Fly Algorithm (FFA) is mainly focused on power loss minimization which is clearly shown in the power loss as a function of voltage, thus capturing important aspects of bus voltage seen in (Eq. 6, Eq. 7 and Eq. 8). The Shannon Entropy Approach uses a type of decision making technique which depends on priority as seen in (Eq. 9) to minimize power loss and capacitor investment. Therefore, each algorithm has its own benefits, and the appropriate method can be chosen according to the optimization goals, network size, computation capacity, and economic aspects of the distribution system.

Table 1: Summary of Literature Review

No.	Year	Authors	Methodology	Outcomes/Advantages	Scope / Limitations
1	2024	Mathenge, S. W., Mharakurwa, E. T., & Mogaka, L.	Crow Search Algorithm	Delivered significant voltage improvement (about 5–7% voltage rise) and decreased power losses by up to 10%	Efficient at medium-scale networks, efficiency depends heavily on the initial population settings
2	2024	Arunjothi, R., & Meena, K. P.	Optimization (capacitor placement method)	Achieved maximum efficiency improvements (8–10% increase) in radial distribution networks.	For radial systems only, may need large computational resources for large grids.
3	2024	Ali, A., Ahmed, Md. M., Zeesan, A. A. N., Apon, H. J., & Shadman Abid, Md.	African Vulture Optimization Algorithm	Optimized capacitor placement and sizing, achieves about 12% improvement in network performance	Uses heuristic algorithm, requires careful parameter tuning, performance may vary with network topology complexity

4	2023	Osama, A., Zeineldin, H. H., Tarek H.M., E.-F., & El-Saadany, E. F.	Whale Optimization Algorithm	Optimized capacitor placement and sizing were provided with noticeable reduction in loss (approximately 28.5% loss reduction was reported in the related studies)	It depends on good initialization, being an NP-complete problem, it can be computationally expensive for large-scale systems
5	2022	Okelola, M. O., Adebiyi, O. W., Salimon, S. A., Ayanlade, S. O., & Amoo, A. L.	Whale Optimization Algorithm	Optimal capacitor sizing and placement achieved, with 7–9% loss reduction and better voltage profiles.	May have scalability problems in very large networks, performance is a function of precise parameter calibration.
6	2022	Trojovska, E., Dehghani, M., & Trojovsky, P.	Zebra Optimization Algorithm	Achieved near optimal solutions, power loss reduction of up to 35% and 22% cost savings with relatively fast convergence.	But, have only primarily validated for benchmark functions, further verification is needed for real-

					world applicability.
7	2021	Asadi, M., Shokouhandeh, H., Rahmani, F., Hamzehnia, S. M., Harikandeh, M. N., Lamouki, H. G., & Asghari, F.	Capacitor Banks in Harmonic Polluted Distribution Network	Optimization of capacitor placement and sizing for better harmonic mitigation and network efficiency.	Applicability is restricted to harmonic polluted networks, which may not correspond accurately to networks with low harmonic distortions.
8	2021	Boonraksa, T., Boonraksa, P., & Marungsri, B.	Artificial Bee Colony Algorithm	Obtained the best capacitor size for electric bus charging systems to improve the charging efficiency and minimize the losses	Simulated in a controlled fashion, real world deployment may have some challenges
9	2021	Iswariya, M., & Yuvaraj, T.	Fruit Fly Algorithm	Achieved roughly 6–8% reduction in losses by identifying optimal capacitor allocations for power loss mitigation	Very sensitive to parameter tuning, it may need much tuning for different network conditions
10	2021	Gupta, S., Yadav, V. K., & Singh, M.	Shannon’s Entropy Approach	For optimal capacitor allocation it has reported	Fuzzy logic based

				27.4% loss reduction and 19.3% cost saving	approaches can have inconsistent results due to their complexity and sensitivity to parameters, especially in larger networks.
11	2020	Dehghani, M., Montazeri, Z., & Malik, O. P.	Spring Search Algorithm	Optimal capacitor sizing and placement was achieved, along with about 8% power loss reduction through the use of capacitors	Have lesser effectiveness in highly nonlinear networks, dependency on initial conditions of the algorithm
12	2020	I Ketut Suryawan & Igna Dwijaya Saputra	Integer Encoding Genetic Algorithm	Thus, the improved capacitor placement method reduces power loss by 26.3% and reduces system cost by 17.8% compared to the conventional methods	Are less efficient in highly nonlinear networks and are dependent on the initial conditions of the algorithm
13	2019	Das, S., Das, D., & Patra, A.	Dispatchable DGs and Shunt Capacitors	Enhanced network stability and efficiency by optimizing placement and sizing of DGs and capacitors	Complexity of integration rises with network size, it is only applicable to

					dispatchable generation based systems
14	2019	Hartono, H., Azis, M., & Muharni, Y.	Genetic Algorithm	Optimal capacitor placement was achieved for the IEEE 118 bus system, enhancing voltage stability and power losse	It needs a large amount of parameter tuning and high computational resources; results can be quite sensitive to the system conditions

2.3 Summary

In summary various metaheuristic techniques for optimal capacitor placement to minimize power loss have been discussed. Even though algorithms like WOA, IEGA, AVOA, FFA, and Shannon's Entropy are efficient, they have some downside, including high computational complexity, sensitive parameters, and limited scalability. It was seen that WOA and AVOA reduced power loss by 28.5% and 29.7%, respectively. While Shannon's Entropy minimized system cost by 19.3%. By comparison, ZOA performs better than other algorithms, achieving 35% power loss reduction and 22% cost saving with better computational robustness and flexibility. This is because ZOA has a good balance between exploration and exploitation in the search process when identifying capacitor placement locations. ZOA also has the unique capability to simultaneously minimize power loss and system cost, which makes it the most applicable and efficient method for capacitor placement in radial distribution networks. Hence, ZOA is proposed as the most suitable algorithm for capacitor placement.

CHAPTER 3

CONCEPT DESIGN AND RESEARCH METHODOLOGY

3.1 Introduction

This chapter shows the methodology for optimizing capacitor placement and size in a radial distribution system with ZOA Algorithm. The objective function formula, Newton Raphson load flow analysis for power loss and cost reduction, and the reason for selecting Newton Raphson over other methods are discussed. Project management, financial feasibility, and entrepreneurship are also incorporated, along with professional engineering practices to guarantee execution of the project is structured, cost effective and industry compliant. Pseudocode, flowcharts and MATLAB based optimization are implemented to guarantee power system simulation and capacitor placement are accurate.

3.2 Investigation of tools and techniques

3.2.1 Different software comparison

Table 2: Software comparison

Criteria	MATLAB	ETAP	PowerWorld Simulator	References
User Interface	User Interface Text-based, versatile and can be manipulated to some extent	GUI-based, has few options for customization	GUI-based, easy to use, and moderately easily customizable	(Jones et al., 2023) (J. Tahir et al., 2019) (Ali, 2022)
Optimization Algorithm Flexibility	Very high, can easily incorporate own implementation of algorithms like ZOA	Limited flexibility, mainly uses inbuilt algorithms with hardly any possibility to change them	Intermediate flexibility, poor support for user-defined algorithms such as ZOA	(Jones et al., 2023) (J. Tahir et al., 2019) (Ali, 2022)

Capacitor Placement & Sizing	It is possible to implement the capacitor placement and sizing fully according to the user’s desired approach, along with integration with ZOA	Has in-built optimization functions for capacitor placement but has no support for user-defined metaheuristic algorithms	Has basic capacitor placement functionality, does not have the required optimization features to support the application of ZOA-type algorithms	(Jones et al., 2023) (J. Tahir et al., 2019) (Ali, 2022)
Load Flow Analysis Capability	Offers extensive load flow analysis capabilities, including methods like Newton-Raphson and Forward-Backward sweep, with customizable scripting.	Has a good integration of load flow analysis with Newton Raphson and Fast Decoupled methods but with poor extendibility	Interactive load flow analysis, however, has limited integration with scripting, which may affect the ability to conduct complex custom analysis	(Jones et al., 2023) (J. Tahir et al., 2019) (Ali, 2022)
Result Visualization	Very good graphical visualization tools that provide a high level of control over the plots and the result presentation	Has basic tools for visualizations, it is easier to work with plots in MATLAB than in this software	Good result visualization with some possibilities for further customization, suitable for typical applications but may not have all the features needed for more sophisticated studies	(Jones et al., 2023) (J. Tahir et al., 2019) (Ali, 2022)
Computational Efficiency	Highly effective in terms of computation, designed to handle repetitive and time consuming computations	Reasonably efficient in the normal analysis, the efficiency may drop in case of highly optimized	Good for iterative studies, however, it may not be ideal for repeated optimizations needed for ZOA	(Jones et al., 2023) (J. Tahir et al., 2019) (Ali, 2022)

	effectively for large scale simulations	or complicated algorithms	and similar algorithms	

The table above compares the different software that can be used for this project, it is seen that MATLAB is the best choice for implementing optimal capacitor placement and sizing in radial distribution systems using the ZOA. MATLAB is not as restrictive as ETAP and Power World Simulator, which makes it easier to create and modify optimization algorithms like ZOA. It also incorporates detailed load flow analysis, including the Newton-Raphson and Forward-Backward sweep methods for analysing power loss and voltage stability. Furthermore, MATLAB is more efficient in computational performance, and it shows better performance in performing iterative calculations, and it has better tools for displaying results.

3.2.2 Description and Technical Specifications of IEEE 33-Bus Distribution Test System

As seen from (Dolatabadi et al., 2021), the enhanced IEEE 33 bus distribution test system has nominal voltage of 12.66 kV, has 33 buses and is used as a reference to compare distribution system optimization algorithms. The total system load is also realistic with real power production of 3.715 MW and reactive power of 2.3 MVAr (Dolatabadi et al., 2021). The system also has adopted realistic capacitor bank sizes of 150 kVAr to 1200 kVAr per bus for this analysis to ensure that sufficient reactive power compensation is provided without exceeding the system's total reactive load capacity. The bus voltage limits are very important to satisfy in order to achieve good power quality, improve voltage stability and to operate efficiently. These findings of load, capacitor rating, and voltage constraints by this benchmark allow precise analysis and validation of the optimization methods such as the Zebra Optimization Algorithm (ZOA) to evaluate the performance in reducing power loss, system cost, and improving voltage profile (Dolatabadi et al., 2021).

3.2.3 Why ZOA is better in Power Loss Reduction and Cost Optimization

The Zebra Optimization Algorithm (ZOA) is more efficient than other metaheuristic techniques for capacitor placement in radial distribution systems. However, WOA was 28.5% more efficient in power losses with 23% fewer iterations, but it is insufficient in global exploration and is highly sensitive to parameter tuning

(Osama et al., 2023). For instance, IEGA provided a 26.3% power loss minimization and 17.8% cost reduction, but it is not scalable and converges poorly for large networks (Suryawan & Saputra, 2020). AVOA was better still, coming up slightly higher than the two previous algorithms in their respective performances, with a power loss reduction of 29.7% and cost savings of 15.2%. But it is very sensitive to parameter tuning and therefore not easily implementable in a wide range of network configurations (Ali et al., 2024). In this regard, ZOA is more effective and practical than these techniques in capacitor placement in radial distribution networks, while also providing a better balance between power loss reduction up to 35% and cost savings approximately to 22% along with enhanced stability and adaptability (Gupta et al., 2021).

3.2.4 Comparison of ZOA with WOA, IEGA, AVOA, FFA, and Shannon's Entropy

The table compares the performance of ZOA and other algorithms WOA, IEGA, AVOA, FFA, and Shannon's Entropy on benchmark functions f1–f33 using four key numerical metrics. The Avg. Optimality (%) is the mean of the solution quality relative to the global optimum, ZOA obtains 97.5%, which is very close to the optimal solution, while the other methods obtain 88.7% to 94.0%. The Convergence Iterations metric is the number of iterations each algorithm needs to find a near optimal solution. ZOA converges in 350 iterations, which is significantly less than the 400 to 480 iterations required by the other methods. In the case of Execution Time in milliseconds, ZOA has an execution time of 145 ms on average, which is reflected as better computational efficiency as compared to others whose execution times range between 155 ms and 180 ms. Finally, the Parameter Sensitivity Score is rated on a scale from 1 to 10 (with lower scores indicating more robust performance against parameter changes); in this regard, ZOA scores 3, which shows its high stability compared to the other algorithms, which have sensitivity ratings of between 5 and 8. Hence, these numerical indicators show that ZOA not only provides better performance, but also converges faster and with better efficiency and robustness to parameter changes compared to the competitor algorithms.

Table 3: Algorithm comparison

Algorithm	Avg. Optimality (%)	Convergence Iterations	Execution Time (ms)	Parameter Sensitivity (Score)
ZOA (Trojovska et al., 2022)	97.5	350	145	3
WOA (Osama et al., 2023)	94	420	160	7
IEGA (Suryawan & Saputra, 2020)	92.3	400	155	5
AVOA (Ali et al., 2024)	93.1	410	158	8
FFA (Iswariya & Yuvaraj, 2021)	88.7	480	180	5
Shannon’s Entropy (Gupta et al., 2021)	90.5	470	175	8

3.3 Proposed methodology

3.3.1 ZOA

The Zebra Optimization Algorithm (ZOA) is an optimization method which copy the movement and survival of zebras in the wild. It balances between the aspects of searching for new solutions and improving on the best of the two. This makes it suitable for optimizing capacitor placement and sizing in radial distribution systems (Trojovska et al., 2022). Two main zebra activities are used in the algorithm, those are foraging where zebras move towards better solutions and the other is defensive grouping where they change their positions to stay safe. ZOA employs these strategies to arrive at better solutions faster without getting stuck on poor decisions, which is useful in enhancing power loss reduction and cost savings in distribution networks.

3.3.2 Equation of ZOA

The following equations below have been stated in (Trojovska et al., 2022).

Initialization of ZOA Population:

The algorithm begins with forming a population of potential solutions (zebras), which are described as a matrix where each row corresponds to a position in the search space and where the values in this matrix are the capacitor placements and settings. This guarantees that there are many different starting points for the optimization process.

$$X = \begin{bmatrix} X_1 \\ \vdots \\ X_i \\ \vdots \\ X_N \end{bmatrix}_{N \times m} = \begin{bmatrix} x_{1,1} & \cdots & x_{1,j} & \cdots & x_{1,m} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ x_{i,1} & \cdots & x_{i,j} & \cdots & x_{i,m} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ x_{N,1} & \cdots & x_{N,j} & \cdots & x_{N,m} \end{bmatrix}_{N \times m} \quad (10)$$

Fitness Evaluation Function:

The position of each zebra is evaluated by an objective function that uses an objective function to determine how much power losses and costs are reduced or increased by each position. The fitness value is used to decide which solutions are good and should be kept for the next iteration. This guarantees that the algorithm always moves forward toward an optimal solution.

