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Optimizing Power Distribution Through Electric Load Modelling Using Hybrid Particle Swarm Optimization – Artificial Neural Network Techniques

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Abstract- The rapid growth in energy demand has highlighted the need for efficient power distribution systems to reduce losses and enhance stability. This thesis presents an innovative approach to optimizing power distribution through electric load modelling by integrating hybrid Particle Swarm Optimization (PSO) and Artificial Neural Network (ANN) techniques. Traditional load forecasting and distribution methods often struggle with dynamic and non-linear energy demands, leading to inefficiencies and increased operational costs. The proposed methodology leverages the predictive capabilities of ANN to model complex load behavior accurately while utilizing PSO to optimize the allocation of power resources. By combining these techniques, the system dynamically adjusts power distribution, addressing fluctuations in load demand in real-time. The hybrid algorithm improves convergence speed and enhances the precision of load forecasts, resulting in reduced energy losses and improved grid reliability. Extensive simulations on benchmark power systems demonstrate that the proposed model outperforms conventional techniques in terms of accuracy, efficiency, and adaptability. The research also includes a sensitivity analysis to evaluate the model's robustness under varying load conditions. These findings underscore the potential of integrating advanced computational intelligence methods for achieving sustainable and efficient energy management in modern power systems. This work contributes to the field of smart grid technologies, offering a scalable and adaptive framework for optimizing power distribution in diverse operational scenarios.

Indexed Terms- Alternating Current (AC), Artificial Neural Network (ANN), Direct Current (DC), IEEE 9 – Bus, Particle Swam Optimization (PSO)

I. INTRODUCTION

Over the years, the Nigerian Electricity Supply Industry has undergone significant reforms aimed at improving the electricity services provision in Nigeria. These reforms began with the rehabilitation of government-owned electricity infrastructures popularly known as National Electric Power Authority (NEPA) in 1999 and the implementation of the 2010 Power Sector Reform. While some stakeholders have observed the benefits of these reforms, others are yet to see their positive impact. The reforms have been a subject of debate, prompting the need for a comprehensive modeling of the industry's past, present, and future [1].

The Nigerian Electricity Regulatory Commission (NERC) has been actively involved in initiatives to improve the power sector. For instance, the commission reported that about 980,000 electricity customers were metered across the country under the Phase Zero, with plans for the second phase (Phase One) to begin in the first quarter of 2022. Additionally, the government introduced a willing seller, willing buyer electricity distribution policy to facilitate direct transfer of electricity from generating companies to willing consumers, aiming to enhance power distribution across various sectors, including communities, commercial clusters, industrial areas, and hospitality sectors [2]. Despite Nigeria's significant energy resources, including oil, gas, hydro, and solar, the country needs help in fully harnessing its potential. While it has the capacity to generate 12,522 MW of electric power from existing plants, it often dispatches only around 4,000 MW, which is insufficient for a population of over 195 million people. The power sector experiences various challenges related to electricity policy enforcement, regulatory uncertainty, gas supply, transmission system constraints, and major power sector planning shortfalls, hindering its commercial viability. [3].

Consequently, The Nigerian Power System has been plagued by problems such as inadequate generation, significant losses in the system, and inefficient use of electricity. A study conducted on the Nigerian distribution network highlighted the energy shortages due to technical losses and their cost implications. The modelling, based on network data collected over a specific period, revealed substantial energy losses in major industrial cities of Nigeria, emphasizing the need for optimization and efficient power distribution [4].

More so, The Nigerian Electricity Supply Industry has also witnessed significant privatization initiatives, including the Nigerian Power Sector privatization, which is considered one of the boldest privatization initiatives in the global power sector. This initiative has been instrumental in addressing the challenges faced by the Nigerian electricity system, which previously failed to meet the country's power needs. The privatization process seeks to expand the market and attract more investors to the power sector, promoting short-term and long-term solutions to the problem of power failure [5]. In conclusion, the Nigerian electricity supply industry has undergone substantial reforms and initiatives to address the challenges in power distribution and optimize the electricity services in Nigeria. The industry's past, present, and future state, along with the various challenges and initiatives, provide a rich context for conducting a case study on optimizing power distribution through electric load modelling in the power distribution network.

II. LITERATURE REVIEW

In this Chapter, the available literature is reviewed in line with the subject matter of the research project, which is the optimization of electric load assessment in a power network through the use of Newton-Raphson, Fast decoupled, and Gauss-Seidel optimization methods. The central themes to be reviewed will include the basic fundamental principles of power system operations and load flow analysis and how the newton's method can improve load flow analysis.

In general term, the electricity supply systems can be categorically stated as the network which aids the transfer of electricity from the source when it is generated or produced to the final destination, which is the consumer [6]. It consists of three major aspects or components. First, we have the power generation plants also called power stations, then medium for the transfer of the power, which is the transmission lines, and finally, the distribution system that aid in the distribution of this transmitted power to the end users or consumers. Hence, these three major components are; power station, transmission lines, and distribution system [7]. A depiction of this system is given in figure 1 below. This diagram gives the basic illustration of the generation, transmission and distribution systems.

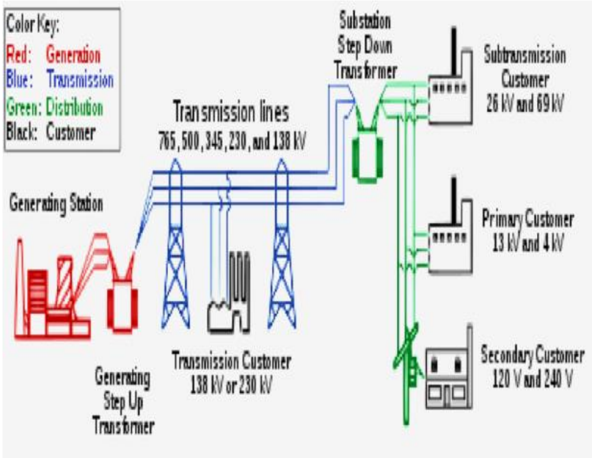


Figure 2.1: Electrical Supply System

Other notable classifications of the power supply systems are; the alternating current (AC) system, and the overhead and underground systems. The Direct current (DC) systems are systems that use DC voltage as their primary power source. These systems have wide applications in telecom, automotive, aircraft, low-voltage, and low-current settings. They also serve as vital components in off-grid solar or wind power systems, where accurate estimation of energy needs is crucial to prevent battery damage and ensure uninterrupted power supply [9], [10]. The characteristics of this DC supply is illustrated in Figure 2.2.

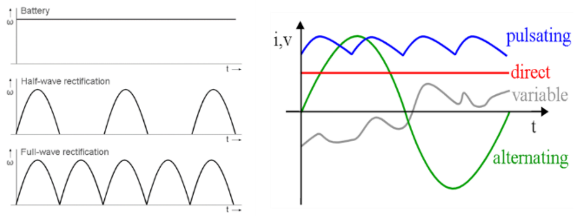


Figure 2.2: DC Supply Characteristics

DC power systems offer advantages in terms of efficiency, reliability, and compatibility with renewable energy sources. They are also crucial in applications where low-voltage, low-current power is required, such as in telecommunications and automotive systems. However, DC systems may not always be compatible with existing AC infrastructure or devices, and the equipment for DC systems can be specific to the application and require expertise in design and installation [12].

An AC power supply system utilizes alternating current (AC) to distribute electricity to various loads as shown in Figure 1.3, typically consisting of three conductors carrying AC of the same frequency and voltage amplitude, but with a relative phase difference of 120 degrees. This configuration is well-suited for delivering substantial power and is often employed in heavy-duty industrial machinery with high power demands. AC power supplies serve applications such as power pumps, electric heaters, and motors, offering cost-effective operation. Additionally, transformers may be incorporated to reduce the AC voltage from transmission lines to a standard level for domestic use. Moreover, AC power supplies find utility in diverse settings including aviation, lighting, laboratory testing, military, and factory production for electrical testing purposes [13], [15].

Furthermore, the AC electrical supply system has been a cornerstone of modern electricity distribution, powering homes, industries, and infrastructure across the globe. This report delves into the history, development, and current state of AC power systems, synthesizing key points from various sources to provide a thorough understanding of this essential technology [16].

AC systems use a range of frequencies depending on the type of load, with lighter systems employing higher frequencies and heavy-duty motor and traction systems utilizing lower frequencies. The economics of the central power plant improved dramatically when standardized lighting and power systems were developed to operate on a common frequency. The same generation plant that feeds the large industrial load during the day can then power railway systems for passengers during rush hour and the lighting loads in the evening. This enhances the system load factor and reduces the overall cost of electrical energy as generating stations are assigned to power or lighting loads according to frequency [17], [18].

