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Application of Electrical Transient Analyzer Programming (ETAP) Algorithmic Power Flow Equations for Load Flow Analysis

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Abstract

Load flow analysis is a critical component of power system analysis, as it allows engineers to determine the steady-state operating conditions of an electrical system. Traditional methods of load flow analysis involve solving a set of nonlinear algebraic equations, which can be time-consuming and prone to errors. In this study, the development of algorithmic power flow equations for load flow analysis in ETAP software was aimed to provide a more efficient and accurate method for analyzing power flow in electrical systems in various power zones in Uyo, Akwa Ibom State, Nigeria. The traditional methods of load flow analysis are often complex and time-consuming, requiring manual calculations and iterations to converge on a solution. This can be a barrier to efficient power system analysis, particularly in large and complex electrical systems. The need for a more efficient and accurate method for load flow analysis has led to the development of algorithmic power flow equations in the ETAP software. The methodology of this study involved the development of algorithmic power flow equations based on the principles of power flow analysis. These equations were then implemented in the ETAP software, allowing the performance load flow analysis with greater efficiency and accuracy. The algorithmic equations were designed to solve the power flow equations iteratively, converging on a solution that accurately represents the steady-state operating conditions of the electrical system. The software revealed a maximum efficiency of 97.66% for the various zones such as Faith Street S/S3, Mask S/S, NEPA Road S/S2, Peter Uboh S/S4, PORT Harcourt Street S/S, Silas Udo S/S and Winners Chapel 47. In all these zones, core losses of 0.375, 0.062, 0.375, 0.625, 0.625, 0.062 and 0.375 were obtained. It was observed that in rural areas with lower electrical demand and less industrial activity, power transformers might have a longer replacement time and lower full-load current. Maximum rated power of 500. The findings demonstrate the effectiveness of the ETAP algorithmic power flow equations in calculating power flow in electrical systems. The algorithm is able to converge on a solution quickly and efficiently, providing a reliable tool for load flow analysis.

Keywords: Load flow, ETAP software, Power flow equations, Power efficiency, Core losses.

1 | Introduction

The load flow analysis, also known as power flow analysis, is a fundamental tool used in power system planning and operation. It is used to determine the steady-state operating conditions of a power system,

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including voltage magnitudes and phase angles, active and reactive power flows, and line losses. The goal of load flow analysis is to ensure that the power system operates within its specified limits and constraints, such as voltage limits, line capacity limits, and generator operating limits. One of the key functionalities of Electrical Transient Analyser Programming (ETAP) is its algorithmic power flow equations for load flow analysis. ETAP's algorithmic power flow equations for load flow analysis are based on the well-known Kirchhoff's laws and power balance equations. These equations are solved iteratively using numerical methods such as the Gauss-Seidel method or the Newton-Raphson method. The algorithm takes into account the complex interconnections and interactions between various components of the power system, such as generators, transformers, transmission lines, and loads.

One of the key advantages of using ETAP's algorithmic power flow equations is their ability to handle large and complex power systems with ease. The software can efficiently analyze systems with thousands of buses and branches, taking into account various operating conditions and contingencies. This makes it an invaluable tool for power system engineers and operators who need to analyze and optimize the performance of their systems. The significance of ETAP's algorithmic power flow equations lies in their accuracy and reliability. By accurately modeling the behaviour of the power system components and solving the power flow equations, ETAP can provide valuable insights into the system's performance and help identify potential issues or bottlenecks. This can lead to improved system reliability, efficiency, and cost-effectiveness. In recent times a number of research have been conducted on this field of studies. For example, Nta [1] evaluated the relevant data, including monthly loading, feeder route length, and cross-sectional area of four 11 kV feeders namely, Aka, IBB, Udo Udoma and Idongesit Nkanga secretariat-dedicated feeders obtained from the Port Harcourt Electricity Distribution (PHED) company technical office, Uyo, Nigeria for four years (January 2018 to December 2021) for the 33/11 kV Akwa Ibom State Secretariat Injection Substation and distribution feeder circuits. Average load, maximum load, load factor, loss factor, power losses in the feeders and total power loss in the system were computed, and the results, which were shown graphically, revealed grid inefficiencies and power imbalance or losses, which increased slightly on a yearly basis. The losses were due to heat dissipation, lack of maintenance of the power system components, transformer overloading, copper losses, core losses, lengthy feeder routes, and location/aging of the transformers. Suggestions were made in order to reduce further losses in the network.