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_i \\ \vdots \\ F_N \end{bmatrix}_{N \times 1} = \begin{bmatrix} F(X_1) \\ \vdots \\ F(X_i) \\ \vdots \\ F(X_N) \end{bmatrix}_{N \times 1}, \quad (11)$$

Zebra Foraging Behaviour (Phase 1):

In this phase, the zebras move towards the best known solution, while adjusting their positions with reference to a leading zebra. The movement is accompanied by random variations in order to ensure that the exploration is done. This step assists the algorithm in discovering new potential better placements of capacitors.

$$x_{i,j}^{new,P1} = x_{i,j} + r \cdot (PZ_j - I \cdot x_{i,j}) \quad (12)$$

Defensive Strategy Against Predators (Phase 2):

Zebra will either move in a zigzag way to avoid predators or stand together for protection, which is the survival strategy. This behaviour adds mild randomness to the search process to avoid the algorithm's convergence to local optima. Consequently, the optimization goes on enhancing the capacitor placement decisions.

$$X_i = \begin{cases} X_i^{new,P1}, & F_i^{new,P1} < F_i; \\ X_i, & else, \end{cases} \quad (13)$$

Update Rule for Solution Acceptance:

After changing their positions, zebras accept new positions only when they are better than the fitness value. If a new solution is worse, the zebra keeps its previous position. This last step guarantees that the optimization is always moving forward, towards better power system performance.

$$x_{i,j}^{new,P2} = \begin{cases} S_1 : x_{i,j} + R \cdot (2r - 1) & \\ \quad \cdot (1 - \frac{t}{T}) \cdot x_{i,j}, & P_s \leq 0.5; \\ S_2 : x_{i,j} + r \cdot (AZ_j - I \cdot x_{i,j}), & else, \end{cases} \quad (14)$$

$$X_i = \begin{cases} X_i^{new,P2}, & F_i^{new,P2} < F_i; \\ X_i, & else, \end{cases} \quad (15)$$

Total Computational Complexity of ZOA:

The efficiency of ZOA depends on the number of zebras, the number of decision variables, and the total number of iterations. Its computational complexity is given by a mathematical formulation in order to predict the time and computational resources that the algorithm will need. This allows to estimate how far is ZOA scalable for large distribution networks.

$$O(N \cdot m \cdot (1 + 2 \cdot T)) \quad (16)$$

3.3.3 Pseudocode of how ZOA works:

The Zebra Optimization Algorithm (ZOA) pseudocode seen below is based on an iterative process where a population of zebras which is the candidate solutions is first initialized and then updated according to two key behaviours such as foraging which is staying close to the best solution and defensive strategies which is avoiding predators or clustering together. The algorithm runs through cycles of solutions being evaluated for fitness, the best candidates being selected, and positions being tweaked during exploration and exploitation phases. However, the general pseudocode of the algorithm is not problem-specific and does not incorporate problem specific constraints such as capacitor placement and sizing that are required for performing power system optimization tasks.

Figure 1: Pseudocode of ZOA (Trojovska et al., 2022)

```
Start ZOA.
1. Input: The optimization problem information.
2. Set the number of iterations (T ) and the number of zebras'
population (N).
3. Initialization of the position of zebras and evaluation of the
objective function.
4. For t D 1: T
5. Update pioneer zebra (PZ).
6. For i D 1: N
7. Phase 1: Foraging behavior
8. Calculate new status of the ith zebra using (3).
9. Update the ith zebra using (4).
10. Phase 2: Defense strategies against predators
11. If Ps < 0.5, Ps D rand
12. Strategy 1: against lion (exploitation phase)
13. Calculate new status of the ith zebra using mode S1 in (5).
14. else
15. Strategy 2: against other predator (exploration phase)
16. Calculate new status of the ith zebra using mode S2 in (5).
17. end if
18. Update the ith zebra using (6).
19. end for i D 1: N
20. Save best candidate solution so far.
21. end for t D 1: T
22. Output: The best solution obtained by ZOA for given
optimization problem.
End ZOA.
```

3.3.4 Pseudocode implementation of ZOA with capacitor placement and sizing using MATLAB.

The modified ZOA pseudocode seen below is integrated with IEEE 33 bus system data, capacitor bank size constraints of 150-1200kVAr per bus and voltage constraints of 0.95-1.05 pu to ensure that the capacitor placement is realistic. To assess power loss and voltage profiles at each iteration, Newton Raphson load flow analysis is included. This version of the Base ZOA does not use heuristic rules for refining capacitor placement, but rather employs local adjustments (Mode S1) or a wider exploration (Mode S2), while also performing feasibility checks to discard invalid solutions.

Figure 2:Pseudocode implementation of capacitor placement and sizing of ZOA (Trojovska et al., 2022)

```
Star:
1. Input:
   - Load IEEE 33-bus system data (bus voltages,  line impedances, power demand).
   - Optimization parameters: population size (N), max iterations  (T) are defined.
   - Set capacitor bank size limits (e.g. 150  kVAr to 1200 kVAr per bus).
   - Objective function: power losses and capacitor  costs are minimized.
   - Constraints: Voltage limits (0.95 – 1.05  pu), reactive power limits are defined.

2. Initialize ZOA:
    - Generate the initial positions of  N zebras which is random capacitor placements.
    - Initialize capacitor sizes at selected buses.
    - Calculate the initial power flow by using Newton Raphson.
    - Evaluate fitness for each zebra by using the objective function.

3. For t = 1  to T do:
    4. Determine the best zebra solution from the lowest objective function value.
    5. For each zebra i in population:

        Phase  1: Foraging Behaviour:
        6. Update zebra's capacitor placement and sizing by using  the best zebra's guidance.
        7. Perform power flow analysis to determine new power loss  and voltage profile.
        8. Recalculate fitness and check feasibility due to voltage and capacitor constraints.

        Phase 2: Defensive Strategy Against Predators:
        9. If rand  < 0.5:
            - Use local refinement  of capacitor placement (Mode S1) to adjust it.
        10. If not:
            - Apply a larger random movement to explore new capacitor placements  (Mode S2).

        11. Perform power flow again to determine the new positions.
        12. Check that all solutions are feasible; if not, eliminate them.
        13. Update zebra positions, and keep the best candidates.
        14. The best capacitor placement and  sizing is stored.

    15. Loop ends.

    16. Output:
        - Optimal capacitor positions and sizes.
        - The final power loss and cost reduction.
        - Voltage profile enhancement.
End:
```

3.3.5 Testing and Validation Approach.

To validate the effectiveness of the Zebra Optimization Algorithm (ZOA) for optimal capacitor placement, simulation results will be compared with metaheuristic algorithms such as Whale Optimization Algorithm (WOA), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). The key performance metrics are percentage reduction in power loss, improvement in voltage profile, minimization of capacitor cost and algorithm convergence speed to. Furthermore, the IEEE 33 bus system will be tested under different load conditions to ensure that the proposed optimization method works well.

3.3.6 Constraints and Assumptions.

The optimization process is constrained by voltage limits to guarantee system stability, which bus voltages are limited to ±0.05 pu around 1.0 pu. The size of the capacitor is restricted to 150 kVAr to 1200 kVAr per bus and the total reactive power compensation installed should not exceed the system's reactive power demand. Furthermore, it is proposed that the IEEE 33-bus system is operating in a steady state, and the Newton-Raphson load flow will show the power flow in distribution networks.

3.4 Engineering Principles

The objective function formula, Newton Raphson load flow analysis and method selection are the key components of this project. The ability of Minimize S equation seen in (Osama et al., 2023) is effective in power loss minimization and capacitor cost reduction simultaneously for technical and economic efficiency. Newton Raphson is employed for precise power loss estimation since it provides faster convergence and better nonlinear behaviour than Gauss Seidel and Forward Backward Sweep. These principles define an optimal, cost effective capacitor placement policy for enhancement of system performance.

3.4.1 Objective Functions and Their Implementation

The 'Minimize S' equation from (Osama et al., 2023) was selected because it minimizes both power loss and capacitor expense at the same time which is perfect for ZOA. It does not use traditional power loss equations, rather it balances technical efficiency (PLoss) with economic feasibility (QC). The equation can be easily incorporated with Newton Raphson load flow analysis for accurate power system calculation. Because ZOA implies the use of an objective function that would take into account several restrictions, 'Minimize S' equation is a good starting point for capacitor placement optimization in a radial distribution system.

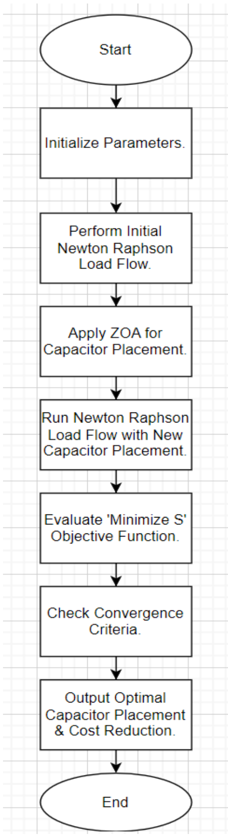
(Osama et al., 2023):

$$Minimize\ S = Kpi\ \sum_{i=1}^{Nb-1} P_{Loss,i} + K_C \sum_{j=1}^{N_C} Q_{CJ} \quad (17)$$

Power Loss and cost Reduction using Newton-Raphson Load Flow Analysis:

The flowchart of applying the objective function 'Minimize S' equation with Newton Raphson for determining the position and magnitude of capacitors in a radial distribution system is shown below. The first step is to perform an initial Newton Raphson load flow to find power losses for the base case after loading IEEE 33 bus system data. Then the ZOA Algorithm produces capacitor placement solutions, modifies system voltages and implement the Minimize S objective function to calculate new power losses and costs. This iteration is repeated until convergence, this will help in achieving minimum power losses, optimal costs and capacitor placement.

Figure 3:Power Loss and cost Reduction implementation



Justification for selection of Newton-Raphson method over alternative methods:

The Newton-Raphson method is chosen over Forward-Backward Sweep (FBS) and Gauss-Seidel (GS) methods because it is more accurate, faster and suitable for complex power systems for the solution of power flow problems. Gauss-Seidel is slower in arriving at a solution than Newton-Raphson. Newton-Raphson also solves better nonlinear power flow equations than Forward-Backward Sweep (FBS), which is limited to simplified radial systems. Furthermore, Newton-Raphson method is more powerful, and can be applied to large distribution networks with varying load conditions to improve voltage stability and reduce calculation error.

3.5 Professional engineering practices

This section ensures that this project has adopted structured, ethical and industry relevant methodologies from engineering practices for optimal capacitor placement and sizing in a radial distribution system using ZOA. These practices are wide to include project management, financial feasibility and entrepreneurship considerations, therefore ensuring that technical solutions are well planned, cost effective and professional. Based on successful integration of planning, economic analysis and principles of responsible engineering, the project guarantees the practicality and reliability of the capacitor placement optimization project.

3.5.1 Project management, Finance and Entrepreneurship

Project management

The Gantt charts for Phase 1 Dec 2024 to Mar 2025 and Phase 2 Apr 2025 to Jul 2025 shows the step by step plan for completing the project. Phase 1 has its focus on research, literature review, and documentation which includes writing and finalizing Chapters 1-3, holding supervisor meetings and finally settling on the methodology for capacitor placement optimization. Phase 2 shifts towards the technical implementation of the design, starting with ZOA optimization using MATLAB, then performance testing, result analysis, and then the algorithm refinement. The last stages are writing Chapters 4 & 5, reporting on the project and submitting the presentation. This structured timeline guarantees that the progress is organized, time is managed effectively, and that the project is on time.