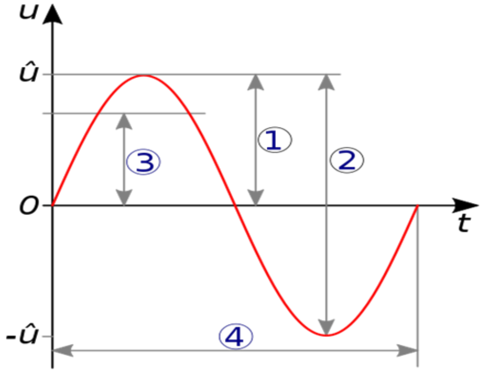


Figure 2.3. AC Characteristics

AC power systems, which alternates direction multiple times per second and can easily be converted to different voltages using transformers is much popular due to their efficiency and practicality. This system was first practically demonstrated by William Stanley in 1886, using transformers to adjust voltage levels for electrical illumination in Great Barrington, Massachusetts [20]. The late 19th century witnessed a fierce competition known as the "War of the Currents," where Thomas Edison's direct current (DC) systems were pitted against Nikola Tesla's alternating current (AC) systems [15]. The first full AC power system, which included all the basic features of modern electric power systems, was demonstrated in Great Barrington and marked a significant milestone in the history of electricity. The Folsom Powerhouse in California later became the first facility to send high-voltage AC over long-distance transmission lines, using newly invented AC generators and hydroelectric power. This event underscored the advantages of AC power for long-distance transmission, which remains the standard today [15].

Considering its standardization and efficiency, [21] considered the standardization of lighting and power systems to operate on a common frequency which significantly improved the economics of central power plants. This allowed the same generation plant to serve various loads throughout the day, from industrial to railway systems during rush hour, and lighting loads in the evening

Recent developments in AC technology include advanced heat exchangers, multipurpose units that consolidate cooling, water heating, and dehumidification, and solid-state heat pumps that could potentially replace standard refrigerant-based AC units [22]

Electrical load refers to any device or equipment that consumes electrical energy from a power source. These loads are essential components of electrical circuits and can be found in various forms such as appliances, lights, and machinery within homes, businesses, and industries. The nature of an electrical load can be resistive, inductive, capacitive, or a combination of these types, each with distinct characteristics and applications [23]. Figure 2.4 shows a simple diagram of how electrical load system is connected in a simple circuit. This illustrates the general principle of the load system.

Theses loads can be grouped under three main types, namely [23];

Resistive loads: electrical energy is converted into heat without altering the current or voltage phase as seen in light bulbs and heaters

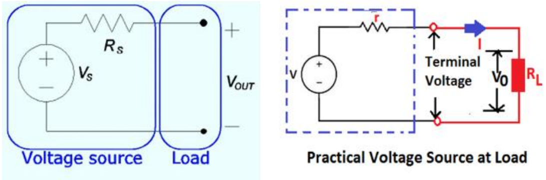


Figure 2.4: Electrical Load

Capacitive loads: store energy in electric field and releases it when there is change in voltage level as seen also in cables and motor starters

Inductive loads: these loads use a magnetic field to operate and are typically found in electric motors, transformers, and generators

Generally, electrical loads are often calculated using ohm's law which gives the relationship between current, voltage, and resistance.

In the realm of electrical engineering, Load Flow Analysis (LFA) emerges as a cornerstone, a notion underscored by [24], with significant implications for power system planning and operation. [33] Confirms its pivotal role, enabling engineers to conduct assessments on voltage stability, optimize power transmission and distribution, and uphold the reliability of the electrical grid. LFA relies on computational models, aiding in determining crucial parameters like voltage magnitude, phase angles, real and reactive power flows, and line losses within the network. Among the techniques commonly utilized, as referenced in [24], [30], [31], [33]–[40], the most commonly used include the Newton-Raphson method, Gauss-Seidel method, and the Fast Decoupled load flow method. Particularly in the context of large-scale power systems, the latter method, stands out for its reduced computational complexity. The significance of LFA, as outlined by [24], cannot be overstated, given its pivotal role in maintaining voltage stability and identifying potential bottlenecks or inefficiencies within the network.

Furthermore, [41] underscores its importance in guiding decisions concerning the placement of new generation sources and transmission lines. Since the capacity of the power plants and grids together with the cost associated in running maintenance, installation, and other energy losses are all very important factor to put into consideration when planning for power distribution network expansion [41], [42], [24] opined that an optimization model can reduce these energy losses and further facilitate the transmission line design while also serving as a guide for how the maintenance plans will be developed.

To achieve the required optimization, energy consumption patterns has to be examined in order to determine time when peak loads occur, and also the state of the equipment [43]. If carried out appropriately, [42] stated that it will show the areas that require improvement and upgrades. Therefore, to optimize the power distribution network through load modeling will involve a multifaceted approach that includes load flow analysis, system upgrades, energy efficiency measures, and the adoption of advanced technologies [43].

Summary of Related Works.

1. A. Ranjan et al. in "Voltage Fluctuations and Sensitivity Assessment of Load Flow Solutions for the IEEE 9-bus System," [59] conducted load flow analysis for voltage-sensitive loads on an IEEE 9-Bus test network and analyzed the impact of voltage-sensitive loads on load flow and assessed variations in initial voltages of load buses. He further developed an iterative load flow model to integrate various load concepts into system parameters while conducting MATLAB simulations for the IEEE 9 Bus system. An in-depth study showed that the author did not delve into the specific numerical results obtained from the simulations nor discuss the detailed methodology of the iterative load flow model development. However, the gap identified is that the research paper does not address the application of the methodology to networks with a mix of the three types of loads on each line.
2. R. Rahimoon, A. Gul, and R. Talani, in "Modelling of IEEE 9-Bus System with Load Flow and Short Circuit Analyses," [60] described the performance of Load Flow and Short Circuit Analyses on the standard IEEE 9-Bus System and detailed how these analyses were conducted and the results that were achieved. The researcher analyses were also performed after removing a voltage-controlled generator from the system, showing a reduction in short-circuit fault current magnitude compared to when all generators were present. Surprisingly, the paper did not delve into the specific technical details of the mathematical models used for the analyses and it did not also discuss the impact of different fault types on the system beyond the short-circuit fault scenario. Of all that, the gaps identified are the lack of exploration into the effects of other types of faults, such as open-circuit or three-phase faults, on the IEEE 9-Bus System, the lack of a detailed discussion on the study's specific methodologies employed for Load Flow and Short Circuit Analyses.
3. S. Tiwari, M. A. Ansari, K. Kumar, S. Chaturvedi, M. Singh, and S. Kumar, in "Load Flow Analysis of IEEE 14 Bus System Using ANN Technique," [61] successfully demonstrated the use of ANN techniques through MATLAB simulations to analyze the steady-state conditions of the power system, including voltage, active and reactive power, and load angle at each bus. Even so, the paper does not delve into the specific details of the learning algorithms used in the feed-forward back propagation network or provide a comparative analysis with other existing methods for load flow analysis. Thorough research identified that the research lacked discussion on the computational efficiency and scalability of the ANN technique compared to traditional load flow analysis methods, which could be a valuable area for future research to explore.
4. Abhishek Kaunar et al. in the paper titled "Comparison of Simulation Tools for Load Flow Analysis," [62] compared the efficacy of two software; Electrical Transient and Analysis Program (ETAP), and Power System Computer-Aided Design (PSCAD) in unbalanced load flow analysis; conducted load flow analysis for voltage-sensitive loads on an IEEE 9-Bus test network. developed an iterative load flow model to integrate various load concepts into system parameters and carried out simulations in ETAP for the IEEE 9 Bus system. Extensive study revealed some undone work which are the paper does not delve into the specific numerical results obtained from the simulations and could not discuss the detailed methodology of the iterative load flow model development. Nevertheless, the researcher failed to address the application of the methodology to networks with a mix of the three types of loads on each line.
5. A. Prasad and O. Singh, in "Analysis of Software Tools Used for Load-Flow Studies," [63] analyzed the load flow of a 5-bus power system using three different simulation tools specifically MATLAB Simulink, ETAP, and Power-world Simulator. The study compares the results and analyzes the software tools in terms of accuracy and ease of use. The Newton-Raphson (NR) load flow method is utilized for the analysis due to its convergence properties, making it suitable for complex power systems with a large number of buses. The IEEE-5

bus system is used for the analysis, and MATLAB is employed to generate output data for comparison with other tools. The undone work is that the study is not explicitly mentioned in the provided sections. With all these, the gap in the research paper lies in the absence of explicit discussion on the limitations or challenges faced during the load flow analysis using different software tools. Additionally, the paper does not delve into the potential areas of improvement or future research directions in the field of load-flow studies using various simulation tools.