Irokwe and Amako [2] conducted an experiment to determine distribution losses and overloading of the system, investigated power system performance (transformer distribution line) under steady conditions and carried out load flow analysis using Electrical Transient Analyzer Program (ETAP) software. The materials used were collected at the Port Harcourt Electricity Distribution Company (PHEDC), Single Line Diagram of 33KV. Load flow equations were formulated, applying Newton Raphson's algorithm. The line diagram was drawn to solve the Newton-Raphson algorithm using ETAP. The result indicated that the transformer at the market square was in critical condition with 101.4% operation, while Alamieseigha, Community Estate 1, Gloryland Hospital, Famgbe and Paulca buses were marginally operating at 97.1%, 97.5%, 97.6%, 97.2% and 97.2% respectively. Optimal Capacitor Placement was used to improve the lines. The total losses reduced from 82.8MW and 124.4MVar to 64.5MW and 96.8 MVar, resulting in the load flow simulation of the network being in normal operation.

Noureddine and Djamel [3] experimented on the IEEE Bus Distribution System load flow analysis using the Newton Newton-Raphson method. The fundamental equations for load flow analysis of the n-bus system were presented along with the algorithm for Newton Raphson load flow analysis and the case study IEEE 33-Bus System dataset. Newton Raphson load flow MATLAB program was developed and used to determine the bus voltages and phase angles at each bus of the case study IEEE 33 bus system. With Newton Raphson's method, convergence occurred at the 4th iteration. The results also show that only four buses (namely, buses 1, 2, 19 and 20) out of the 33 buses have voltages that satisfied the acceptable voltage level of 95% or 0.95 p.u. The rest of the buses have voltage values that are below the acceptable value. The result presented was relevant for evaluating the stability of the power system. With most of the bus voltages below the acceptable minimum value, it called for voltage profile enhancement on the bus system.

Bello et al. [4] investigated PHCN's current power generating forecast and arrived at a capacity of 26,561MW outlined in the Vision 20:2020 plan. Now, out of the seventeen operational power-producing stations, eight of them are under the ownership of the Federal Government. These stations have a total installed capacity of 6,256MW, out of which 2,484MW is now accessible for use. Out of the total of nine (9) power projects, some are from the National Independent Power Project (NIPP) and the Independent Power Project (IPP). These projects have a combined intended capacity of 2,809MW, out of which 1,336.5MW is now available. These power plants are occasionally linked to load centers by lengthy, delicate, and unbranched transmission cables. After the completion of all power projects in Nigeria, the total installed capacity of the country would reach 12,054 MW. The application of ETAP's algorithmic power flow equations for load flow analysis is essential for ensuring the reliable and efficient operation of power systems. By accurately modeling the behavior of the system components and solving the power flow equations, ETAP can help engineers and operators optimize the performance of their systems and make informed decisions. ETAP's algorithmic power flow equations are a valuable tool for power system engineers and operators, providing accurate and reliable analysis of power systems. By accurately modeling the behavior of the system components and solving the power flow equations, ETAP can help optimize the performance of power systems and make informed decisions.

2 | Methodology

Load flow data collection is a crucial step in power system analysis, as it provides valuable information about the flow of electrical power within a network. The first step in the load flow data collection process was to identify the different zones within the power system. These zones can be geographical areas, which in this case was Uyo, Akwa Ibom State, substations, or specific sections of the network that are of interest for analysis, which are presented in *Table 1*. Once the zones were identified, the next step was to gather relevant data for each zone. The data collection process typically involves collecting information on the electrical parameters of the network, such as line impedance, transformer ratings, and load profiles. This data was obtained from various sources, including utility records, equipment specifications, and field measurements. In this case, the network consists of no generator, 24 load points or sub-stations, 71 buses, 71 branches and one 132kv utility power grid coming in from Afam, which is being tied to Aloja 330kv transmission network.

Hence, the bulk power from these sources is stepped down to the ratio of 132/33/11/0.415v, and a total generation capacity is obtained as 2.361MW with an installed load capacity of 1.161MW and losses of about 1.2mw. In the process, a simple load flow study was carried out to ascertain the state of the 11kv IBB Uyo feeder and from the above parameters, which indicated that out of the 2.361MW of power generated, 1.161MW was used to drive the load centers and approximately 1.2MW was being recorded as total losses within the distribution network. After the data had been collected, the next step was to input it into a load flow analysis software program, which uses mathematical algorithms to calculate the flow of power within the network and determine the voltage and current levels at different points in the system. To achieve this, ETAP software was employed as the analytical tool for the simulation and computations. The results of the load flow analysis can help identify potential issues such as voltage drops, overloads, and power losses. One of the key advantages of using a load flow analysis software program is that it allows for the simulation of different scenarios and the evaluation of potential solutions. For example, the software can be used to assess the impact of adding new generation capacity or upgrading existing equipment on the overall performance of the network.

Table 1. Load flow data for various zones.