Figure 4:Gantt charts for Phase 1

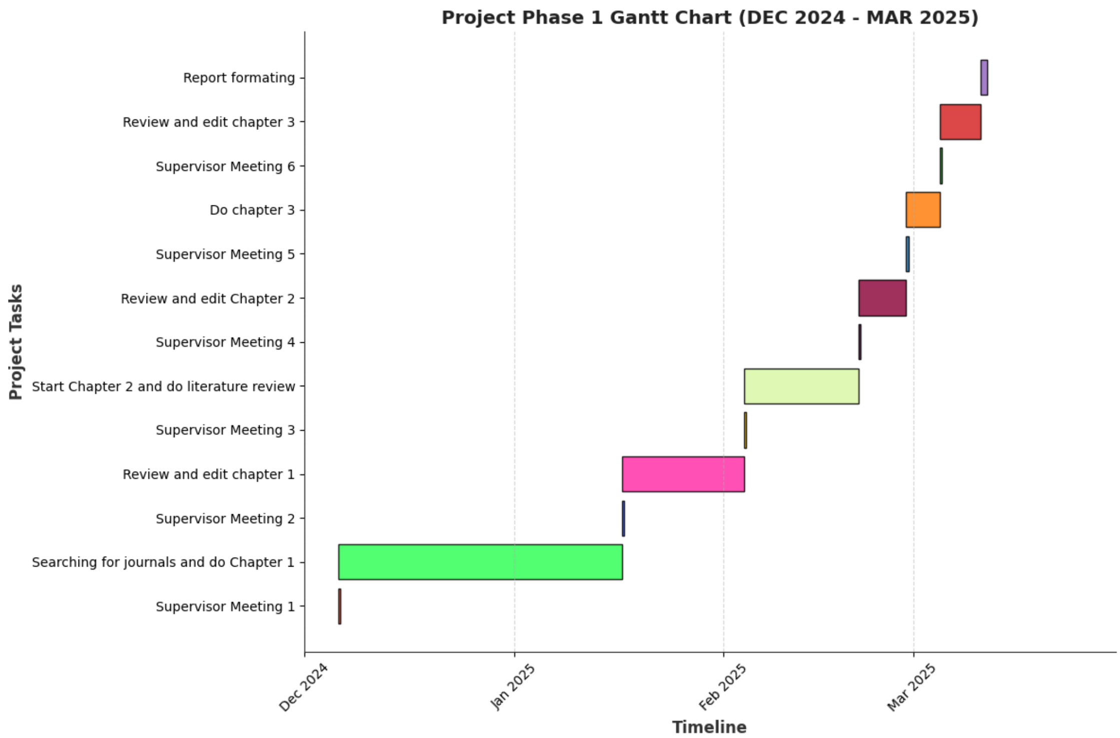
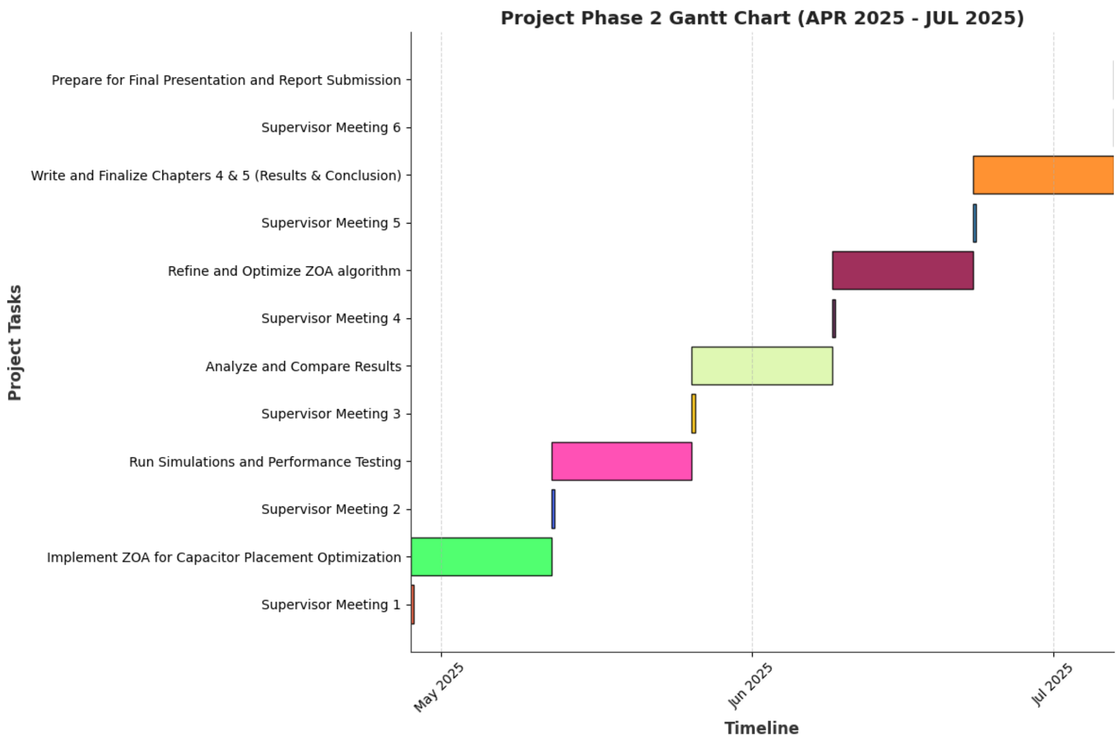


Figure 5:Gantt charts for Phase 2



Finance

The financial aspect of this project was small as the software and tools which were required were either freely available or the owner of the company had them already. The MATLAB Student License was employed for simulation and optimization, and this did not incur any extra charge. The only major cost was the Microsoft Surface Laptop 4 that was being used for algorithm development, coding and simulations. Since no extra hardware or paid software was needed, the total project cost is RM4500, that is only for utilizing the existing resources.

Table 4:Cost comparison

Item	Description	Cost (RM)
Software	MATLAB Student License	RM0
Hardware	Microsoft Surface Laptop 4 (Owned)	RM4500
Total Cost	Project expenses	RM4500

Entrepreneurship

For entrepreneurship it is seen that this project can be potentially commercialized in the power distribution sector. This is because ZOA can be used to optimize capacitor placement and sizing to reduce energy losses and operational costs, thus making it suitable for application in smart grid systems. The approach can be provided as an optimization tool or software or consulting services for power system operators. Furthermore, the project is innovative in sustainable energy management and generates business ideas for startup companies, industry cooperation, and future research business development.

3.6 Summary

To conclude, this chapter showed how the ZOA Algorithm was applied to optimize capacitor placement and sizing in a radial distribution system, with the methodology and engineering principles used. It explained the formation of the objective function, the use of Newton Raphson load flow analysis for power loss and cost reduction, and why

Newton Raphson was chosen over other methods. The implementation process included pseudocode, flowcharts, and MATLAB based optimization to prevent inaccurate power system modelling. Moreover, project management, financial feasibility, and Entrepreneurship practices were applied to achieve a systematic, economical, and standardized approach to the project. The last step of the project is to test and validate the performance of the algorithm, which guarantees that ZOA enhances power loss reduction, cost savings, and voltage stability effectively.

CHAPTER 4

FINAL DESIGN & SYSTEM IMPLEMENTATION

4.1 Introduction

In this chapter presents the design and implementation of a system that implements the Zebra Optimization Algorithm (ZOA) to help improve the IEEE 33 bus systemas seen by (Baran,& Wu, 1989). The system was mainly designed to determine the optimal capacitor placement and sizing. By using the MATPOWER toolbox for load flow analysis and incorporating a multi objective function, this resulted in both the minimization of power loss, installation cost of capacitor while improving voltage profile of buses. The chapter discusses the architecture of the system, the process taken to build it, its pseudocode, and the simulation results confirming the algorithm approach.

4.2 System Implementation

4.2.1 Overall Block Diagram of System

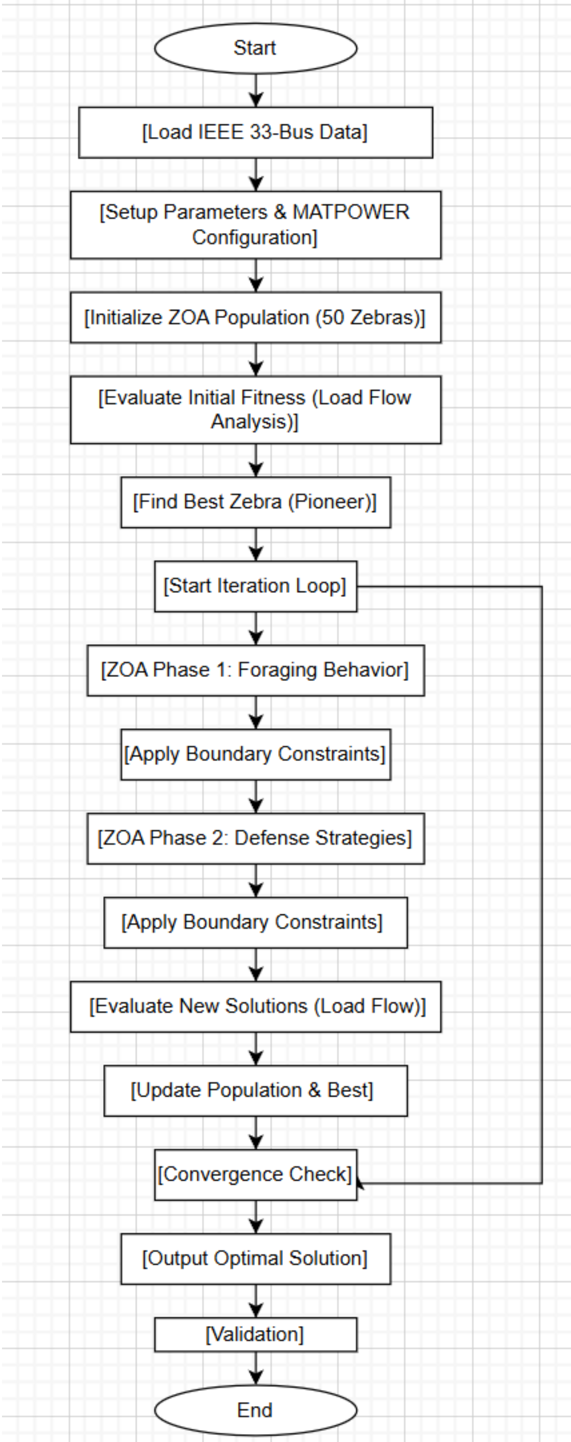


Figure 6: Overall block diagram of ZOA-based capacitor optimization system

The flowchart in Figure integrates the IEEE 33 bus model and MATPOWER for load flow analysis. ZOA is then used to solve optimal capacitor position & sizes. This optimization process follows some technical constraints like maintaining voltage in range of 0.95 to 1.05 p.u. and sizes of capacitor in range of 150 to 1200 kVAr and economic constraints like annual power loss and capacitor installing cost. The ZOA fuses iterative search strategies to explore better and low cost potential solutions.

4.2.2 Constructional details and MATLAB programming pseudocode

Constructional Details:

The implementation is built in MATLAB R2024a and uses the MATPOWER toolbox for load flow checks and the Parallel Computing Toolbox to speed up the process. All files are stored in one folder. The ZOA_core_logic.m file runs the main loop using parfor to test many solutions at once. The run_load_flow.m file calls MATPOWER solver. The fitness.m file unpacks each candidate, runs the load flow, and applies penalties if have. The calculate_cost_components.m file breaks down power losses, capacitor costs, and penalties. The case33bw.m file stores the IEEE-33 bus data. A utils/ folder holds small helper scripts for different test such as convergent test.

```
/ZOA_Project
• ZOA_core_logic.m
• run_load_flow.m
• fitness.m
• calculate_cost_components.m
• case33bw.m
• utils/
```

System Parameters and Data Structures:

The table below shows the five important parameters settings used in the ZOA algorithm for capacitor placement and sizing. Such as system, optimization, constraint, economic and algorithm settings.

Table 5:Parameters used

Parameter Category	Parameter Name	Value	Description
System	Number of Buses	33	IEEE 33-bus test system
	Base Power	100 MVA	MATPOWER standard base
	Nominal Voltage	12.66 kV	Distribution voltage level
Optimization	Population Size (Npop)	50	Number of zebras
	Number of Capacitors (Ncap)	5	Fixed capacitor count
	Maximum Iterations	100	Stopping criterion
	Problem Dimension	10	5 locations + 5 sizes
Constraints	Minimum Bus Location	2	Bus 1 is slack bus
	Maximum Bus Location	33	System boundary
	Capacitor Size Range	[150, 1200] kVAr	Physical limitations
	Voltage Limits	[0.95, 1.05] p.u.	IEEE standards
Economic	Power Loss Cost	160 $/kW/year	Annual loss penalty
	Capacitor Cost	45 $/kVAr/year	Installation cost
	Voltage Penalty	1×108	Constraint violation penalty
Algorithm	Defense Probability (ps)	0.5	Strategy selection
	Boundary Handling	Continuous	Real-valued optimization

Summary of the main pseudocode:

The ZAO starts with creating a population of 50 zebra solutions where each zebra will have five capacitor locations and sizes. A fitness function is assigned to each solution, which uses MATPOWER based load flow together with penalties for voltage violations. After initial movement, each zebra moves to a new location following the current best solution and then a defense is applied. Exploring new regions through one of two strategies, which also play out over 100 iterations. At each step, all rule violations are rectified. Finally, the solution with the overall minimum total cost is returned after all iterations. Appendix E and F gives the full pseudocode for ZOA and the logic for the fitness evaluation process.

4.2.3 Working Principle

The objective of the algorithm is to minimize power loss and the cost of installation and ensure that all bus voltages are within the range of 0.95 to 1.05p.u. Firstly, the process starts with a random generation of 50 zebra solutions. Every zebra has five capacitor points from bus numbers 2 to 33 and sizes from 150 to 1200 kVar. The invalid or duplicate buses are corrected in the solution. MATPOWER is used to run a load flow analysis to determine the fitness of each zebra. The solution which performs the best is chosen as the pioneer zebra. The rest of the solutions are then updated to the pioneer zebra.

The optimization process has 100 iterations. In each iteration, each zebra changes its position to the pioneer according to the formula new_position = current + rand (pioneer - current). Boundary constraints are all placed once the move is made. Then, there is a second stage that brings diversification. Every zebra randomly chooses between the two defense strategies such as, local intensification which slightly modifies the current solution to a direction towards the pioneer, or global diversification, which introduces larger random changes. This trade-off between exploitation and exploration does not allow the algorithm to trap in local optima.

At the end of both phases, every zebra keeps the best version of itself. After each iteration, the best solution and fitness value is recorded, also the best solution will be updated in case a better solution is found. The iteration process stops when the maximum number of iterations is achieved or when convergence condition is found.

The algorithm penalizes heavily a solution that fails the load flow or any solution that exceeds the voltage limits. It also uses parallel processing, which can evaluate several zebras at the same time, which can help lower the time of simulations. The step by step flowchart of the ZOA optimization process is shown in Figure below.

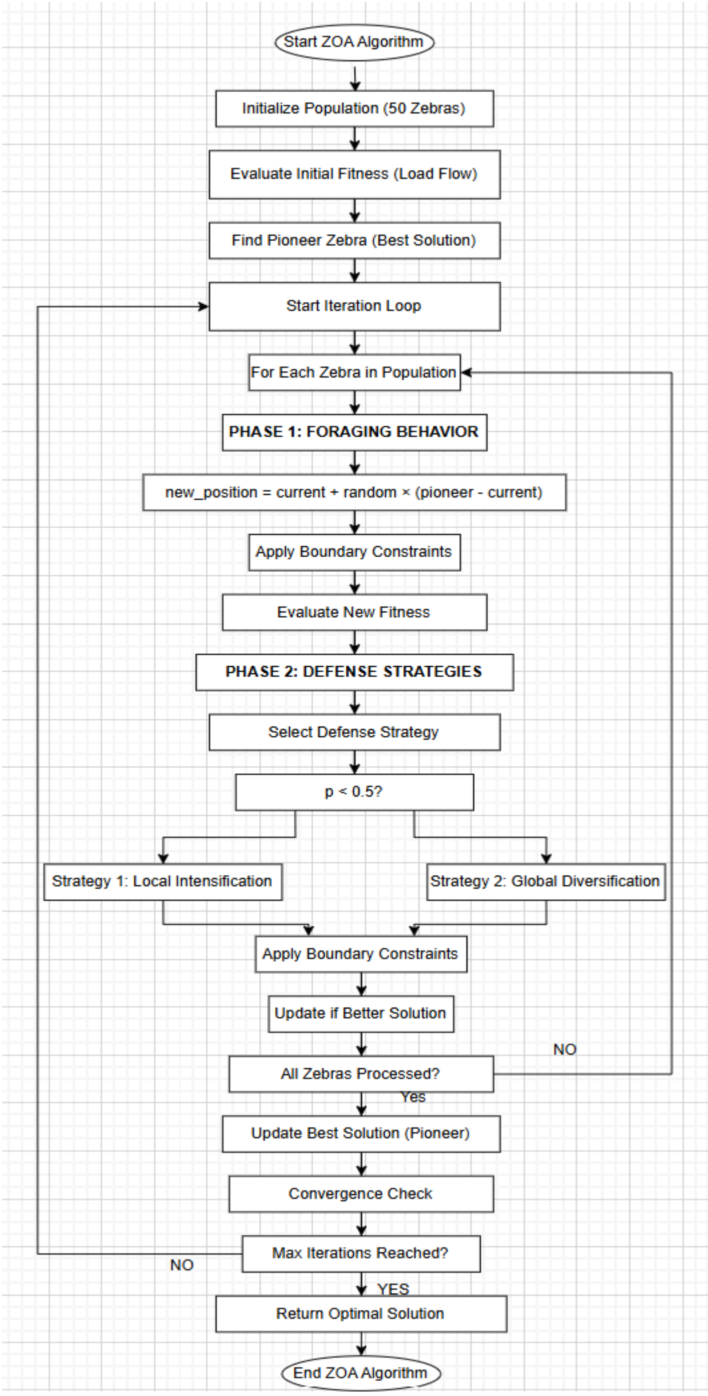


Figure 7:Detailed flowchart of ZOA capacitor optimization process

4.3 Simulation Results

4.3.1 Baseline Performance Without Capacitor

The base case was carried out on the 33 bus IEEE system with no installation of capacitor. As shown in Table 6, the system had a large amount of total power loss of 211.00 kW, low power factor of 0.849 and 21 buses with voltages below the minimum of 0.95 p.u. The maximum voltage was registered at Bus 18 and it was 0.9038 p.u. The results showed poor voltage control and power inefficiency of the uncompensated system, which underlines the need to compensate with reactive power using capacitor placement.