6. P. V Rajesh Varma, M. K. Kar, and A. K. Singh, in "Transient Analysis of a Standard IEEE-9 Bus Power System Using Power World Simulator," [64] analyzed the system for different fault conditions such as three-phase balanced, line to ground, line to line, and double line to ground fault using the standard IEEE 9 bus system and utilized the Power World Simulator software to conduct the analysis. More so, he studied the effects of generator outage and bus outage on the system and effectively discussed how the system retains its stability after the outage. Finally, the researcher conducted transient analysis of the power system network to facilitate the design of a better smart grid. The work undone or areas that could be further explored based on the provided context included: detailed discussion on the specific methodologies used in the transient analysis process and in-depth exploration of the impact of various fault conditions on the power system components. Nonetheless, the gap in the research that could be addressed in future studies is the need for a more comprehensive analysis of the system's response to different fault scenarios to enhance the understanding of power system stability and reliability.
7. R. Jena, S. Chirantan, S. C. Swain, and P. C. Panda, in "Load flow analysis and optimal allocation of Static Var Compensator (SVC) in nine bus power system," [65] focused on the analysis of a shunt type Flexible AC Transmission System (FACTS) controller, specifically a Static Var Compensator (SVC), in a nine-bus power system. The researcher conducted load flow studies for both an uncompensated system and an SVC compensated system by varying the installation location of the SVC from bus 1 to bus 9 with the sole aim of enhancing voltage stability and minimize losses by analyzing voltage magnitude variations and overall real and reactive power losses at each bus concerning the SVC installation location. All the performance analyses were carried out using MATLAB/SIMULINK software. However, the author did not explicitly mention any specific work that remains undone within the scope of the study. Be it as it may, the potential gap in the study could be the lack of detailed discussion on the specific challenges or limitations encountered during the implementation of the SVC in the nine-bus power system. Another gap could be the absence of a comparative analysis with other types of FACTS devices or control strategies to highlight the unique advantages of using an SVC in this particular power system scenario.
8. Ajith. M and D. Rajeswari, in "Load Flow Analysis in Hybrid AC-DC Transmission Network," [66] concentrated on constructing and analyzing load flow and short circuit behavior in an IEEE 14 bus power system with a DC link using MATLAB software, parameters for converter transformer, rectifier, inverter, and DC cable were determined for modeling the DC link. The analysis included the incorporation of a DC link at a weak bus in the power system and the results of load flow analysis, comparison of reactive power flow, system losses, and voltage in both AC and AC-DC systems are provided. A comprehensive review of the work shows the paper did not explicitly mention specific aspects of work that were left undone or areas for further investigation. Despite the above, the gap in the research lies in the lack of discussion regarding the limitations or challenges faced during the load flow analysis in the hybrid AC-DC transmission network. Also, further exploration could include addressing the impact of different DC link configurations on system stability and efficiency in hybrid transmission networks.
9. R. K. Pal and R. S. Lodhi, in "Optimal Load Flow Analysis in Interconnected Network Using MATLAB," [67] interest was on presenting an optimal load flow method for solving Interconnected Distribution Systems. He successfully solved the load flow test case problem for interconnected distribution systems using methods like Newton-Raphson, Gauss-Seidel, and

Fast-Decoupled. In comparing the results for the IEEE 30 bus network, it showed that the Newton-Raphson method efficiently obtained optimal solutions for load flow problems. The power loss was reduced via the implementation of remedial actions through MATLAB programming. The specific aspects of work left undone are not explicitly mentioned in the provided sections. The gap in the research paper highlights the effectiveness of the Newton-Raphson method in obtaining optimal solutions for load flow problems in interconnected distribution systems. However, it does not delve into potential limitations or challenges faced when applying this method in real-world scenarios.

10. S. Mishra and Y. S. Brar, in "Load Flow Analysis Using MATLAB," [34], the research paper focused on performing load flow analysis using the Newton Raphson method for both the IEEE 14 Bus System and the IEEE 30 Bus System. It calculates scheduled active power, scheduled reactive power for each generating unit, active power injections, reactive power injections, active power loss, and reactive power loss in each branch for the mentioned bus systems. Graphs were plotted to visualize the active power loss and reactive power loss for both the IEEE 14 Bus System and the IEEE 30 Bus System. Unfortunately, the specific aspects of work left undone are not explicitly mentioned in the provided sections. The potential gap in the research could be the lack of discussion on the impact of different load flow analysis methods on the overall efficiency and stability of power systems. More so, the absence of a comparative analysis with other optimization techniques commonly used in power system analysis.

III. METHODOLOGY

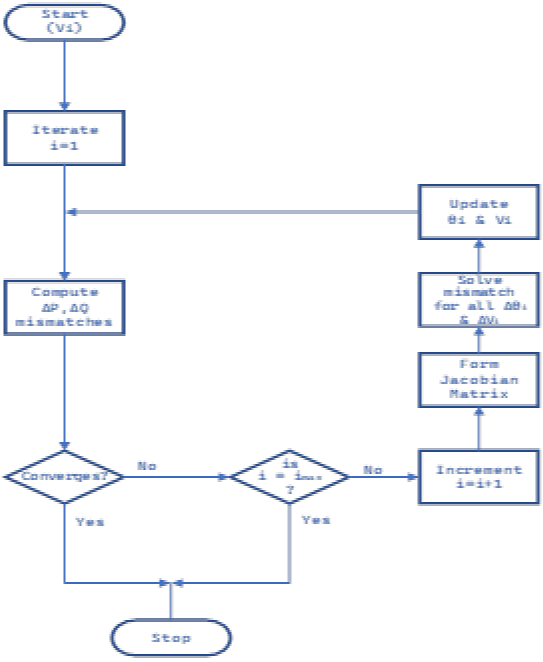


Figure 3.1: Generic Flowchart for conventional methods

Proposed Hybrid PSO-ANN Method

The proposed hybrid PSO-ANN method leverages on the combination of two important properties to enhance the load flow analysis accuracy and convergence speed. These two properties are the predictive capabilities of a well-trained Artificial Neural Networks (ANNs) and the optimization efficiency of Particle Swarm Optimization (PSO). The process is simply data collection, neural network design, PSO optimization, training and validation as shown in Figure 3.2

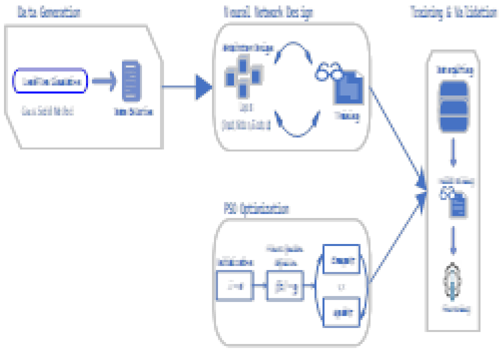


Figure 3.2: The Proposed Hybrid PSO-ANN process

Data Generation

To train the ANN, synthetic load flow data is generated using the traditional methods described in the Newton-Raphson method of load flow analysis in section 3.3.2 above

- Load Flow Simulation:
  - Multiple load flow scenarios are simulated using Gauss-Seidel, Newton-Raphson, and Fast Decoupled methods.
  - Load and generation values are perturbed within realistic ranges to create a diverse dataset.
- Data Collection:
  - Collect input data (loads and generations) and target data (voltage magnitudes and angles) from each simulation.
  - Normalize the data to ensure effective ANN training.

ANN Design

The ANN is designed to predict bus voltage magnitudes and angles based on input power data.

- Architecture:
  - Input layer: Number of neurons equal to the number of load and generation data points.
  - Hidden layers: One or more layers with sufficient neurons to capture non-linear relationships.
  - Output layer: Neurons corresponding to voltage magnitudes and angles.
- Training:
  - Use back propagation for initial training to achieve a reasonable starting point.

PSO Optimization

PSO optimizes the ANN's weights to minimize prediction error. This is done by three processes; first is the PSO initialization, which entails the generation of an initial swarm particles representing potential neural network weights. Furthermore, the fitness function is defined based on the mean squared error (MSE) between the neural net prediction and the actual results. Finally, the particles velocities and positions are updated iteratively to find the optimal weights in the optimization process.

Training and Validation

The data set is divided into three set for training, validation and testing according. Moreso, the initial training is performed using back propagation for the feedforward network. Then, the PSO is applied to fine-tune the neural network. All these are carried out as three process which are grouped as data splitting, initial training, and fine-tuning processes.

COMPARATIVE ANALYSIS

The comparative analysis of this work was done by comparing the Hybrid PSO-ANN technique with other methods for optimizing power distribution in the IEEE 9 bus system. Specific parameters or performance metrics used for the comparison and the unique contributions of the Hybrid PSO-ANN approach in the context of your research are as below:

Performance Metrics

The performance of each load flow method that is, the Newton-Raphson, Gauss-Siedel, and Fast decouple method were evaluated based on:

- Convergence speed
- Accuracy of voltage magnitude and angle predictions
- Computational efficiency

Subsequently plots and graphs gotten from the output are recorded in the result sections.

Benchmarking

The results obtained from the traditional methods as above and the proposed hybrid PSO-ANN method are compared with published results from journals. This comparative analysis involves:

- Extracting benchmark data from WSCC 9 data and journal publications.
- Comparing the accuracy and efficiency of the proposed method against these benchmarks.
- Discussing the findings and implications in the result and the discussion of result section.