Zones	Date When Data Was Obtained	Core Loss	Efficiency
ABAK ROAD S/S2	02/02/2023	0.375	57.66
ABAK ROAD S/S6	02/02/2023	0.375	47.66
ABAK ROAD S/S	17/09/2023	0.375	67.66
ATIKU	17/09/2023	0.375	47.66
CITY CENTRE S/S2	04/02/2023	0.375	57.66
ESUENE STR S/S3	17/09/2023	0.062	47.77
ESUENE STR S/S	17/09/2023	0.375	67.66
ESUENE STR S/S2	17/09/2023	0.062	85.76
EXISTING 2X 11/33 INJ	30/01/2023	0.187	69.38
EXISTING 2X 11/33 INJ	30/01/2023	0.187	59.38
FAITH STREET S/S3	02/02/2023	0.375	97.66
FHE RD S/S	17/09/2023	0.062	67.77
IBB MAIN TRX INJ S/S2	17/09/2023	0.312	59.38
IBOKO STR S/S2	17/09/2023	0.375	67.66
INACTIVE	17/09/2023	0	87.66
INACTIVE T2	17/09/2023	0	67.66
INACTIVE 2	17/09/2023	0	57.66
MASK S/S	17/09/2023	0.062	97.66
MECHANIC VILLAGE S/S	17/09/2023	0.062	87.75
MKPONG STR. S/S3	04/02/2023	0.375	67.66
NEPA ROAD S/S2	17/09/2023	0.375	97.66
OLD RING ROAD S/S5	04/02/2023	0.625	67.66
PETER UBOH S/S4	17/09/2023	0.625	97.66
PORT HARCOURT STR S/S	17/09/2023	0.625	97.66
S/S4	17/09/2023	0.375	97.66
SILAS UDO S/S	30/01/2023	0.062	97.66
SLOT 10 S/S	17/09/2023	0.062	77.72
TANTALISER S/S	17/09/2023	0.062	67.72
UDO STR S/S 1	17/09/2023	0.062	87.77
UDO UDOETOR S/S	17/09/2023	0.375	67.66
UMOH OBOT S/S	17/09/2023	0	77.78
WATER BOARD S/S4	02/02/2023	0.375	47.66
WINNERS CHAPEL S/S	17/09/2023	0.375	97.66

3 | ETAP Load Flow Results and Discussion

The algorithm flowchart for ETAP load flow analysis consists of several steps that are executed sequentially to determine the voltage magnitudes and phase angles at each bus in the power system. The algorithm starts with initializing the system parameters, such as the bus admittance matrix, the load data, and the generation data. Next, the algorithm iterates through each bus in the system and calculates the power injections and the voltage at each bus using the power flow equations. The fundamental power flow equations are based on Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL) and can be written as follows for a balanced three-phase system:

Nodal equations (Polar form): At each node (Bus) 'i', the sum of the complex power injections equals the sum of the complex power withdrawals:

$$\mathrm{Si} = \mathrm{Pi} + \mathrm{jQi} = \mathrm{Vi} * (\mathrm{Ii} * -\mathrm{Yi} * \mathrm{Vi}). \quad (1)$$

S_i Is the complex power injection at bus 'i', P_i and Q_i are the real and reactive power injections at bus 'i', V_i is the complex voltage magnitude at bus 'i', Ii is the complex current injection at bus 'i', YI is the complex admittance matrix for bus 'i', '*' denotes the complex conjugates.

$$S_i = P_i + jQi = V_i * (I_i * -Y_i * V_i), \quad (2)$$

where S_i is the complex power injection at bus 'i', Iij is the complex current flowing from bus 'i' to bus 'j', Y_{ij} is the complex admittance between bus 'i' and 'j', V_i and V_j are the complex voltage magnitudes at buses 'i' and 'j', respectively.

$$P_i = \sum_{j=1}^{N} V_i V_i \left(G_{ij} COS(\theta_i - \theta_j) + B_{ij} \, Sin(\theta_i - \theta_j)\right), \quad (3)$$

where P_i is the real power injection or consumption at node I, Vi is the voltage magnitude at node I, θ_i is the phase angle of the voltage at node i, N is the total number of nodes in the system, G_{ij} is the real part of the admittance between nodes i and j (Conductance), Bij is the imaginary part of the admittance between nodes i and j (Susceptance). The objective of this work is to conduct a comprehensive Load Flow analysis using ETAP for the Uyo IBB feeder, with the aim of advancing knowledge in this area. Electric power systems are complex networks that require careful analysis to ensure efficient and reliable operation. Load flow analysis is a crucial tool in power system planning and operation, as it helps determine the steady-state operating conditions of the system. One widely used software tool for load flow analysis was ETAP, which utilizes algorithmic power flow equations to calculate the flow of power through the system. To apply the ETAP algorithmic power flow equations for load flow analysis, a detailed methodology must be adopted. The following detailed procedure outlines how to use ETAP for load flow analysis effectively:

I. Data input: The first step in conducting the load flow analysis using ETAP was to input the necessary data into the software. This includes information such as the system topology, equipment ratings, load profiles, and generation schedules. It is essential to ensure that the data input is accurate and complete to obtain reliable results [5].