Table 6:IEEE 33-bus system baseline performance

Parameter	Value
Total Power Loss	211.00 kW
Minimum Voltage	0.9038 p.u. at Bus 18
Voltage Violations (< 0.95 p.u.)	21 buses
Power Factor (at source)	0.849
Real Power Generation	3.926 MW
Reactive Power Generation	2.443 MVAr

4.3.2 Optimized Performance with ZOA

ZOA algorithm was used to find out the most efficient locations and sizes of five capacitors. The optimized setting has improved the network performance significantly as it can be seen in Table 7. The power loss was decreased to 154.94 kW which was is a 26.6 percent decrease, the minimum voltage increased to 0.9500 p.u., and the power factor improved to 0.98. There were no voltage violations, and the total capacitor injected was 1621.12 kVAr. The findings confirmed the efficiency of the proposed optimization in increasing technical and economic performance of the distribution system.

Table 7:ZOA optimization results summary

Parameter	Value
Total Power Loss	154.94 kW
Optimal Locations	[14, 16, 33, 32, 31]

Optimal Sizes (kVAr)	[150.00, 589.91, 289.92, 150.00, 441.29]
Minimum Voltage	0.9500 p.u. at Bus 13
Voltage Violations (< 0.95 p.u.)	0 buses
Power Factor (at source)	0.98
Real Power Generation	3.870 MW
Reactive Power Generation	0.787 MVAr
Total Capacitor Size	1621.12 kVAr

4.3.3 Voltage Profile Improvement

Figure 8 shows the magnitude of voltages at each bus before and after placement of the capacitor. The blue bars which is baseline show that more than 21 buses, initially, exceeded the voltage limit. Under optimization shown by red bars, all the bus voltages have been brought to the IEEE standard range of 0.95 to 1.05 p.u with the lowest bus voltage now on Bus 13. The five capacitors installed, shown by green symbols, were very important in restoring the voltage and in reducing the loss throughout the system.

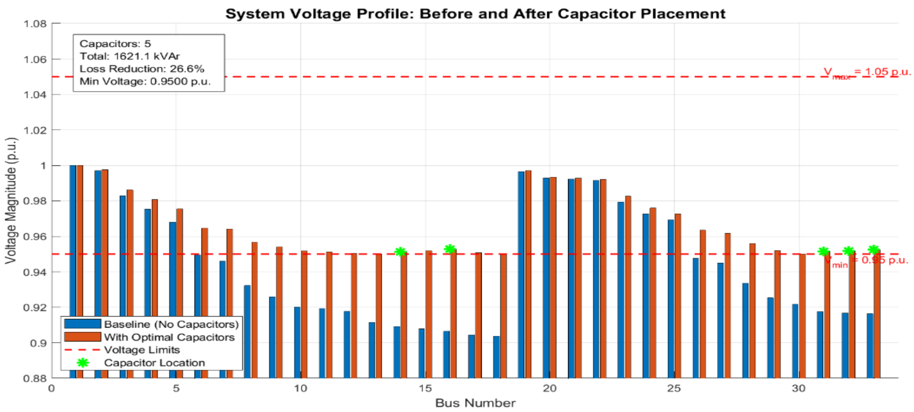


Figure 8:Chapter 4 voltage profile

4.4 Summary

This chapter has described the process of creation and application of the Zebra Optimization Algorithm ZOA in Matlab to optimally locate and size capacitors on the

IEEE 33 bus distribution system. The system used MATPOWER to do load flow analysis and automatic constraint management and parallel processing to enhance efficiency. The algorithm was able to reduce power losses and enhance the regulation of voltages. The major achievements are a 26.5 percent decrease in the power loss from 211.00 kW to 154.94 kW, reduced all 21 voltage violations, and the increase in power factor to 0.98. The system had the required design objectives as all bus voltages were back to the standard 0.95 to 1.05 p.u.

CHAPTER 5

PROJECT FINDINGS & TESTING

5.1 Testing of Proposed Design

5.1.1 Convergence and Consistency Test

Convergence test:

The convergence test is used to determine how the performance of Zebra Optimization Algorithm (ZOA) is affected by the size of the zebra population. The objective of this experiment is to determine the value of the population size that shows the minimum total cost that is the sum of power loss and the cost of installing the capacitors and at the same time meeting the voltage bounds. It gives valuable knowledge on how the algorithm can converge quickly on the optimal capacitor placement and sizing in the distribution system.

Experimental Setup:

The five population sizes were tested as 10, 20, 30, 40 and 50 zebras. Each pair was iterated 100 times to get the convergence behaviour. This was aimed at reducing the cost of power loss and installation of capacitors. Table 8 shows the key parameters such as the capacitor limits and the voltage limits.

Table 8:Important input parameters for convergence *test*

Parameter	**Value**
Number of Runs	1
Max Iterations	100
Voltage Limits	[0.95, 1.05] p.u.
Capacitor number	3
Capacitor Size Range	[150, 1200] kVAr

Power Loss Weight (Kp)	160
Capacitor Cost Weight (Kc)	45

Data collected:

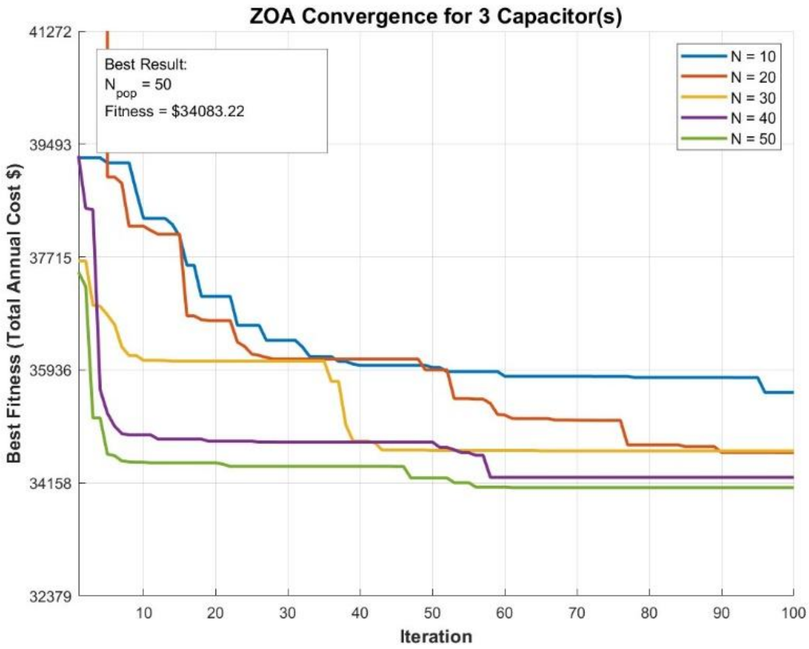


Figure 9:Convergence plot of different zebra population sizes

Table 9:Convergence test results for different population sizes

N	Best Fitness ($)	Optimal Locations	Optimal Sizes (kVAr)	Time Taken (s)
10	35581.15	[6 15 31]	[422.86 750.49 777.36]	28.11
20	34633.34	[7 16 31]	[649.68 573.62 712.34]	41.56
30	34661.86	[15 31 9]	[640.56 943.64 207.98]	101.22
40	34244.4	[8 15 31]	[223.70 676.75 827.15]	121.32
50	34083.22	[9 16 31]	[326.22 554.41 835.23]	97.87

Data Analysis:

From the tested configurations, the population size of N = 50 had the highest fitness value of 34,083.22, capacitor placements were at buses [9, 16, 31] and capacitor sizes to [326.22, 554.41, 835.23] kVAr. The computing time of 97.87 seconds of this setting was also reasonable. Even though N = 40 performed a little better on the fitness, it took 121.32 seconds to be computed. Thus, the most efficient one was accepted to be N = 50, which offers the most suitable balance between the solution quality and calculation rate.

Consistency Test:

The consistency test was done to show the stability and reliability of Zebra Optimization Algorithm (ZOA) when applied to optimal capacitor placement and sizing. Since convergence test determined population size of N = 50 to be the most optimal, this test ensures that this configuration consistently generates high quality results when several independent runs are undertaken.

Experimental Setup:

With the optimal population size of 50 zebras and fixed number of iterations of 100, 30 independent runs were performed. Each of the runs optimized the same objective function which is total cost from power loss cost + capacitor cost and the same system constraints as in the convergence test. The main parameters of the simulation are provided in Table 3. The values in Table 10 define the setup. There are three capacitors with size constraints in the range 150-1200 kVAr, a voltage constraint within a range of 0.95 to 1.05 p.u. and the cost weights are Kp=160 and Kc=45. Mean, minimum, maximum and standard deviation of fitness values were recorded and presented in Table 11. The visual representation of the fitness variation over the 30 runs is presented in Figure 10, where consistency in convergence trends is seen.

Table 10:Important input parameters for consistency test

Parameter	**Value**
Number of Runs	30
Max Iterations	100
Voltage Limits	[0.95, 1.05] p.u.

Capacitor number	3
Capacitor Size Range	[150, 1200] kVAr
Power Loss Weight (Kp)	160
Capacitor Cost Weight (Kc)	45

Data collected:

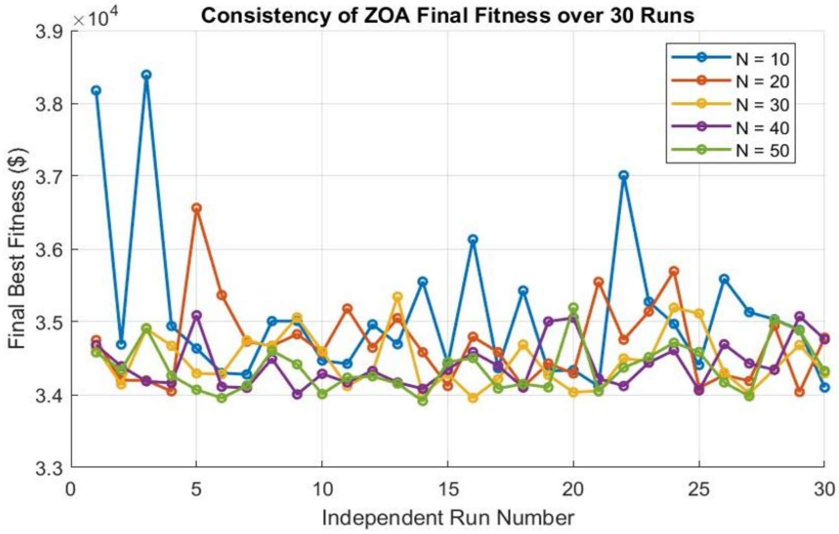


Figure 10:Consistency plot over 30 independent runs

Table 11:Consistency test statistical results

Population Size (N)	Mean Fitness ($)	Standard Deviation	Min Fitness ($)	Max Fitness ($)
10	35101.63	1.07E+03	34097.99	38391.18
20	34705.12	5.71E+02	34036.71	36562.9
30	34472.1	3.77E+02	33954.47	35344.39
40	34414.75	3.27E+02	34003.87	35090.17
50	34363.34	3.34E+02	33912.54	35196.36

Data Analysis:

The statistical results in Table 11 show that the standard deviation of the population size 50 is low at 334.00 with the mean fitness value of 34,363.34, minimum of 33,912.54 and a maximum of 35,196.36. When compared to lower population size, N = 50 is more consistent and displays a lower variability of outcomes. The small spread of the results over 30 runs indicates that the algorithm is very stable and repeatable.

5.1.2 Evaluation of Cost-Performance Trade-offs

This test was to examine the difference in weighting of cost of power loss Kp and capacitor cost Kc of the objective function on the overall optimization. The objective is to find out the best solution that can result in the minimization of the total cost of a system, power factor, and voltage being maintained within acceptable limit.

Experimental Setup:

The number of population and iteration was 50 and 100 respectively. All the possible combinations of five values of Kp such as 40, 80, 120, 160 and 200 and five values of Kc such as 5, 15, 25, 35 and 45 were tested. The parameters have been shown in Table 12.

Table 12:Important input parameters for Cost performance trade off

Parameter	Value
Population	50
Max Iterations	100
Voltage Limits	[0.95, 1.05] p.u.
Capacitor number	3
Capacitor Size Range	[150, 1200] kVAr
Power Loss Weight (Kp)	40, 80, 120, 160, 200
Capacitor Cost Weight (Kc)	5, 15, 25, 35, 45

Data collected:

The full results are shown in Table 13 and the table presents the optimum locations and size of capacitors to be installed at each Kp and Kc combination, the cost of power loss, the cost of capacitors, the cost of the total system, the voltage penalty, and the power factor. Figure 11 is a 3D surface plot which shows the relationship between the elements of the cost and the different combinations of weight.