THE INSTRUMENT AND TOOLS USED IN THE PROJECT

The experimental set up comprise of the following both software and hardware items

- Trained network or dataset
- MatLab 2023a and simulation software
- Simulink
- Neural Network Toolbox
- Parallel Computing Toolbox
- MatPower toolbox
- Core i5 processor laptop

IV. RESULTS

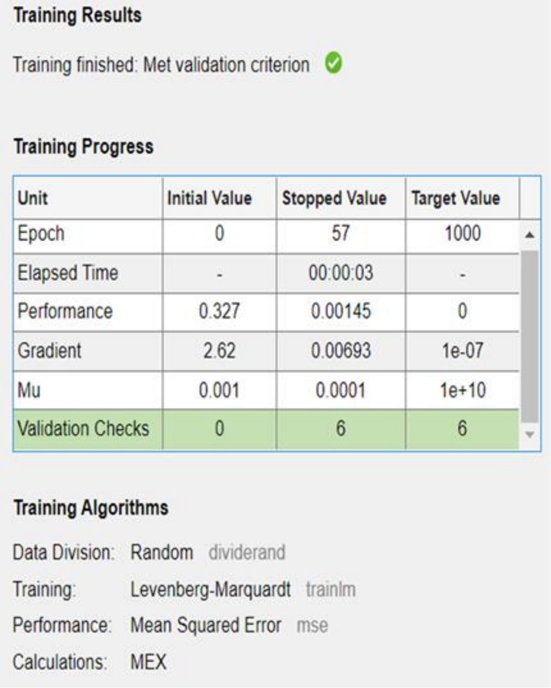
This chapter delves into the presentation of the subsequent results obtained from the simulation of the processes associated with the implementation of the hybrid PSO-ANN Load Flow method. The results representing the outcomes from the PSO algorithm, ANN trainings, power flow implementations as recorded are thus presented accordingly.

Outcome of the Neural Network from PSO algorithm setup

This section presents the results obtained from integrating the Neural Network with the Particle Swarm Optimization (PSO) algorithm. The combined approach aimed to optimize the power flow across the system, focusing on minimizing power losses and improving voltage profiles. The subsequent graphs illustrate the active and reactive power flows, voltage magnitude, and angle profiles, as well as the overall system performance achieved through this hybrid PSO-ANN setup.

Neural Network Outcome

Using MATLAB, the GUI of the final result of the neural network which shows the subsequent training progress and the algorithms implemented is as represented in Figure 4.1. The initial and stop value, including the target value for the epoch, elapsed time, performance, gradient, Mu, and validation checks as gotten from the simulation/trainings are shown inclusively.



Training Results

Training finished: Met validation criterion ✓

Training Progress

Unit	Initial Value	Stopped Value	Target Value
Epoch	0	57	1000
Elapsed Time	-	00:00:03	-
Performance	0.327	0.00145	0
Gradient	2.62	0.00693	1e-07
Mu	0.001	0.0001	1e+10
Validation Checks	0	6	6

Training Algorithms

Data Division: Random dividerand
Training: Levenberg-Marquardt trainlm
Performance: Mean Squared Error mse
Calculations: MEX

Figure 4.1: Neural Network Training Results

During the artificial neural network, the mean squared error (MSE) metric evaluates how the model performs based on the training data over several iterations, which, in this case, took 57 epochs. In all, to assess the neural network generalized ability, it is expected to monitor the training, validation, and test errors to ensure that overfitting or underfitting does not occur. The performance plot, training state, and error histogram are depicted in Figure 4.2, Figure 4.3, and Figure 4.4.

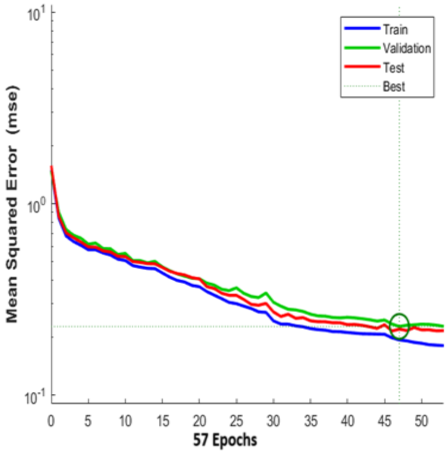


Figure 4.2: Performance Plot

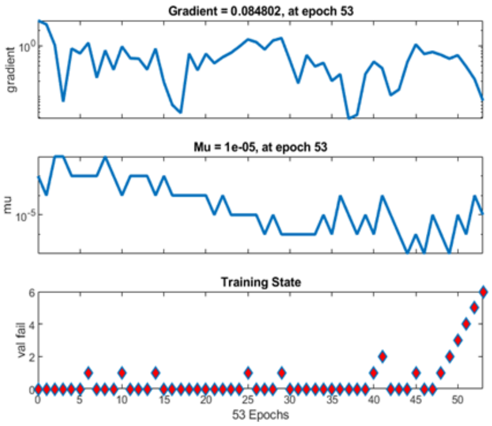


Figure 4.3: Training State

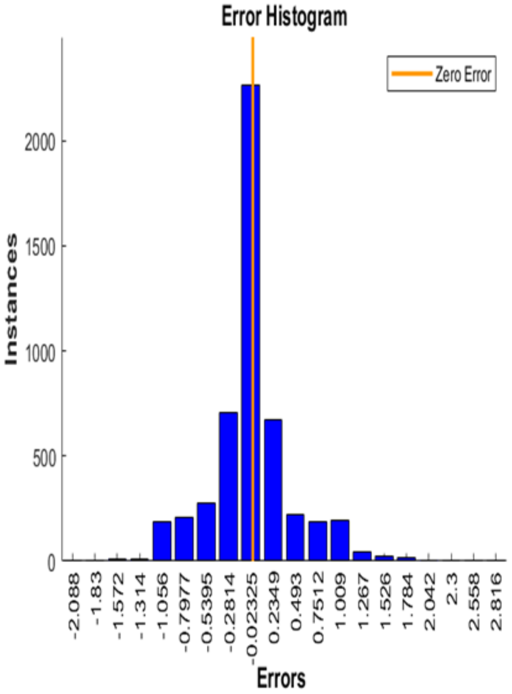
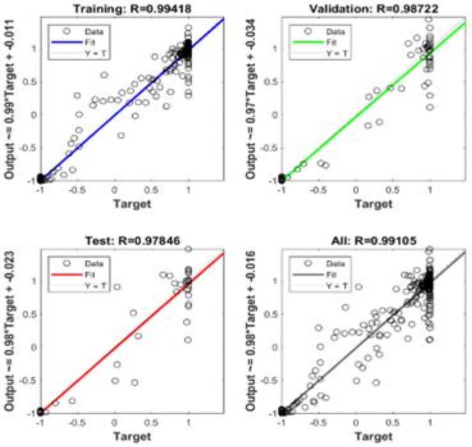


Figure 4.4: Error Histogram

These figures from the plots shown in Figure 4.2, Figure 4.3, and Figure 4.4 shows the MSE for training, validation, and test datasets over epochs. Since the training error decreases over time, it indicates that the neural network model is learning effectively. Also, since the validation error closely follows the training error, it implies that the generalization is good and that there is no over-fitting. Moreover, it is worthy of note that spread of the data around the zero-point in Figure 4.4 depicts that it is a better fit.

Another good indicator of the training performance is the regression plots. It shows the relationship between the predicted and the actual target values for the training, validation, test, and overall dataset. These regression plots gotten from the training are shown in Figure 4.5.



PFigure 4.5: Neural Network Training Regression

In each subplot of Figure 4.5, the line represents the ideal scenario that shows how the predicted values relate to the actual values. A regression value R closer to 1 indicates a strong predictive model, and looking at each subplot, the R value is very close to 1, which implies that there exists a very close relationship between the output and the desired target or outcome. Hence, the general R-value of approximately 0.99105 indicates the relationship is better.

Outcome from PSO algorithm setup

To measure how well a solution meets the optimization objective the fitness function is monitored over several iterations to determine whether the implemented algorithm converges towards an optimal solution as is expected of the PSO technique. Figure 4.6 which is the plot of the fitness function vs. iterations elaborates on the PSO convergence.

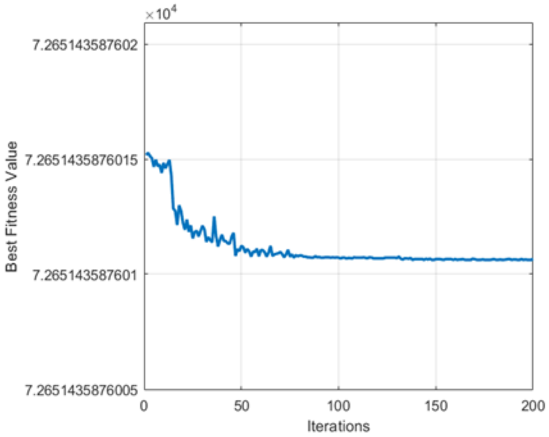


Figure 4.6: Graph of Fitness Function against iterations

Given that the fitness function's value decreases over successive iterations, it indicates that the PSO algorithm is optimizing the solution accordingly and also effectively. The notable reduction in the fitness observed in Figure 4.6 suggests that the particles are actually converging towards the solution that minimizes the objective function, which in this case is minimizing the power losses or mismatches. Furthermore, to gain insights into the overall progress of the PSO optimization algorithm, it is necessary to consider tracking both best and mean fitness values. While the best fitness represents the way the performance of the top solution is faring, the mean fitness shows the average performance across all particles. This is as illustrated in Figure 4.7 where the plot shows how both the best and mean fitness values evolve over iterations.