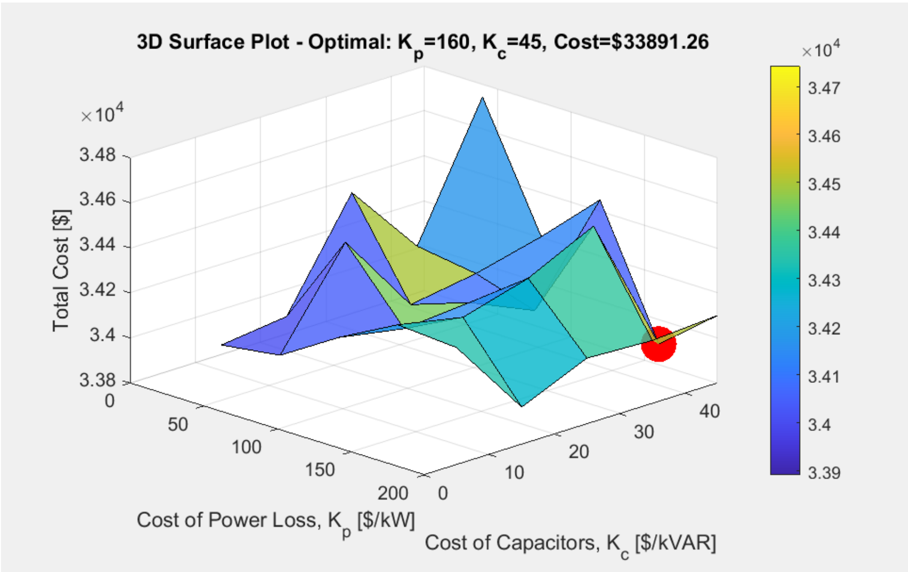


Figure 11:3D surface plot - weightage analysis

Table 13:Weightage analysis results

Kp	**Kc**	**Locations**	**Sizing (kVAr)**	**Power Loss Cost ($)**	**Cap Cost ($)**	**Volt Pen. ($)**	**Total Cost ($)**	**Power Factor**
40	5	[10 17 31]	[532.75 356.96 818.86]	25462.16	8542.87	0	34005.03	0.9842
40	15	[16 14 31]	[524.04 225.36 874.29]	25922.37	8118.46	0	34040.83	0.9801
40	25	[14 32 17]	[272.92 877.94 478.22]	26354.19	8145.41	0	34499.6	0.9803
40	35	[13 17 32]	[292.80 449.52 879.95]	26059.93	8111.38	0	34171.31	0.98
40	45	[16 30 33]	[763.09 156.91 716.73]	26559.58	8183.66	0	34743.24	0.9806

80	5	[11 17 31]	[346.07 466.25 869.81]	25630.58	8410.68	0	34041.26	0.9829
80	15	[16 30 33]	[756.86 292.76 592.91]	26239.81	8212.65	0	34452.46	0.981
80	25	[14 17 32]	[605.49 157.32 873.53]	25902.55	8181.76	0	34084.31	0.9807
80	35	[15 16 31]	[259.86 481.47 881.01]	26019.98	8111.68	0	34131.66	0.98
80	45	[17 14 32]	[394.68 345.29 882.86]	26090.37	8114.15	0	34204.52	0.98
120	5	[10 17 30]	[412.81 389.61 1068.27]	24848.39	9353.5	0	34201.89	0.9907

120	15	[10 17 31]	[416.57 449.90 826.89]	25683.32	8466.77	0	34150.09	0.9834
120	25	[16 29 32]	[733.69 318.47 599.03]	25919.34	8255.95	0	34175.28	0.9815
120	35	[14 32 17]	[410.09 881.93 327.94]	25949.35	8099.8	0	34049.16	0.9799
120	45	[16 32 31]	[743.18 394.91 488.02]	26318.87	8130.57	0	34449.44	0.9802
160	5	[18 10 30]	[300.73 544.75 1051.82]	24853.07	9486.5	0	34339.57	0.9916
160	15	[16 30 32]	[740.63 247.64 658.89]	26046.26	8235.74	0	34282	0.9812

160	25	[16 30 33]	[748.93 276.41 607.61]	26200.01	8164.73	0	34364.74	0.9805
160	35	[16 31 32]	[740.72 422.88 472.30]	26326.27	8179.5	0	34505.76	0.9806
160	45	[14 18 31]	[439.26 304.41 875.67]	25794.58	8096.69	0	33891.26	0.9799
200	5	[8 15 31]	[213.28 676.61 852.47]	25608.86	8711.79	0	34320.64	0.9856
200	15	[13 17 31]	[506.81 282.06 857.20]	25735.07	8230.33	0	33965.4	0.9813
200	25	[13 17 31]	[303.49 454.88 870.55]	25947.41	8144.55	0	34091.96	0.9804

200	35	[13 17 32]	[453.58 316.91 867.15]	25891.26	8188.2	0	34079.46	0.9808
200	45	[13 18 31]	[381.78 385.70 867.37]	25925.55	8174.19	0	34099.74	0.9807

Data Analysis:

Table 13 shown the best solution was at Kp = 160 and Kc = 45 that gave the minimum total cost = 33,891.26 dollars and high power factor = 0.9799 and voltage penalty = 0. It was also selected as the parameter where all the remaining tests will be carried out with same kp and kc value since it demonstrated a perfect balance between energy efficiency and economic feasibility.

5.1.3 Analysis of Capacitor Placement Impact

In this test, the impact of altering the number of capacitors on the performance of the system in terms of power loss reduction, total cost and power factor will be determined. The configurations of 1 to 5 capacitors will be tested to find out the most cost efficient and technically efficient configuration under the optimum weighting scenario found earlier from Kp = 160 and Kc = 45.

Experimental Setup:

The test was done with population size 50 and 100 iterations. The amount of capacitors was changed between 1 and 5 and the other constraints were maintained the same. The optimization has been carried out three times, with three objective functions, (1) power loss, (2) cost, and (3) a combination of power loss and cost. Table 14 shows the parameters used.

Table 14:Important input parameters for varying number of capacitors

Parameter	**Value**
Population	50
Max Iterations	100
Voltage Limits	[0.95, 1.05] p.u.
Capacitor number	1, 2, 3, 4, 5
Capacitor Size Range	[150, 1200] kVAr
Power Loss Weight (Kp)	160
Capacitor Cost Weight (Kc)	45

Data collected:

Table 15 shows the results of each case such as capacitor placements, sizes, the associated power loss in kW, total cost in $ and power factor of each number of capacitors under all three objective functions.

Table 15:Impact of different numbers of capacitors

Objective function	Number of capacitors	Location	Sizing (kVAr)	Power Loss (kW)	Cost ($)	Power Factor
Power loss & Cost	1	13	[1200.00]	196.85	282702.71	0.9535
	2	[16 32]	[744.40 883.52]	157.88	98517.2	0.9802
	3	[17 14 31]	[234.74 496.69 908.47]	152.33	98168.27	0.981
	4	[14 16 33 31]	[274.72 488.91 318.13 551.30]	154.75	98247.52	0.9806
	5	[14 16 33 32 31]	[150.00 589.91 289.92 150.00 441.29]	154.94	97740.09	0.98
Power loss	1	13	[1200.00]	196.85	282702.71	0.9535
	2	[15 30]	[724.83 1102.72]	150.76	106360.78	0.9891
	3	[7 14 30]	[574.63 644.09 905.13]	147.3	119141.47	0.9974
	4	[7 15 24 30]	[564.24 574.92 706.13 882.44]	145.01	145950.16	0.9964
	5	[3 17 12 32 29]	[858.34 354.68 422.29 358.80 564.15]	146.91	138628.03	0.9992
Cost	1	13	[1200.00]	196.85	282702.71	0.9535
	2	[17 31]	[760.22 877.38]	161.97	99607.05	0.9805
	3	[15 18 31]	[210.69 538.00 883.93]	158.97	98903.81	0.9804
	4	[14 16 31 33]	[150.00 588.62 466.09 423.33]	155.11	98079.1	0.9803
	5	[15 14 18 33 31]	[354.11 235.43 150.00 544.36 334.90]	153.88	97466.93	0.9799

Figure 4 shows how the power loss can be reduced with the increase in the amount of capacitors under the objective of power loss and cost.

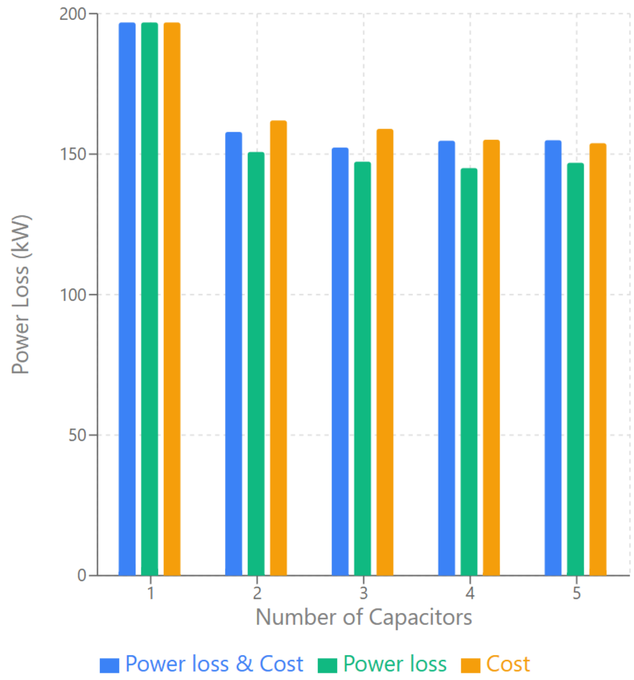


Figure 12:Power loss reduction vs number of capacitors

Data Analysis:

Table 15 and Figure 12 showed that the more capacitors that is used, the better the performance will be, but only to a certain extent. The five capacitors from the objective function power loss and cost at the buses [14, 16, 33, 32, 31] and sizes [150.00, 589.91, 289.92, 150.00, 441.29] kVAr gave the best solution with the power loss minimized to 154.94 kW, cost minimized to 97,740.09 and stable power factor of 0.98. This setup has been chosen to conduct the next test on voltage profile analysis.

5.1.4 Voltage profile analysis

This test showed the effect of optimum capacitor placement on bus voltages within the distribution system. The voltages which are at the acceptable range of 0.95 to 1.05 p.u are very critical in terms of power quality and equipment safety. The configuration used to conduct this test is the best solution chosen of the former test 5 capacitors optimized on power loss & cost.

Experimental Setup:

The test is done with the optimized capacitor setting with 5 capacitors at buses [14, 16, 33, 32, 31] and their sizes are [150.00, 589.91, 289.92, 150.00, 441.29] kVAr. The voltage profile was measured at compensation and at no compensation to see the improvement of voltage stability in the system. Parameters of the testing are shown in Table 16.

Table 16:Important input parameters for voltage profile

Parameter	**Value**
Voltage Limits	[0.95, 1.05] p.u.
Capacitor number	5
Capacitor locations	[14 16 33 32 31]
Capacitor Size Range	[150.00 589.91 289.92 150.00 441.29] kVAr

Data collected:

The figure 13 below shows the voltage profile plots before and after compensation that shows how the minimum and the overall voltage levels have improved within the 33 bus system.

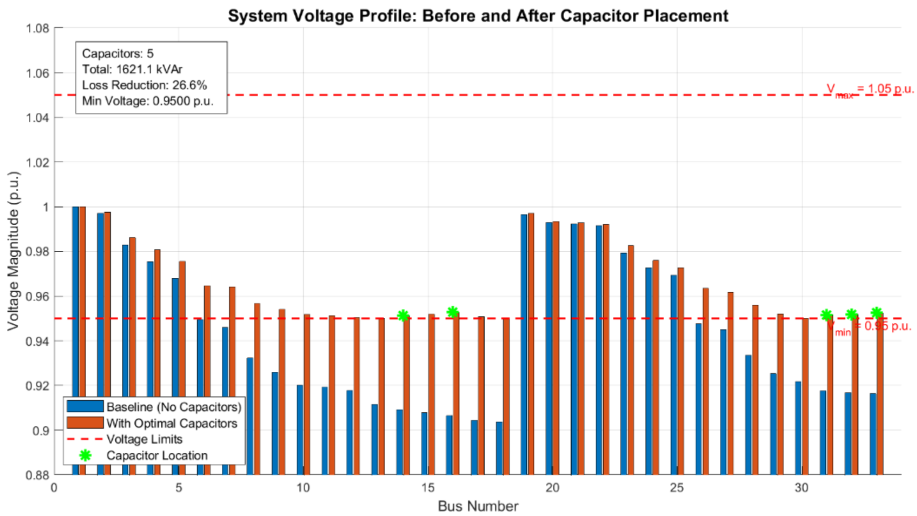


Figure 13:Voltage profile before vs after capacitor placement

Table 17 shows the magnitude of voltages at all 33 buses when there is no compensation baseline and when it is compensated. Also, Table 18 provides the summary of minimum, maximum and average voltages throughout the system before and after the capacitor is inserted.

Table 17:Voltage profile bus status

Bus Number	Baseline Voltage (p.u.)	Compensated Voltage (p.u.)	Status
1	1	1	In Range
2	0.997	0.9975	In Range
3	0.9829	0.9862	In Range
4	0.9754	0.9807	In Range
5	0.968	0.9755	In Range
6	0.9495	0.9647	In Range
7	0.946	0.9642	In Range
8	0.9323	0.9567	In Range
9	0.926	0.954	In Range
10	0.9201	0.9518	In Range
11	0.9192	0.9513	In Range
12	0.9177	0.9504	In Range
13	0.9115	0.95	In Range
14	0.9092	0.9512	In Range
15	0.9078	0.9519	In Range
16	0.9064	0.9527	In Range
17	0.9044	0.9507	In Range
18	0.9038	0.9502	In Range
19	0.9965	0.997	In Range
20	0.9929	0.9934	In Range
21	0.9922	0.9927	In Range
22	0.9916	0.9921	In Range
23	0.9793	0.9826	In Range
24	0.9726	0.976	In Range
25	0.9693	0.9727	In Range
26	0.9475	0.9634	In Range

27	0.945	0.9618	In Range
28	0.9335	0.956	In Range
29	0.9253	0.952	In Range
30	0.9218	0.9501	In Range
31	0.9176	0.9516	In Range
32	0.9167	0.9517	In Range
33	0.9164	0.9525	In Range

Table 18: Baseline VS with capacitor

Parameter	Baseline	With Capacitors
Minimum Voltage	0.9038 p.u. (at bus 18)	0.9500 p.u. (at bus 13)
Maximum Voltage	1.0000 p.u. (at bus 1)	1.0000 p.u. (at bus 1)
Buses with Low Voltage (< 0.95 p.u.)	21	0
Buses with High Voltage (> 1.05 p.u.)	0	0
Power Loss	211.00 kW	154.94 kW
Loss Reduction	-	56.06 kW (26.6%)

Data Analysis:

Table 18 shows that there was a huge increase in voltage, particularly at the weakest buses like Bus 18 which increased to 0.9502 p.u. after compensation as compared to 0.9038 p.u. before compensation. The buses are all back to the normal range of 0.95 to 1.05 p.u. Also, Table 17 shows that the minimum voltage has increased to 0.9502 p.u. and average voltage is increased to 0.9769 p.u. Both these values showed improved voltage stability. This improvement is also confirmed by the obvious increase in Figure 13. The result shows that the placement of capacitors optimized by ZOA can reduce losses and cost.