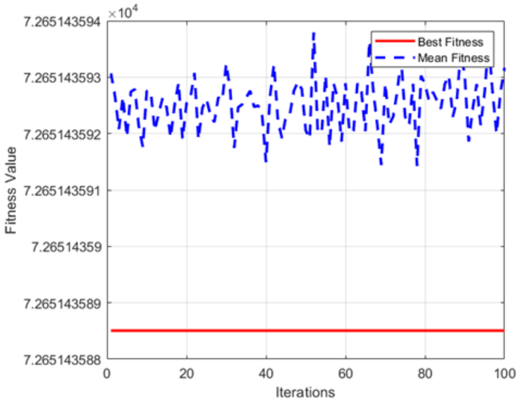


Figure 4.7: PSO Best and Mean Fitness over Iterations

Voltage Magnitude and Angle profile

Since in power system, each bus (node) should ideally maintain a specified magnitude within its permissible limits, it is thus a crucial point to maintain the voltage levels thereby ensuring the overall reliability and stability of the entire power network. Deviating from this tends to inefficiencies, equipment damage, and subsequently system failures. In addition, the voltage angles reflect the phase difference across the buses and determines the direction of flow of power in the system. While Figure 4.8 specifies the magnitude of the voltage pu at each bus, Figure 4.10 which depicts the voltage angle assists in providing information necessary for maintaining the systems stability and synchronism.

Figure 4.8 shows the magnitude of the voltage across all the buses after the power flow analysis is carried out. Each bar represents the voltage magnitude (pu) at that corresponding bus. Since it is pu the voltage values are close to 1, indicating that the systems is operating within acceptable limits. The deviations above or below the set point shows the areas or buses that potentially require voltage control or regulations interventions. These interventions can be in form of capacitor replacements or even transformer tap adjustments amongst others.

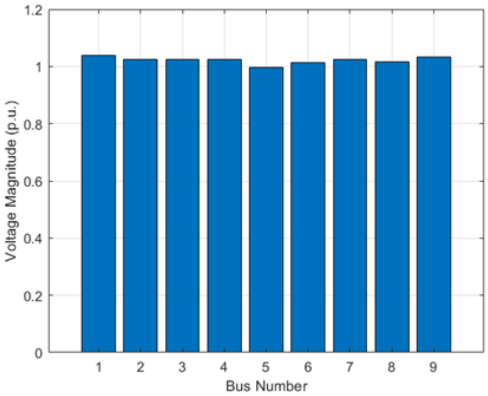


Figure 4.8: Bus Voltage Magnitude

To compare the value before and after the power flow analysis, Figure 4.9 gives an insight into the behavior and notable changes in value of the voltage magnitude. Note that for a start, the initial values of the voltages are set to 1 before running the power flow analysis.

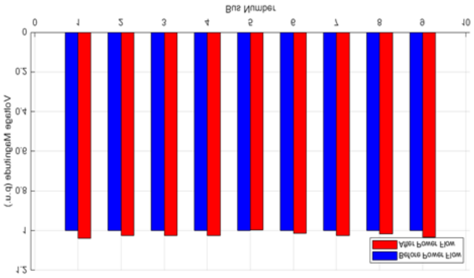


Figure 4.9: Bus Voltage Magnitude Profile Before and After Power Flow

Figure 4.10 illustrates how the voltage angles vary across buses. Using a reference point of 0 degrees, the other buses can be noted to have positive or negative deviations. A clear deviation is seen from the standard indicates the area where issues with power flow requiring system adjustments. Such system adjustments can be in the form of changing the generator dispatch.

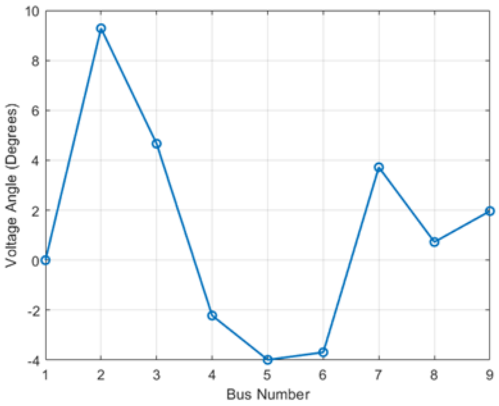


Figure 4.10: Voltage Angle Profile at Each Bus

Considering the value of the set voltage angles before the simulation and the value after the power flow analysis had been carried out is represented in Figure 4.11.

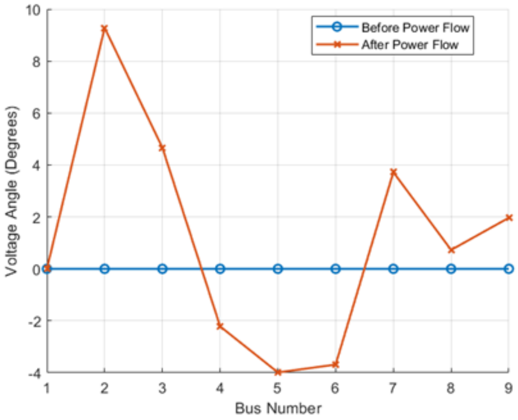


Figure 4.11: Voltage Angle Characteristic across Each Bus

Since all the initial voltage angles were set at 0 before the analysis, figure 4.11 show the voltage angle behavior after the analysis. Using bus 1 as the reference bus, it can be noted that bus 2, 3, 7, 8, and 9 showed a positive deviation from the reference, while three other buses (4, 5, and 6) indicated a negative deviation. Thus, comparing the initial and optimized voltage magnitude using the initial value set for the IEEE 9 bus, and not just setting the values to 1 will illustrate the behavior as expressed in Figure 4.12.

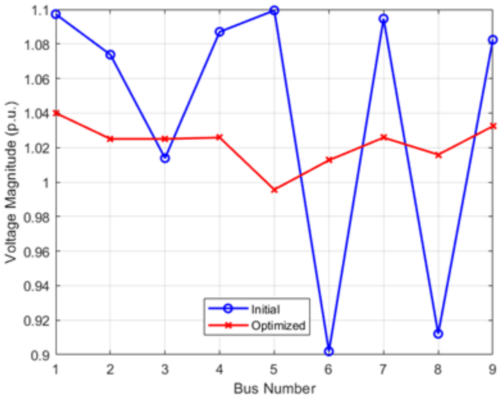


Figure 4.12: Comparison of Initial vs. Optimized Voltage Magnitudes

The power mismatch which occurs when there is a difference between the power generated and the power demanded at each bus is shown in Figure 4.12. It is noteworthy that achieving minimal power mismatches is vital for ensuring that the system meets the load demands efficiently without excessive losses.

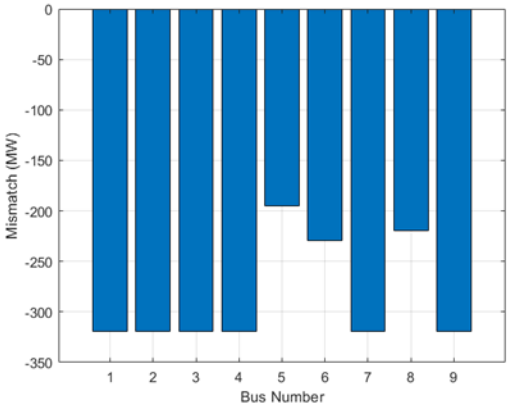


Figure 4.13: Power Mismatch at Each Bus

Figure 4.13 displays the power mismatches across all the buses. Since positive values indicates that generation exceeds demand (i.e. surplus) and negative values suggest that demand exceeds generation (i.e. deficit). Hence, buses with high mismatches as shown in figure 4.13 can be adjusted in the generation or load.

Figure 4.14 compares the total system load against the total generation, showing how well the system's generation meets the overall demand.

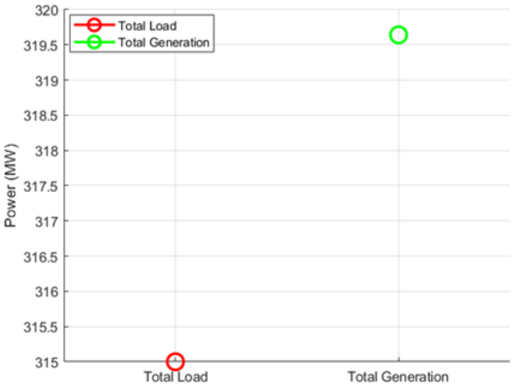


Figure 4.14: Total Load vs. Total Generation

Line/Branch Power Flow Results

As explained earlier, the power flow through transmission lines or branches is a critical aspect of power system analysis. Also essential is the ability of the power flows to remain within the thermal limits of the transmission lines for stability and safety of the system. To show the active power flow (in MW) across each branch, Figure 4.15 illustrates its characteristics. Likewise, figure 4.16 represents the reactive power flow through the lines or branches.

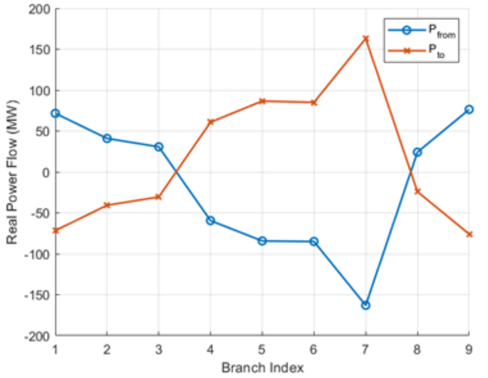


Figure 4.16: Real Power Flow Results

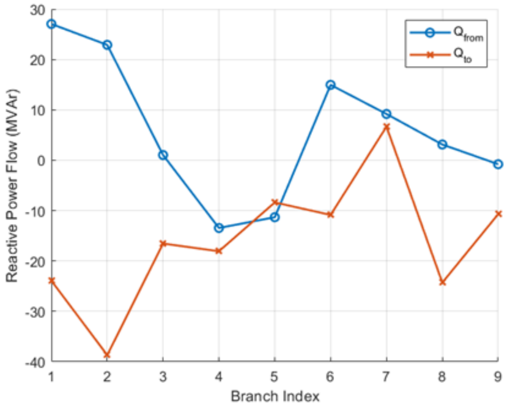


Figure 4.17: Reactive Power Flow Results

Considering Figure 4.15 which shows the results of the real power flow (measured in MW) along each branch of the network. From the legend P_from represents the real power flowing from the sending end, while the P_to is used to represent the real power at the receiving end of each branch. It can be noted that the real power flow exhibited a mixture of positive and negative values across different branches, indicating the regions of power injection and consumption present within the network. Also, the P_to curve indicates that the power that is received is generally less than what was sent (represented by the corresponding point on the P_from curve), this is consistent with the expected power losses in the line. Furthermore, the branches 3 to 8 show noticeable difference in P_from and P_to suggesting significant power losses or high power consumption in those sections.

In the case of the reactive power flow, Figure 4.17 show the reactive power flow (which is measured in MVAR) along each branch of the power network before and after optimization using the PSO-ANN. Note that the curve labelled Q_from representing the reactive power flowing from the sending end of each branch, while the curve Q_to indicates the reactive power at the receiving end. Hence, it can conclusively mean that the Q_from and the Q_to represent the reactive power flowing from the sending end bus to the receiving end bus of each branch.

When the Q_from values start high and decrease steadily, it indicates a reduction in reactive power injection from the sending end of these branches as the optimization process proceeds as seen in branches 1 to 5. In contrast, the Q_to values are generally lower which indicates that there is lesser reactive power absorbed or drawn by the receiving end buses. In the case of branches 6 to 9, The reactive power flow Q_from increases and peaks around Branch 7, suggesting increased reactive power injection into this branch, possibly due to voltage regulation improvements by the hybrid PSO-ANN optimization. The Q_to values exhibit similar patterns but with more fluctuations, indicating a dynamic adjustment in reactive power at these branches.

Moreover, to represent the active and reactive power losses across the different transmission lines or branches, figure 4.18 clearly presents the line losses. This refers to the energy dissipated as heat due to the transmission lines resistance. For the Active power losses (measured in MW), there is a noticeable spike in the active power losses as seen in Line 7, reaching up to approximately 350 MW, which suggests significant power dissipation in this particular branch. Lines 2 and 8 exhibit the lowest active power losses, indicating that these lines are more efficient in transmitting power. There is a general trend where active power losses increase from Line 1 to Line 7 and then drop significantly afterward.

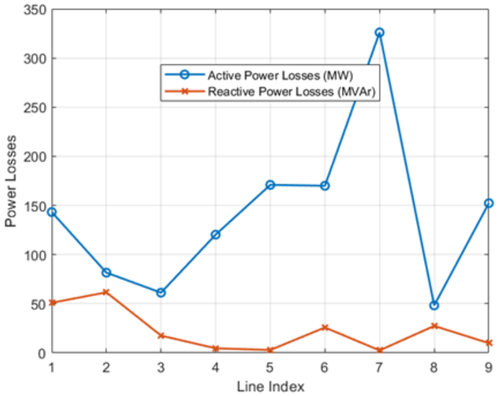


Figure 4.18: Line Losses in Transmission Lines

Performance Evaluation and System Summary

System Summary				
How many?		How much?	P (MW)	Q (MVAr)
Buses	9	Total Gen Capacity	820.0	-900.0 to – 900.0
Generators	3	On-line Capacity	820.0	-900.0 to – 900.0
Committed Gens	3	Generation (actual)	319.6	22.8
Loads	3	Load	315.0	115.0
Fixed	3	Fixed	315.0	115.0
Dispatchable	0	Dispatchable	-0.0 of -0.0	-0.0
Shunts	0	Shunt (inj)	-0.0	0.0
Branches	9	Losses ($I^2 * Z$)	- 147.94	52.66
Transformers	0	Branch Charging (inj)	-	140.5
Inter-ties	0	Total Inter-tie Flow	0.0	0.0
Areas	1			

	Minimum	Maximum
Voltage Magnitude	0.996 p.u. @ bus 5	1,040 p.u. @ bus 1
Voltage Angle	-3.99 deg @ bus 5	9.28 deg @ bus 2
P Losses ($I^2 * R$)	- 147.94 MW	
Q Losses ($I^2 * X$)	52.66 MW	

Table 4.1 System Summary

For the reactive power losses (which is measured in MVAR), it remains relatively stable and low across all lines, ranging between 20 to 50 MVAr. This suggests that the reactive components of the power system are managed efficiently by the hybrid PSO-ANN algorithm. Unlike active power losses, there are no extreme spikes, and the reactive losses exhibit a consistent pattern across the different lines.

Generally, Figure 4.1 provides a comprehensive visualization of how voltage magnitudes vary across different buses. It illustrates the voltage distribution across all buses, with color intensity representing the voltage magnitude. Buses with voltage values outside the acceptable range (that is, below 0.95 p.u. or above 1.05 p.u.) can be identified, aiding in pinpointing areas requiring voltage regulation.

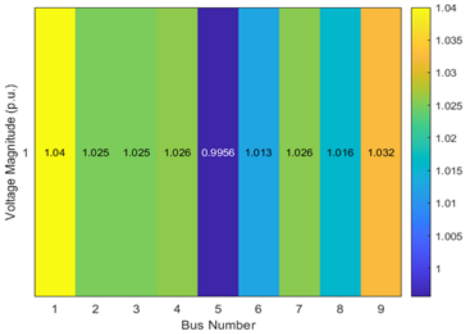


Figure 4.19: Heat map of the Bus Voltages.

Data information (Generator, Bus, and Branch)

Table 4.2 Generator Data

Gen	Bus	PG (MW)	QG (MVAr)	Qmax (MVAr)	Qmin (MVAr)	Vset (p.u.)
1	1	71.64	27.05	300.0	-300.00	1.04
2	2	163.00	6.65	300.0	-300.00	1.02
3	3	85.00	-10.86	300.0	-300.00	1.02

Table 4.3 Bus Data

Bus	*Vm (p.u.)*	*Va (deg)*	*Pd (MW)*	*Qd (MVAr)*
1	*1.04*	*0.00*	*0.00*	*0.00*
2	*1.025*	*9.28*	*0.00*	*0.00*
3	*1.025*	*4.66*	*0.00*	*0.00*
4	*1.0258*	*-2.22*	*0.00*	*0.00*
5	*0.9956*	*-3.99*	*125.00*	*50.00*
6	*1.0127*	*-3.69*	*90.00*	*30.00*
7	*1.0258*	*3.72*	*0.00*	*0.00*
8	*1.0159*	*0.73*	*100.00*	*35.00*
9	*1.0324*	*1.97*	*0.00*	*0.00*

Table 4.4 Convergence Time Comparison

Technique Employed	Number of Iterations	Convergence time (s)
Newton's Method	4 – iterations	0.05
Gauss-Siedel's Method	211 iterations	0.16
Fast Decoupled Method	6-P iterations and 6-Q iterations	0.33
Hybrid PSO-ANN Method	57 iterations	0.186

Table 4.5 Branch Data

From	To	Pfrom (MW)	Qfrom (MVAr)	Pto (MW)	Qto (MVAr)
1	4	71.64	27.05	-71.64	-23.92
4	5	40.94	22.89	-40.68	-38.69
4	6	30.70	1.03	-30.54	-16.54
6	9	-59.46	-13.46	60.82	-18.07
5	7	-84.32	-11.31	86.62	-8.38
9	3	-85.00	14.96	85.00	-10.86
7	2	-163.00	9.18	163.00	6.65
9	8	24.18	3.12	-24.10	-24.30
7	8	76.38	-0.80	-75.90	-10.70

CONCLUSION

A hybrid PSO-ANN (Particle Swarm Optimization - Artificial Neural Network) approach was successfully developed and implemented for power flow analysis, with the aim of optimizing voltage magnitudes in an electrical power system. The study employed the MATPOWER 'case9_1' file as the test system, where the PSO and ANN worked in tandem to enhance the convergence speed and accuracy of power flow solutions. The PSO algorithm optimized voltage magnitudes, while the ANN predicted power flow mismatches, thereby reducing computational time and improving performance. This approach demonstrated effective convergence, with accurate voltage profiles, minimized power losses, and efficient handling of non-linearities inherent in power systems. The method not only proved to be robust but also offered a significant improvement over conventional techniques in terms of accuracy and computational efficiency.