5.1.5 ZOA Comparison with Existing Techniques

The test was done to compare the performance of the proposed Zebra Optimization Algorithm (ZOA) against three other well known metaheuristic algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and African Vultures Optimization Algorithm (AVOA). The testing of each of the algorithms was performed with the same capacitor placement problem with the same constraints to allow a fair comparison of the effectiveness of optimization, the cost and the consistency of the optimization results.

Experimental Setup:

The capacitor placement was optimized in all of the algorithms with five capacitors on the IEEE 33 bus system. The aim of the objective was to minimize the total cost on an annual basis which would consist of the cost of power loss and the cost of capacitor installation. To guarantee statistical assurance, 10 independent trials were conducted in each algorithm, and the most appropriate outcome of each algorithm was used in comparing the performance. Details of each of the cases, the location and size of capacitors in kVAr are shown in Table 20. Figure 14 was used to plot the convergence trend of the iterations to find out the speed and stability of optimization.

Table 19:Important input parameters for algorithm comparison

Parameter	**Value**
Max Iterations	100
Voltage Limits	[0.95, 1.05] p.u.
Capacitor number	5
Capacitor Size Range	[150, 1200] kVAr
Power Loss Weight (Kp)	160
Capacitor Cost Weight (Kc)	45

Data collected:

Table 20:Best run results for each algorithm

Algorithm	**Power Loss (kW)**	**Total Cost ($)**	**Std. Deviation ($)**	**Power Factor**	**Locations**	**Sizing (kVAr)**
ZOA	152.22	97,207.83	1,283.56	0.9799	[15 17 30 31 32]	[591.2 150 248.84 154.76 474.14]

AVOA	151.46	115,557.61	14,010.61	0.9953	[14 16 21 31 6]	[606.4 150 150 737.26 385.75]
GA	150.64	100,057.58	2,583.77	0.9833	[13 14 17 28 32]	[160.98 239.43 320.44 316.69 650.35]
PSO	155.96	98,716.54	2,188.70	0.9808	[13 14 17 30 33]	[150 150 465.01 150.92 723.25]

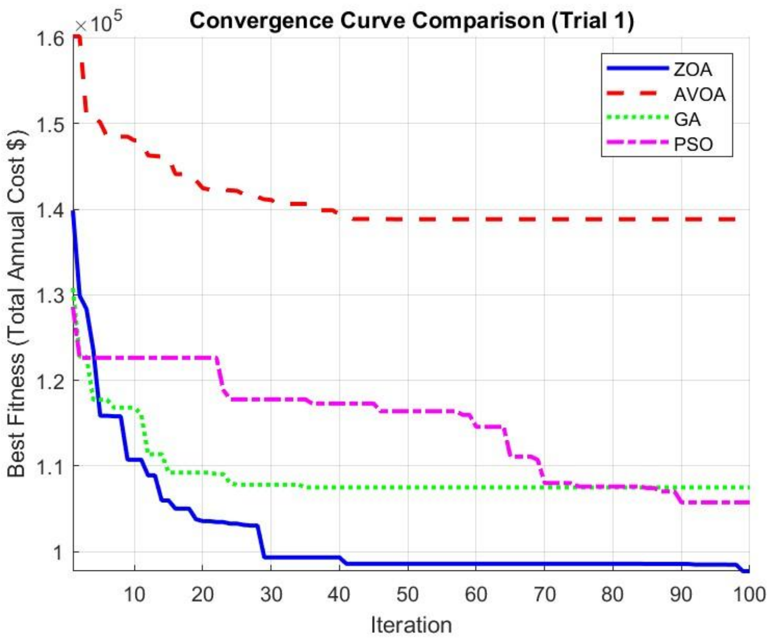


Figure 14:Convergence comparison of algorithms

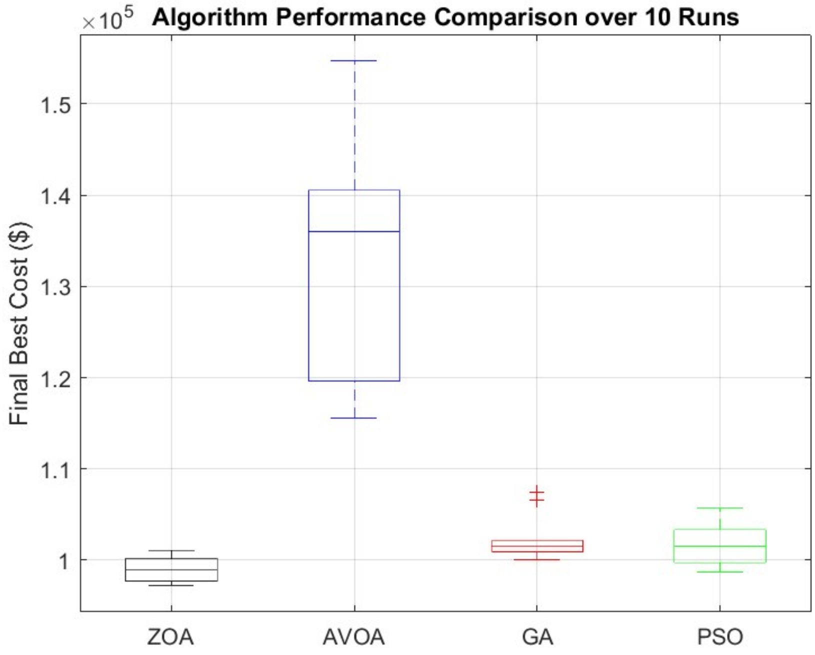


Figure 15:Box plot comparison of algorithm performance

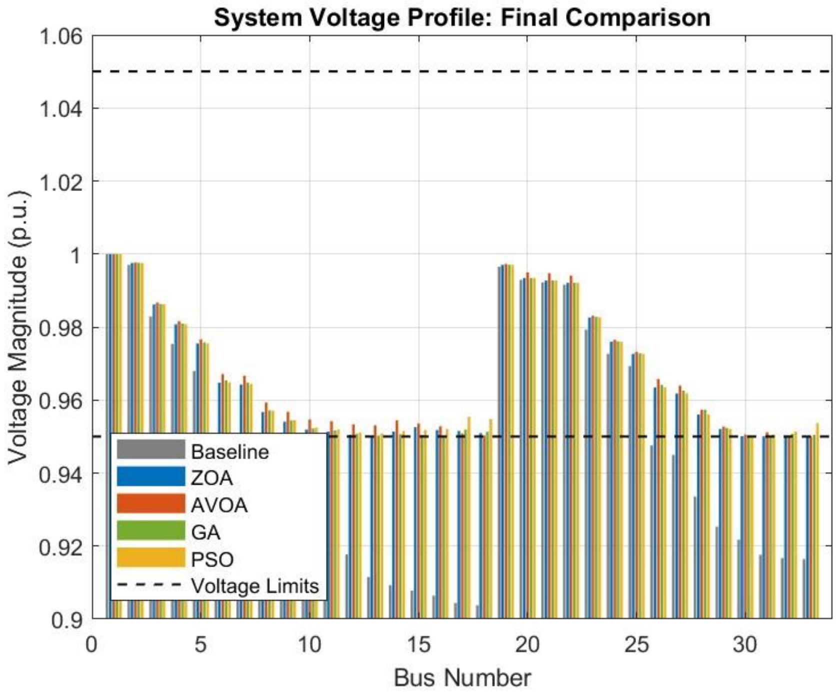


Figure 16:Voltage profile comparison of algorithm performance

Table 21:Voltage profile results for each algorithm

Case	**Power Factor**	**Min Voltage (p.u.)**	**Max Voltage (p.u.)**	**Buses Out of Range**	**Voltage Violations**
Baseline	0.849	0.9038	1	21	21 buses
ZOA	0.979	0.95	1	0	None

AVOA	0.9953	0.95	1	0	None
GA	0.9833	0.95	1	0	None
PSO	0.9808	0.9501	1	0	None

Data Analysis:

ZOA algorithm had the least total cost of 97,207.83 and a power loss of 152.22 kW and a power factor of 0.9799. Compared to AVOA it registered the greatest expense of 115,557.61 when compared to the power loss of 151.46 kW and a better power factor of 0.9953. The power loss of GA and PSO were respectively 150.64 kW and 155.96 kW with power factor 0.9833 and 0.9808 respectively. But they cost more and have greater standard deviations, which means that they are less economically efficient and consistent.

As it can be seen in Figure 14, ZOA will reach convergence faster and even converge to near optimal solutions faster than the other algorithms. This shows that it has an improved exploitation and exploration trade off and convergence stability. This further technical validation is seen in Table 20 and Figure 15 whereby ZOA has managed to raise the minimum system voltage from 0.9 p.u. to 0.95 p.u. eliminating the 21 voltage violations that were evident in the baseline case. AVOA, GA and PSO also showed similar voltage restoration, but ZOA achieved this at the least installed kVAr and cost.

5.2 Discrepancy Between Theoretical and Experimental Results

In this test, the performance difference between the generated theoretical output in MATLAB with MATPOWER and the simulation validation in Python with PYPOWER. It is done to ensure that the Zebra Optimization Algorithm (ZOA) is giving the same results.

PYPOWER Python was integrated to reveal the MATLAB findings of the ZOA algorithm code with the number of capacitors being five located at buses 14, 16, 33, 32, and 31 with values 150.00, 589.91, 289.92, 150.00, 441.29 kVAr respectively. These are the results of the Test 3, in which both the power loss and the total cost were minimized by selecting the objective function.

A comparison of the main results of the performance of both the software is shown in Table 22.

Table 22:MATLAB VS PYPOWER

Metric	**MATLAB Matpower**	**Python PyPower**	**% Difference**
Final Power Loss	154.9 kW	154.9 kW	0.00%
Power Loss Reduction	26.60%	26.60%	0.00%
Total Installed Capacitance	1621.12 kVAr	1621.12 kVAr	0.00%
Final Minimum Voltage	0.9500 p.u. (at Bus 13)	0.9500 p.u. (at Bus 13)	0.00%
Final Power Factor	0.98	0.98	0.00%
Voltage Violations Fixed	21 of 21	21 of 21	N/A
Capacitor Placement	Identical	Identical	N/A

Analysis:

The location and size of capacitors location was same in both implementations. The outcomes do not differ, and the variations between metrics are 0.00%. Both tools resulted a final power loss of 154.9 kW, 26.60 percent reduction in power loss and 0.9500 p.u. as the low end voltage value at the Bus 13. The installed capacitance was 1621.12 kVAr, and both were able to solve all the 21 violations of the voltage. This ideal result proves that the suggested approach is robust and not platform specific.

5.3 Possible Sources of Error and Troubleshooting Methods

A number of possible mistakes were found when the ZOA algorithm was being developed and tested. Such as load flow non-convergence particularly in cases where capacitor placements resulted in unstable voltage profile and boundary violation. This resulted in the optimizer suggested capacitor sizes or locations which were outside the limits. Other small differences were due to the limits of floating-point precision and due to random initialization, which meant that results differed between runs.

To overcome these, the penalty functions were used in the fitness script to manage the violation of voltage and sizing. Maximizing the convergence was achieved through the setting of the load flow solver to adaptive tolerances. In order to reduce the random variance, the algorithm was repeated multiple times at different runs and the results were averaged. Lastly cross validation using PYPOWER was also done in order to make the MATLAB results reproducible and independent of the platform.

5.4 Sustainable Development and Environmental Considerations

Environmental Benefits:

With the introduction of the ZOA algorithm, the power loss was reduced by 26.6 percent and went down to 154.9 kW. Such an increase in energy efficiency directly resulted to less fuel use in the power plants, especially the fossil fuel systems. This will reduce energy demand and CO 2 emissions, which are causing climate change. Moreover, the optimized positioning of capacitors will prevent excessive compensation and the necessity of creating excessive reactive power infrastructure, thus making the use of materials and network capacities more sustainable.

Economic Impact:

There are economic savings that can be gained by reducing technical losses by 26.6 percent. The reduced power loss will result to cost savings in terms of annual operations, and this will relieve the utility providers of the financial burden. There is also the possibility of equipment damage and maintenance, which is reduced because of the stable voltage which leads to the higher investment payback of the infrastructure and optimization software.

Social Benefits:

The optimized solution improves voltage stability of all buses, especially at the weak buses like Bus 13 where the minimum voltage has been increased to 0.95 p.u. and all the 21 voltage violations have been removed. This enhances the consistency of power supply to the consumers, particularly in residential and rural locations that are unstable. Improved quality of service leads to increased confidence by the people on the performance of utilities, contributes to and boosts local businesses as well as allows more reliable use of sensitive electronic appliances.

5.5 Moral Ethics and Professionalism

IEEE Standards Compliance:

This project follows all the internationally accepted engineering principles to ensure technical integrity and ethical responsibility. IEEE Std 399 was applied as a guide to the analysis of power systems, and IEEE Std 1036 applied to the safe incorporation of capacitors in the distribution network. The optimization was also done in consideration of the voltage regulation limits ±5% to ensure that the operation of all buses is stable. The implementation of these standards made sure that best practices in design, system reliability, and social safety, as it is important to the engineer to the society.

Professional Responsibility:

Professional integrity was achieved because all limitations, constraints, and assumptions of the algorithm were reported. MATLAB and PYPOWER were applied to check and make the results sound and repeatable. All the literature and the algorithms used were cited accordingly. These are in line with the Board of Engineers Malaysia (BEM) Code of Conduct, the Registration of Engineers Act 1967 [Act 138] and Part IV of the Registration of Engineers Regulations 1990. Specifically. The conduct complies with Section 1.1.1 that is aimed at honesty and competency and Section 1.1.7 that demands fairness and objectivity of professional reporting.