The results from the various analyses, including voltage magnitude profiles, power mismatches, ANN training performance, PSO fitness evaluations, branch power flow, line losses, voltage angle profiles, and load distribution, validated the efficacy of the proposed hybrid model. The solution maintained a balanced trade-off between exploration and exploitation by integrating PSO with ANN, leading to optimized power flow solutions. This advancement in hybrid power flow analysis presents a valuable tool for researchers and practitioners in the field of electrical power systems, especially in complex and dynamic networks.

REFERENCES

[1] O. Babatunde, E. Buraimoh, O. Tinuoye, C. Ayegbusi, I. Davidson, and D. E. Ighravwe, “Electricity sector assessment in Nigeria: the post-liberation era,” *Cogent Eng.*, vol. 10, no. 1, 2023, doi: 10.1080/23311916.2022.2157536.

[2] B. Nkwoh, “Electricity Power Systems and Renewable Energy,” *Int. Trade Adm. U.S. Dep. Commer.*, no. september 2016, pp. 1–6, 2023, [Online]. Available: https://www.trade.gov/country-commercial-guides/electricity-power-systems-and-renewable-energy#:~:text=Nigeria generates most of its,capacity of about 12%2C522 MW.

[3] Power Africa/Tochukwu Mbachu, “Nigeria Power Africa Fact Sheet,” *An official website of the United States government*, 2023. https://www.usaid.gov/powerafrica/nigeria (accessed Apr. 02, 2024).

[4] H. N. Amadi, E. N. C. Okafor, and F. I. Izuegbunam, “Assessment of Energy Losses and Cost Implications in the Nigerian Distribution Network,” *Am. J. Electr. Electron. Eng.*, vol. 4, no. 5, pp. 123–130, 2016, doi: 10.12691/ajeee-4-5-1.

[5] C. M. A. and C. N. E. Charlotte Remteng, Muhammad Bello Suleiman, “Nigeria Electricity Sector,” *Energypedia*, 2021. https://energypedia.info/wiki/Nigeria_Electricity_Sector (accessed Apr. 02, 2024).

[6] C. Weber, D. Möst, and W. Fichtner, “Fundamentals of Energy and Power Systems,” in *Economics of Power Systems: Fundamentals for Sustainable Energy*, Cham: Springer International Publishing, 2022, pp. 7–42. doi: 10.1007/978-3-030-97770-2_2.

[7] M. Sarwar, “Power System: Basic Structure and Functioning,” *EEPower School*, 2019. https://eepowerschool.com/energy/power-system-basic-structure-functioning/#:~:text=The transmission of electric power from a power,station%2C the transmission lines and the distribution system. (accessed Apr. 21, 2024).

[8] D. S. Jawd, T. Helal, W. Almuhana, and T. abd-alameer al Zubaidi, “Review on Stations and Sources for Generating and Storing Electric Energy,” vol. 6, pp. 1–7, 2021.

[9] IQSdirectory, “DC Power Supply,” *IQSdirectory.com*, 2021. https://www.iqsdirectory.com/articles/power-supply/dc-power-supply.html (accessed Apr. 17, 2024).

[10] Unified Power, “The Main Components of a DC Power System,” 2020. https://unifiedpowerusa.com/main-components-dc-power-system/ (accessed Apr. 17, 2024).

[11] D. De Rooij, “Direct Current (DC) Power: definition and applications,” *SINO VOLTAICS*, 2015. https://sinovoltaics.com/learning-center/basics/direct-current-dc-power-definition-and-applications/ (accessed Apr. 17, 2024).

[12] B. W. F. Dale R. Patrick, Stephen W. Fardo, “Direct Current Power Systems,” in *Electrical Power Systems Technology*, Fourth edi.River Publishers, 2021, pp. 167–212.

[13] Anker, “AC vs DC Power: The Ultimate Guide to Electrical Currents,” 2023. https://www.anker.com/blogs/ac-power/ac-vs-dc-power-the-ultimate-guide-to-electrical-currents (accessed Apr. 21, 2024).

[14] M. Tabari and A. Yazdani, “Stability of a dc Distribution System for Power System Integration of Plug-In Hybrid Electric Vehicles,” *IEEE Trans. Smart Grid*, vol. 5, pp. 2564–2573, 2014, doi: 10.1109/TSG.2014.2331558.

[15] A. Lantero, “The War of the Currents: AC vs. DC Power,” *Energy.gov*, 2014.

[16] J. Goodrich, “The Birthplace of the AC Grid > Folsom Powerhouse was the first to transmit power over long distance,” *IEEE Spectrum*, Sep. 2021.

[17] G. Zheng, S. Chen, and S. Fan, “A Power Load Forecasting Method Based on Matching Coefficient of Meteorological Factors and Similar Load Modification,” in *2012 4th International Conference on Intelligent Human-Machine Systems and Cybernetics*, 2012, pp. 216–219. doi: 10.1109/IHMSC.2012.61.

[18] S. Nuchprayoon, “Calculation and allocation of load losses in distribution system using load research data and load factor method,” in *2016 6th IEEE International Conference on Control System, Computing and Engineering (ICCSCE)*, 2016, pp. 85–90. doi: 10.1109/ICCSCE.2016.7893550.

[19] Saure, “File:Sinusspannung.svg,” *Wikimedia Commons*, 2009. https://commons.wikimedia.org/wiki/File:Sinusspannung.svg

[20] T. J. Blalock, “Milestones:Alternating Current Electrification, 1886,” in *IEEE Berkshire Section*, Great Barrington, MA, U.S.A.: ETHW, 2004.

[21] A. G. Fishov and D. V Toutoundaeva, “Power system stability standardization under present-day conditions,” in *2007 International Forum on Strategic Technology*, 2007, pp. 411–415. doi: 10.1109/IFOST.2007.4798618.

[22] A. Umunnakwe, H. Huang, K. Oikonomou, and K. R. Davis, “Quantitative analysis of power systems resilience: Standardization, categorizations, and challenges,” *Renew. Sustain. Energy Rev.*, vol. 149, p. 111252, 2021, doi: https://doi.org/10.1016/j.rser.2021.111252.

[23] “Electrical Load Classification and Types,” *Electrical KnowHow*, 2012.

[24] J. Kamal, W. Alharbi, Y. Muqaybil, and E. Barkat, “Optimizing Smart Grid Integration: A Comprehensive Analysis Review of Load Flow and Advanced Optimization Strategies,” *21st Int. Learn. Technol. Conf. Real. Sci. Fict. Educ. L T 2024*, pp. 115–120, 2024, doi: 10.1109/LT60077.2024.10469403.

[25] H.-Z. Wang and F. Long, “Analysis of power supply and demand balance in electricity market considering time delay,” in *2020 7th International Conference on Information, Cybernetics, and Computational Social Systems (ICCSS)*, Nov. 2020, pp. 569–574. doi: 10.1109/ICCSS52145.2020.9336905.

[26] M. Khanna and N. D. Rao, “Supply and demand of electricity in the developing world,” *Annu. Rev. Resour. Econ.*, vol. 1, no. 1, pp. 567–596, 2009.

[27] M. A. Mostafa, M. E. El-Hawary, G. A. N. Mbamalu, M. M. Mansour, K. M. El-Nagar, and A. M. El-Arabaty, “Effects of prioritizing demand on optimal load shedding policy,” *Int. J. Electr. Power Energy Syst.*, vol. 18, no. 7, pp. 415–424, 1996, doi: https://doi.org/10.1016/0142-0615(95)00076-3.

[28] M. Wiese and L.-M. van der Westhuizen, “Impact of planned power outages (load shedding) on consumers in developing countries: Evidence from South Africa,” *Energy Policy*, vol. 187, p. 114033, 2024, doi: https://doi.org/10.1016/j.enpol.2024.114033.

[29] M. Khalid, “Smart grids and renewable energy systems: Perspectives and grid integration challenges,” *Energy Strateg. Rev.*, vol. 51, p. 101299, 2024, doi: https://doi.org/10.1016/j.esr.2024.101299.

[30] Electrical4U, “Load Flow or Power Flow Analysis,” *Electrical4U*, 2020. https://www.electrical4u.com/load-flow-or-power-flow-analysis/#google_vignette (accessed Apr. 20, 2024).

[31] A. Dubey, “LOAD FLOW ANALYSIS OF POWER SYSTEMS,” *Int. J. Sci. Eng. Res.*, vol. 7, p. 6, 2016.

[32] B. C. Virgil, “What is alternating current.” Electrician Baluna, 2018.

[33] X.-F. Wang, Y. Song, and M. Irving, “Load flow analysis,” *Mod. power Syst. Anal.*, pp. 71–128, 2008.

[34] S. Mishra and Y. S. Brar, “Load Flow Analysis Using MATLAB,” in *2022 IEEE International Students’ Conference on Electrical, Electronics*

and Computer Science (SCEECS), Feb. 2022, pp. 1–4. doi: 10.1109/SCEECS54111.2022.9741005.

[35] F. J. R. da silva, A. P. de Moura, and G. C. Barroso, "Novel proposal for the analysis of technical losses in medium-voltage feeders from single-phase and three-phase load flow data," *Electr. Power Syst. Res.*, vol. 211, p. 108239, 2022, doi: https://doi.org/10.1016/j.epsr.2022.108239.

[36] I. Samuel, A. Soyemi, A. Awelewa, and A. Adekitan, "Artificial Neural Network Based Load Flow Analysis for Power System Networks.," *IAENG Int. J. Comput. Sci.*, vol. 48, no. 4, 2021.

[37] S. B. Z. Homayie and B. Venkatesh, "General Multi-Phase Element-Based Load Flow for AC-DC Power Systems," *IEEE Trans. Power Deliv.*, 2024.

[38] B. Muruganantham, R. Gnanadass, and N. P. Padhy, "Performance analysis and comparison of load flow methods in a practical distribution system," in *2016 National Power Systems Conference (NPSC)*, 2016, pp. 1–6.

[39] R. N. Allan and M. R. G. Al-Shakarchi, "Probabilistic techniques in ac load-flow analysis," in *Proceedings of the Institution of Electrical Engineers*, 1977, pp. 154–160.

[40] K. M. Nor, H. Mokhlis, and T. A. Gani, "Reusability techniques in load-flow analysis computer program," *IEEE Trans. power Syst.*, vol. 19, no. 4, pp. 1754–1762, 2004.

[41] O. A. Afolabi, W. H. Ali, P. Cofie, J. Fuller, P. Obiomon, and E. S. Kolawole, "Analysis of the load flow problem in power system planning studies," *Energy Power Eng.*, vol. 7, no. 10, pp. 509–523, 2015.

[42] M. Ghiasi, "A detailed study for load flow analysis in distributed power system," *Int. J. Ind. Electron. Control Optim.*, vol. 1, no. 2, pp. 153–160, 2018.

[43] R. W. Hurst, "Load Flow Analysis - Optimizing Power," *The Electricity Forum*, 2021.

[44] J. A. P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities," *Electr. power Syst. Res.*, vol. 77, no. 9, pp. 1189–1203, 2007.

[45] J. O. Dada, "Towards understanding the benefits and challenges of Smart/Micro-Grid for electricity supply system in Nigeria," *Renew. Sustain. Energy Rev.*, vol. 38, pp. 1003–1014, 2014.

[46] L. F. Cabeza, D. Urge-Vorsatz, M. A. McNeil, C. Barreneche, and S. Serrano, "Investigating greenhouse challenge from growing trends of electricity consumption through home appliances in buildings," *Renew. Sustain. Energy Rev.*, vol. 36, pp. 188–193, 2014.

[47] Y. Tan, L. Meegahapola, and K. M. Muttaqi, "A review of technical challenges in planning and operation of remote area power supply systems," *Renew. Sustain. Energy Rev.*, vol. 38, pp. 876–889, 2014.

[48] W. Ketter, J. Collins, M. Saar-Tsechansky, and O. Marom, "Information systems for a smart electricity grid: Emerging challenges and opportunities," *ACM Trans. Manag. Inf. Syst.*, vol. 9, no. 3, pp. 1–22, 2018.

[49] D. U. Onyishi and G. Ofualagba, "Analysis of the Electricity Distribution Supply in Eastern Nigeria: Current Challenges and Possible Solutions," *J. Electr. Eng. Electron. Control Comput. Sci.*, vol. 7, no. 3, pp. 1–8, 2021.

[50] M. Fotuhi-Friuzabad, A. Safdarian, M. Moeini-Aghtaie, R. Ghorani, M. Rastegar, and H. Farzin, "Upcoming challenges of future electric power systems: sustainability and resiliency," *Sci. Iran.*, vol. 23, no. 4, pp. 1565–1577, 2016.

[51] J. Stamp, A. McIntyre, and B. Ricardson, "Reliability impacts from cyber attack on electric power systems," in *2009 IEEE/PES Power Systems Conference and Exposition*, 2009, pp. 1–8.

[52] N. I. Voropai, I. N. Kolosok, E. S. Korkina, and A. B. Osak, "Issues of cybersecurity in electric power systems," *Energy Syst. Res.*, vol. 3, no. 2 (10), pp. 19–28, 2020.

[53] C. Tranchita, N. Hadjsaid, and A. Torrès, "Overview of the power systems security with regard to cyberattacks," in *2009 Fourth International Conference on Critical Infrastructures*, 2009, pp. 1–8.

[54] I. N. Toman and Kessides Michael, "The Global Energy Challenge," *Let's Talk Development*, 2011.

[55] J. H. T. K. S. Sanborn, "2024 power and utilities

industry outlook." Energy & Industrials, 2024.

[56] and M. National Academies of Sciences, Engineering, "Modernizing the Electric Power System to Support the Development and Deployment of Increasingly Clean Technologies," in *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies*, Washington, DC: The National Academies Press, 2016, pp. 158–159. doi: 10.17226/21712.

[57] M. Toghyani and A. Saadat, "From challenge to opportunity: Enhancing oil refinery plants with sustainable hybrid renewable energy integration," *Energy Convers. Manag.*, vol. 305, p. 118254, 2024.

[58] Fuergy, "7 major challenges of a power grid and their solutions," 2020.

[59] A. Ranjan, D. V. Bhaskar, O. Al Zaabi, P. Kumar, K. Al Hosani, and U. R. Muduli, "Voltage Fluctuations and Sensitivity Assessment of Load Flow Solutions for the IEEE 9-bus System," in *2023 IEEE IAS Global Conference on Renewable Energy and Hydrogen Technologies (GlobConHT)*, Mar. 2023, pp. 1–6. doi: 10.1109/GlobConHT56829.2023.10087888.

[60] R. Rahimoon, A. Gul, and R. Talani, "Modelling of IEEE 9-Bus System with Load Flow and Short Circuit Analyses," *Sukkur IBA J. Emerg. Technol.*, vol. 5, pp. 1–9, 2023, doi: 10.30537/sjet.v5i2.1062.

[61] S. Tiwari, M. A. Ansari, K. Kumar, S. Chaturvedi, M. Singh, and S. Kumar, "Load Flow Analysis of IEEE 14 Bus System Using ANN Technique," in *2018 International Conference on Sustainable Energy, Electronics, and Computing Systems (SEEMS)*, 2018, pp. 1–5. doi: 10.1109/SEEMS.2018.8687353.

[62] A. Kuanar, B. Panda, and D. Behera, "Comparison of Simulation Tools for Load Flow Analysis," in *2021 1st International Conference on Power Electronics and Energy (ICPEE)*, Jan. 2021, pp. 1–5. doi: 10.1109/ICPEE50452.2021.9358568.

[63] A. Prasad and O. Singh, "Analysis of Software Tools Used for Load-Flow Studies," in *2022 4th International Conference on Advances in Computing, Communication Control and Networking (ICAC3N)*, Dec. 2022, pp. 2400–2405. doi: 10.1109/ICAC3N56670.2022.10074587.

[64] P. V Rajesh Varma, M. K. Kar, and A. K. Singh, "Transient Analysis of a Standard IEEE-9 Bus Power System Using Power World Simulator," in *Advances in Smart Grid Automation and Industry 4.0*, M. J. B. Reddy, D. K. Mohanta, D. Kumar, and D. Ghosh, Eds., Singapore: Springer Singapore, 2021, pp. 233–243.

[65] R. Jena, S. Chirantan, S. C. Swain, and P. C. Panda, "Load flow analysis and optimal allocation of SVC in nine bus power system," in *2018 Technologies for Smart-City Energy Security and Power (ICSESP)*, 2018, pp. 1–5. doi: 10.1109/ICSESP.2018.8376741.

[66] A. M and D. Rajeswari, "Load Flow Analysis in Hybrid AC-DC Transmission Network," *Int. J. Adv. Res. Sci. Commun. Technol.*, pp. 617–624, Jun. 2021, doi: 10.48175/IJARSCT-1445.

[67] R. K. Pal and R. S. Lodhi, "Optimal Load Flow Analysis in Interconnected Network Using MATLAB," *Int. J. Eng. Res. Technol.*, vol. 4, 2015, [Online]. Available: https://api.semanticscholar.org/CorpusID:60478039