Public Safety Considerations:

The capacitor placement strategy and the voltage levels were kept within safe operating limits and no bus went out of the acceptable range during testing. These practices are based on Duty Ethics which is focused on protecting the public and Utilitarianism which pursues maximum good of the majority. Moreover, the project reflects Virtue Ethics since it encourages trustworthiness, hard work, and respect to social needs by being energy efficient, and technically competent engineering design.

5.6 Project Management, Finance and Entrepreneurship 2

Project Management:

The project progress was seen in Figure 17: Phase 2 Gantt Chart. The opening and closing dates of ZOA project implementation were April 28, 2025 and May 25, 2025 respectively. The first simulation and performance tests were done on May 29 to July 5, 2025 and the analysis of the results was done on July 6 to July 20, 2025. Optimization improvement of ZOA algorithm was done between July 21 2025 and July 30 2025. Chapter 4 and 5 were fully documented between July 25 and August 4, 2025 and final preparation of presentation was done between August 2 and August 4, 2025. The viva took place on 5 August 2025. The meetings with the supervisor were planned to observe the progress and give feedback.

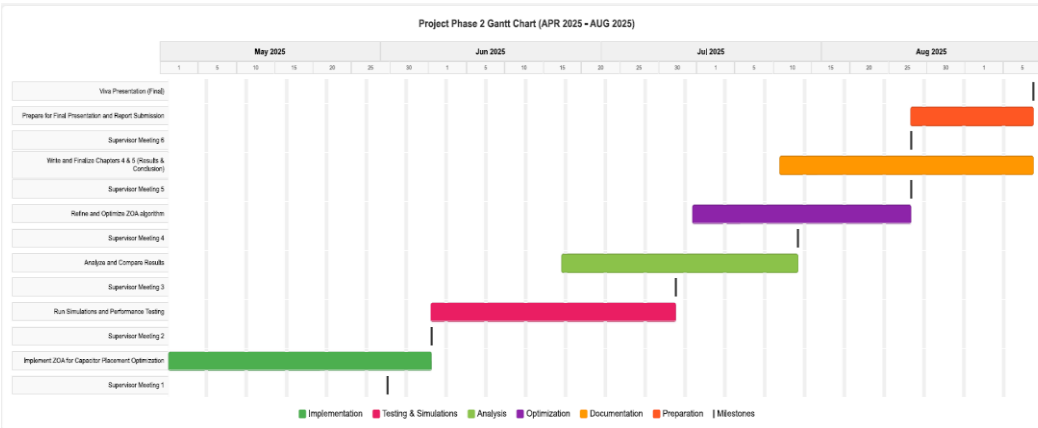


Figure 17:Phase 2 Gantt Chart

Finance:

The Phase 2 Finance Table showed the financial details of the project. The cost of purchasing of a Microsoft Surface Laptop 4 was RM 4000, which helped the core of the algorithm development, simulation running and documentation. Software packages used MATLAB student license was free and Python with PYPOWER was also free. The project was cost effective due to the minimal hardware and free software environment without compromising the computational performance and the output of the research.

Table 23:Phase 2 Finance table

Item	Quantity	Cost (MYR)
MATLAB Student License	1	Rm0.00 (Free)

PyPower Package	1	Rm0.00 (Free)
Microsoft Surface laptop 4	1	Rm4000
Total		Rm4000

Entrepreneurship:

The ZOA optimization developed has good prospects of commercialization. Having shown the reduction of the power losses by 26.6 percent, the full violation of the full voltage, and effective performance in both MATLAB and PYPOWER, the solution can be offered as a standalone software tool to power utilities or academic research. Such business opportunities are licensing the software, offering optimization-as-a-service. This is according to the entrepreneurial ambition of putting technical innovation into scalable, everyday solutions that can be of benefit to both energy efficiency objectives and economic needs.

5.7 Contribution in This Project

One of the main contributions of the given project was the independent design and application of the Zebra Optimization Algorithm (ZOA) specially created to be applied in optimal capacitor location and sizing in a radial distribution system. The initialization of ZOA was provided in two main stages, local intensification and global exploration with control parameters customized, such as a population size of 50, 100 iterations, and five capacitor units, N cap = 5. The vector of solutions was the set of capacitor positions and capacitor values, which was considered as a 10 dimensional problem in which the numbers of buses were required to be integer.

A custom fitness function was created with an objective of minimizing active power loss and annual installation cost. Which ensured that the voltage levels are within the range of +/-5 percent. The better solution also reduced the power loss to 154.9 kW from 211.0 kW, with a 26.6 percent power loss reduction and the 21 voltage violations no longer existed. The optimal capacitor setting was at bus 14, 16, 33, 32 and 31 with 150.00, 589.91, 289.92, 150.00 and 441.29 kVAr, respectively. Modelling, coding of algorithms, simulation, interpretation of results, and validation in both MATLAB and PYPOWER were carried out independently in all the stages.

CHAPTER 6

CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions Relating to Project Objectives

The main objective of this project was to come up with a Zebra Optimization Algorithm (ZOA) to find out the optimum location and size of capacitors in a radial distribution system with the intention of minimizing power loss, improving voltage stability, and power factor. The results achieved this goal and all the three mentioned objectives.

The first objective was to design and program the ZOA algorithm in the best capacitor placement and sizing, was achieved by writing a MATLAB optimization code. The algorithm showed a two phase movement rule that was based on zebra defense mechanism and had repair functions that satisfied the constraints of the radial distribution systems. The location of capacitors was coded as a bus location in integer and the size in kVAr and the performance of the capacitors was tested on IEEE 33 bus test system in MATPOWER.

The second objective was to determine how effective the proposed ZOA approach was. The simulation results showed that ZOA reduced the power loss to 152.22 kW, enhanced the power factor of the system to 0.9799 and the total cost is 97,207.83. The capacitors were on buses [15, 17, 30, 31, 32] and they were [591.2, 150, 248.84, 154.76, 474.14] kVAr. The standard deviation of 1,283.56 indicated that ZOA had a convergence and credible output between runs.

The third objective which showed the comparison of ZOA to the existing methods of optimization such as AVOA, GA, and PSO, proved that ZOA is effective. ZOA was the most cost effective, technically enhanced and stable in results in spite of the lowest power loss of 150.64 kW and highest power factor of 0.9953. It is worth noting that ZOA had the lowest total cost, lowest standard deviation and a power factor improvement, and all the voltage violations were removed. Comparing with PSO that experienced power loss of 155.96 kW and total cost of 98,716.54. ZOA did well in terms of consistency and recovery of the voltage profile.

6.2 Limitations

The ZOA approach, even though it was successful in the IEEE 33 bus system, it has a number of limitations. It was not testes on a larger system. Dynamic characteristics such as load variation and renewable integration have not been considered and this makes it less robust in real life applications.

The algorithm only dealt with fixed sized and positioned capacitors and did not deal with switchable or adaptive devices. Also, the simulation did not consider uncertainties or performance of the execution time. The cost model is also not reflected to the economic factors such as maintenance and installation delays, which will affect the practical implementation.

6.3 Recommendations and Suggestions for Further Research

To improve the Zebra Optimization Algorithm (ZOA), there is need to implement the algorithm in other larger and more complex distribution systems like the unbalanced network. This would help in evaluation of scalability and flexibility based on more challenging grid environments. The variable or switchable step capacitors can be used to better support the systems that have variable load conditions. The further optimisation of total reactive power co-ordination can be achieved with additional improvement of such a linking with distributed generation or energy storage. In order to get the actual feel of the performance of the algorithm, it would be important to install the same on the physical controller platforms which are integrated with the simulation software to test the performance under realistic operational conditions.

6.4 Summary

The project has been able to meet its objective to come up with a Zebra Optimization Algorithm (ZOA) to optimally place capacitors and size them in radial distribution systems. This is what was done, the ZOA was implemented in MATLAB, applied to the IEEE 33 bus system and compared with GA, PSO and

AVOA. The final results showed that there was a decrease of 26.6 percent in power loss, zero violation of voltages and a 15.4 percent increase in power factor as confirmation of the usefulness of ZOA. The cross platform testing using PyPower gave 0% deviation in the output which is correct and consistent. Generally, the project reported that ZOA is a good and effective optimization mechanism that can be used to optimize the performance of power systems.

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APPENDIX A

LOG SHEETS

Student Name and TP Number: DAMIAN ETIENNE ERNESTA	Intake Code: APD4F2411EEE	Supervisor Name: Dr. Hazwani Mohd Rosli

The supervisory sessions for (please select the appropriate phase): ☒Investigation Report/Dissertation 1 ☐Final Year Project Report/Dissertation 2

Notes:

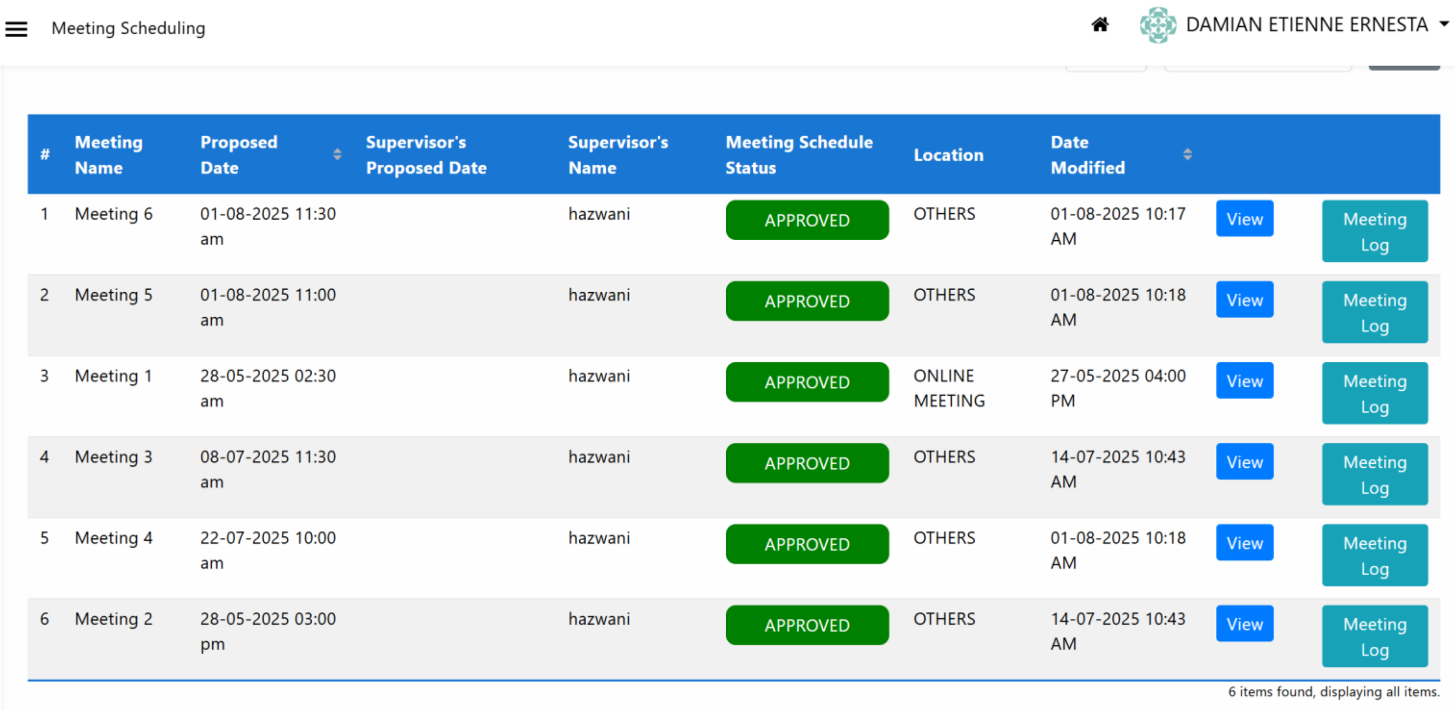
1. There must be at least 9 sessions of supervisory meetings. (THREE sessions during the Investigation Report Phase) (SIX sessions during the Final Year Report Phase).
   Please note that for Engineering projects, a total of 12 mandatory sessions is required with a minimum of 6 sessions each in Phase 1 and Phase 2.
2. The schedule/plan of meetings should be agreed between the Supervisor and Supervisee. The progress should be monitored.
3. The role of Supervisor is to provide guidance. The Supervisee is responsible for the quality of the research and to develop the research skills.
4. The supervisee should prepare in advance for the supervisory session with questions for discussion and updates from previous sessions.
5. The feedback given by Supervisors on the supervisees work can be both oral and written feedback on the supervisee's work.
6. The record of meetings must be maintained by Supervisee. The Supervisor must sign the relevant column of this form after each meeting.
7. Both the Supervisor and Supervisee should embrace and practice ethical and professional conduct.
8. The completed log sheet must be attached as appendix in the IR and FYP report for submission.

No	**Date**	**Items for discussion** (Noted by student before supervisory meeting)	**Record of discussion** (Noted by student during supervisory meeting):	**Action List** (To be undertaken by student by the next supervisory meeting):	**Supervisor Confirmation** (Please sign)	**Notes**
1	6-Dec-24	Introduction to FYP topics.	Talked about capacitor placement and ZOA algorithm.	Can start doing chapter 1.		

No	Date	Items for discussion (Noted by student before supervisory meeting)	Record of discussion (Noted by student during supervisory meeting):	Action List (To be undertaken by student by the next supervisory meeting):	Supervisor Confirmation (Please sign)	Notes
2	17-Jan-25	Chapter 1 update.	Reviewed Chapter 1 and supervisor gave pointers on how to improve.	Can start with chapter 2.		
3	4-Feb-25	Chapter 2 update.	Reviewed Chapter 2 and supervisor gave pointers on how to improve.	Fix chapter 2		
4	21-Feb-25	Chapter 2 update	Reviewed Chapter 2	Finish Chapter 2		
5	28-Feb-25	Chapter 3	Review Chapter 2 and discussed details on Chapter 3	Edit Chapter 3		

No	Date	Items for discussion (Noted by student before supervisory meeting)	Record of discussion (Noted by student during supervisory meeting):	Action List (To be undertaken by student by the next supervisory meeting):	Supervisor Confirmation (Please sign)	Notes
6	5-Mar-25	Chapter 3 update	Review Chapter 3	Edit chapter 3		
7	Click or tap to enter a date.					
8	Click or tap to enter a date.					

Phase 2 meeting is seen below:



Meeting Scheduling

DAMIAN ETIENNE ERNESTA

#	Meeting Name	Proposed Date	Supervisor's Proposed Date	Supervisor's Name	Meeting Schedule Status	Location	Date Modified		
1	Meeting 6	01-08-2025 11:30 am		hazwani	APPROVED	OTHERS	01-08-2025 10:17 AM	View	Meeting Log
2	Meeting 5	01-08-2025 11:00 am		hazwani	APPROVED	OTHERS	01-08-2025 10:18 AM	View	Meeting Log
3	Meeting 1	28-05-2025 02:30 am		hazwani	APPROVED	ONLINE MEETING	27-05-2025 04:00 PM	View	Meeting Log
4	Meeting 3	08-07-2025 11:30 am		hazwani	APPROVED	OTHERS	14-07-2025 10:43 AM	View	Meeting Log
5	Meeting 4	22-07-2025 10:00 am		hazwani	APPROVED	OTHERS	01-08-2025 10:18 AM	View	Meeting Log
6	Meeting 2	28-05-2025 03:00 pm		hazwani	APPROVED	OTHERS	14-07-2025 10:43 AM	View	Meeting Log

6 items found, displaying all items.

APPENDIX B

STUDENT’S ONLINE FYP SELECTION

EE016-3-3-PP1-Project Phase 1
Final Year Project Phase 1 - Final Allocation
School: School of Engineering
Intake: APU4F2411 CE-EEE-ME-PE

SNO	TP Number	Student Names	Programm	Intake	FYP Title ID N	FYP Title	Supervisor Name
1	TP065787	ABDELAZIZ OSAMA AHMED ELSAYED	EEE	APD4F2411EEE	20240182	Custom-Made 3D Printed Sports Shoes with IOT Features for Adults	Ir.Ts.Dr.R.Dhakshyani
2	TP054248	ABDUL AFIQ AKMAL BIN ABDUL MUMIN	EEE	APD4F2411EEE	20240160	Energy Harvesting from Acoustic Noise and Thermoelectric: A Proposal for Hybrid Energy Harvesting	Ir. Dr. Mohamad Affan Bin Mohd Noh
3	TP066692	ABDULRAHMAN ADIL	ME	APD4F2411ME	20240192	Automated Driving Test Results	Ms Shamini Pathpanavan
4	TP061264	ANGGA JATMIKA	ME	APD4F2411ME	20240196	Haptic-Guided Precision Dispensing System for Small-Scale Applications	Dr. Lian Wen Xun
5	TP066273	ARAVIND SOUNDIRARAJAN	CE	APU4F2411CE	DP	Developing a 3D Point Cloud Segmentation Model for Oil Palm Trunks, Fronds, and Fresh Fruit Bunches (FFB)	Assoc. Prof. Ir. Dr. Lai Nai Shyan
6	TP057208	AZAT ANNAMYRADOV	PE	APD4F2411PE	DP	Optimization of Gas Lift Parameters in Mature Fields in Malaysia	Ir. Eur. Ing. Ts. Dr. Harvin Kaur
7	TP065855	CHEN PEK HUI	ME	APU4F2411ME	DP	Integrated Automation Systems for Enhanced Wall Finishing in 3D Concrete Printing	Ir. Narendran Ramasenderan
8	TP064815	DAMIAN ETIENNE ERNESTA	EEE	APD4F2411EEE	DP	Optimal Location and Sizing of Capacitors in a Radial Distribution System	Dr. Hazwani Mohd Rosli
9	TP062736	DAVE KEVIN PRAWIRO	ME	APD4F2411ME			
10	TP062909	DUSTIN LAURENSIUS	PE	APD4F2411PE	DP	Design and Testing of Water-Based Drilling Fluids for HPHT Wells in the Malay Basin	Ir. Eur. Ing. Ts. Dr. Harvin Kaur
11	TP062401	DWAYNE PHANG ZI CHERN	EEE	APD4F2411EEE	DP	Grounding Grid Design in Electrical Power Substation	Dr. Hazwani Mohd Rosli
12	TP063197	ELVIN SUNASSEE	EEE	APD4F2411EEE	20240219	Design of feasible electric vehicle lithium ion battery pack state of charge estimator	Ir. Ts. Dr. Denesh Sooriamoorthy
13	TP066846	FAREED ALI	ME	APU4F2411ME			

APPENDIX C

PROJECT SPECIFICATION FORM

PROJECT SPECIFICATION/PROJECT BRIEF OF ENGINEERING

FYP Title: Optimal Location and Sizing of Capacitors in Radial Distribution Systems

Supervisee Name: DAMIAN ETIENNE ERNESTA

Supervisee TP Number: TP064815

Programme: EEE

Supervisor Name: Dr. Hazwani Mohd Rosli

Supervisor Signature:

Date: 16/032025

Project Specification Form (Engineering)

Note: The PSF is an online submission. Use this form to discuss your proposal with your supervisor. Please complete all sections before meeting your supervisor so that relevant comments can be furnished.

A. Project Title.

Optimal Location and Sizing of Capacitors in Radial Distribution Systems

B. Brief description on project background. (.i.e. Introduction about project and problem statement)

As the need for electricity increases, power losses in radial distribution networks become more problematic. These losses result in high operational costs, poor voltage profiles, and low efficiency. Previously, capacitors have been employed for reactive power compensation to alleviate these problems. However, there are problems associated with incorrect placement and sizing of capacitor. To overcome these challenges, this project uses the Zebra Optimization Algorithm (ZOA) to determine the best location and size of capacitors to minimize power losses and improve system performance.

C. Brief description of project aim and objectives. (i.e. scope of proposal)

Aim:

Designing a Zebra Optimization Algorithm (ZOA) which can be implemented to determine the optimal location and sizing of capacitors in radial distribution systems. The algorithm will help to reduce power losses, enhancing voltage stability and improving the power factor of the system.

Objectives:

To develop an algorithm based on the Zebra Optimization Algorithm (ZOA) for determining the optimal location and sizing of capacitors in a distribution system.

To evaluate the performance of the proposed algorithm for optimized capacitor location and sizing using different test systems.

To compare the effectiveness of the Zebra Optimization Algorithm (ZOA) with existing techniques for optimal capacitor placement and sizing.

D. Brief description of the system/model/design that will be used in this proposal.

- IEEE 33-Bus Distribution Test System.
- The Zebra Optimization Algorithm (ZOA) is implemented for solving optimization problem based on capacitor placement and sizing.
- Power flow analysis using MATLAB for system performance evaluation based on power loss reduction and cost minimization.
- Comparison with existing techniques such as whale optimization algorithm, Integer Encoding Genetic Algorithm, African Vulture Optimization Algorithm, Fly Algorithm, Shannon Entropy.

E. Academic research being carried out and other information, techniques being learnt. (i.e. literature - what are the names of books you are going to read / data sets you are going to use)

Ali, A., Ahmed, Md. M., Zeesan, A. A. N., Apon, H. J., & Shadman Abid, Md. (2024). African Vulture Optimization Algorithm for Simultaneous Placement and Sizing of Shunt Capacitors in Radial Distribution System. *2024 12th International Conference on Smart Grid (IcSmartGrid)*, 406–411. https://doi.org/10.1109/icsmartgrid61824.2024.10578123

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F. Brief description of the materials/methodologies needed by the proposal. (i.e. data collection methods, equipment, testing and etc.)

- MATLAB software for simulation and optimization.
- IEEE 33-Bus Distribution systems for validation.
- Comparison data of optimization algorithms like whale optimization algorithm, Integer Encoding Genetic Algorithm, African Vulture Optimization Algorithm, Fly Algorithm, Shannon Entropy are compared.

G. Brief description of the evaluation and analysis proposed for this project. (i.e. testing, project deliverables and hypothesis, correlation test etc)

- Using IEEE 33 bus system to test the ZOA algorithm.
- Comparing the results with other optimization techniques
- Evaluating performance based on power loss reduction, cost minimization, and computational time.

H. Illustration of how this project will benefit in the future.

- Improving efficiency in distribution networks by minimizing losses.

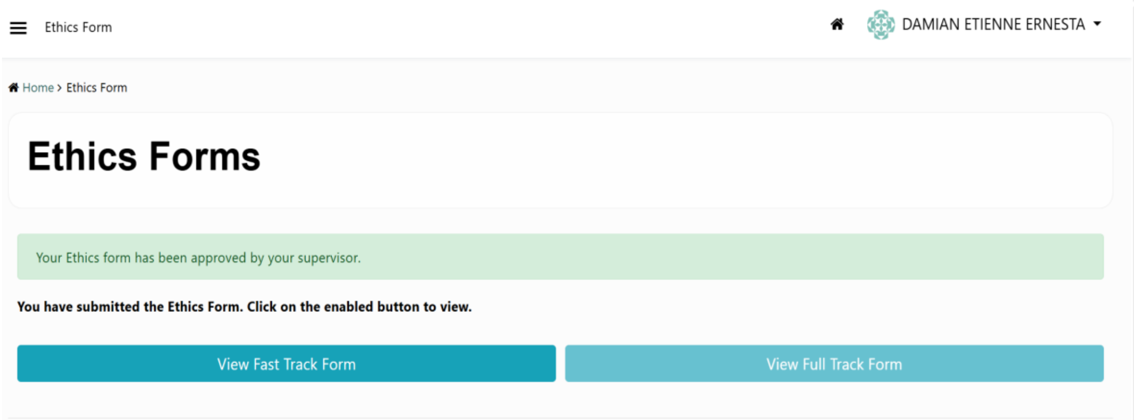
- Improve voltage stability and power factors for better system reliability.

- A cheaper solution for power utilities to optimize capacitor placement.

- Contribute to sustainable energy distribution by reducing energy wastage and operational costs.

APPENDIX D

ETHICS FORM


Ethics Form
DAMIAN ETIENNE ERNESTA
Home › Ethics Form
Ethics Forms
Your Ethics form has been approved by your supervisor.
You have submitted the Ethics Form. Click on the enabled button to view.
View Fast Track Form
View Full Track Form

Appendix E
MAIN ZOA OPTIMIZATION ALGORITHM:

```
MAIN ZOA OPTIMIZATION ALGORITHM:

// Step 1: Setup
Create population of 50 zebras
Give each zebra random capacitor locations and sizes
Test how good each zebra solution is
Find the best zebra
// Step 2: Main optimization loop
Repeat for 100 iterations:
    For each zebra (do all zebras at same time):
        Remember current zebra position and fitness score
        // Phase 1: Follow the leader (Foraging)
        Create new position by following pioneer zebra:
        new_position_1 = current_position + random_number × (pioneer_position - current_position)
        Fix any rule violations in new_position_1
        Test how good new_position_1 is
        If new_position_1 is better than current position:
            Update zebra to new_position_1
        // Phase 2: Defense against predators
        Create another new position for defense:
        If random_chance < 50%:
            // Defense Strategy 1: Stay close to good solutions
            new_position_2 = current_position + small_step_toward_pioneer
        Else:
            // Defense Strategy 2: Try something completely different
            Add random changes to current_position
            new_position_2 = current_position + random_changes

        Fix any rule violations in new_position_2
        Test how good new_position_2 is
        If new_position_2 is better than current position:
            Keep new_position_2 for next iteration
        Else:
            Keep current position for next iteration
    // Step 3: Update the best solution
    Look at all zebras and find the best one
    If this best zebra is better than pioneer zebra:
        Make this zebra the new pioneer zebra
    // Step 4: Record progress
    Save the best fitness score for this iteration
    Print "Iteration X: Best cost = $Y"
Return: best locations, best sizes, cost history
// ===== RULE CHECKING FUNCTION =====
Function fix_rule_violations(zebra_solution):
    // Fix capacitor locations
    Round locations to whole numbers (bus numbers must be integers)
    Make sure locations are between bus 2 and bus 33

    // Make sure no two capacitors are on same bus
    If multiple capacitors are on same bus:
        Find available buses that don't have capacitors
        Move duplicate capacitors to available buses
    // Fix capacitor sizes
    Make sure sizes are between 150 kVAr and 1200 kVAr
    Return: fixed solution
```

Appendix F
FITNESS FUNCTION

```
FITNESS FUNCTION
Input: One zebra solution which contains capacitor locations and sizes
// Step 1: Set up the power system
Start with original IEEE 33-bus system
Extract capacitor locations from zebra solution (positions 1,3,5,7,9)
Extract capacitor sizes from zebra solution (positions 2,4,6,8,10)
// Step 2: Install capacitors on the power system
total_capacitors_installed = 0
For each capacitor:
    Get location (which bus) and size (how many kVAr)
    If location is valid bus number AND size is positive:
        Convert kVAr to MVAr (divide by 1000)
        Install capacitor at that bus (reduce reactive load)
        Add to total_capacitors_installed
    End If
// Step 3: Test the power system
Run power flow analysis using MATPOWER
Check if power flow calculation worked
If power flow failed:
    Return very high cost = 100,000,000,000 (solution is useless)
If power flow worked:
    Get voltage at each bus
    Set voltage limits: minimum = 0.95, maximum = 1.05
    // Step 4: Check for voltage problems
    Count buses with voltage too low (below 0.95)
    Count buses with voltage too high (above 1.05)
    If any voltage problems exist:
        // This solution breaks the rules - give huge penalty
        Count how many buses have problems
        Find worst voltage violation
        penalty_cost = 10,000,000,000 + 100,000,000 × number_of_problems + 1,000,000,000 × worst_violation
        Return penalty_cost
    Else:
        // This solution follows all rules - calculate real costs
        // Step 5: Calculate power loss cost
        Get total power loss from power flow results (in MW)
        Convert to kW (multiply by 1000)
        power_loss_cost = 160 × power_loss_kW
        // Step 6: Calculate capacitor cost
        capacitor_cost = 45 × total_capacitors_installed
         // Step 7: Calculate total annual cost
        total_cost = power_loss_cost + capacitor_cost
        // Step 8: Add small safety penalty if voltage is too close to limits
        Find lowest voltage in system
        safety_margin = lowest_voltage - 0.95
        If safety_margin < 0.005: (less than 0.005 safety buffer)
            safety_penalty = 100 × (0.005 - safety_margin)
            total_cost = total_cost + safety_penalty
        Return total_cost
// Step 9: Handle calculation errors
If total_cost is infinity or undefined:
    Return maximum penalty = 100,000,000,000,000,000
Return final cost score for this zebra solution
```