II. Network modelling: Once the data was inputted, the next step was to create a detailed model of the power system network in ETAP. This involved defining the buses, branches, transformers, generators, and loads in the system [6]. The accuracy of the network model is crucial for obtaining accurate load flow results.

III. Initialization: After the network model was created, the system was initialized to establish the initial conditions for the load flow analysis. This included setting the initial voltage magnitudes and phase angles at each bus in the system. Proper initialization ensured convergence of the load flow solution [7].

IV. Load flow calculation: With the data inputted, the network model and the system initialized, the load flow analysis was performed using the ETAP software. The algorithmic power flow equations were solved iteratively to calculate the voltage magnitudes and phase angles at each bus, as well as the power flows through the branches of the system [8]. The load flow solution provided valuable insights into the operating conditions of the power system.

V. Analysis of results: Once the load flow calculation was complete, the results were analyzed to assess the system's performance. This included evaluating voltage profiles, power flows, line losses, and system stability. Any violations of operating limits or constraints were identified and addressed through system optimization.

The aforementioned steps were adopted and illustrated on the algorithm flowchart in *Fig. 1*. This included the Calculation of the bus admittance matrix, which represents the impedance between each pair of buses in the system, and convergence criteria, which determines when the algorithm has reached a solution, where the algorithm iterates through the power flow equations until the difference between the calculated and the actual power injections at each bus is within a specified tolerance.

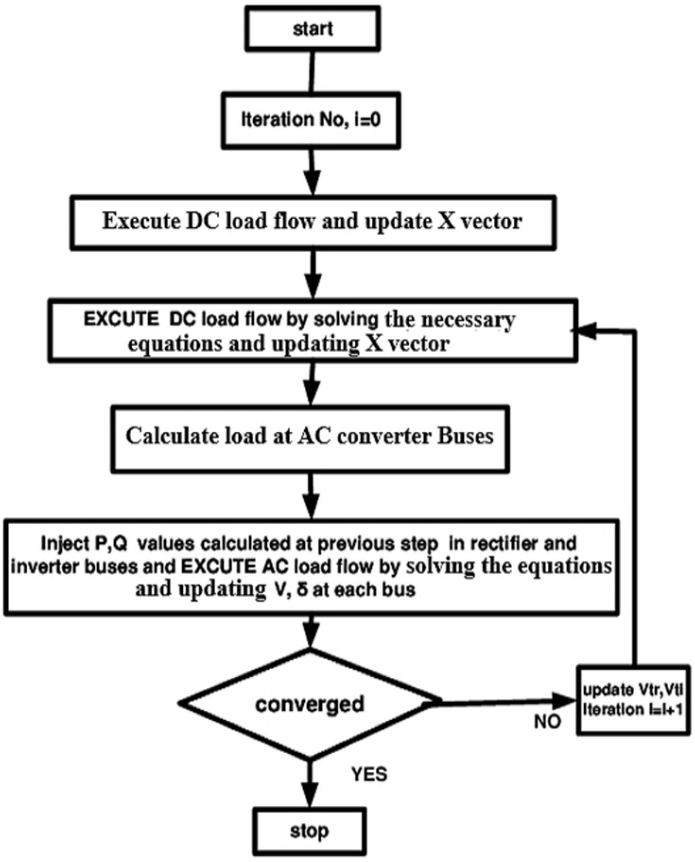

Fig. 1. Algorithm flowchart for ETAP load flow Analysis.

The ETAP load flow program features an advanced graphical interface that presents results with precision. This includes calculations for voltage drop, load terminal voltage, branch losses, and transformer LTC settings. Effortlessly and precisely generate and verify system models by utilizing ETAP's load flow analysis software. Simultaneously compute power flow for three-phase, single-phase, panel, and UPS systems. Key features of the Load Flow Software Analysis of voltage loss and power flow Power factor correction refers to the process of improving the power factor of an electrical system [9].

Automated device assessment, automated temperature adjustment, Actions of Load Tap Changer (LTC) in two-winding and three-winding transformers, actions of an automatic voltage regulator power losses due to both resistance and reactance, comprehensive notifications and documentation of violations, analysis of the results of a power flow analysis using many reports performs load flow analysis automatically in response to system modifications. A toolbar that allows for effortless changing and displaying of result units with a single click. Capabilities of Load Flow Software Simulation of power flow under various loading and generation situations. Automatically modify the transformer tap and LTC/voltage regulator configurations. Convergence parameters for load flow calculations modified by the user utilize the load flow result analyzer to compare and evaluate numerous reports. Incorporate the impact of phase-shifting transformers [10]. Visualize power flow results visually. Analyze instances of critical and marginal limit breaches. ETAP load flow profile employed in the load flow analysis in this study is presented in *Fig. 2*.

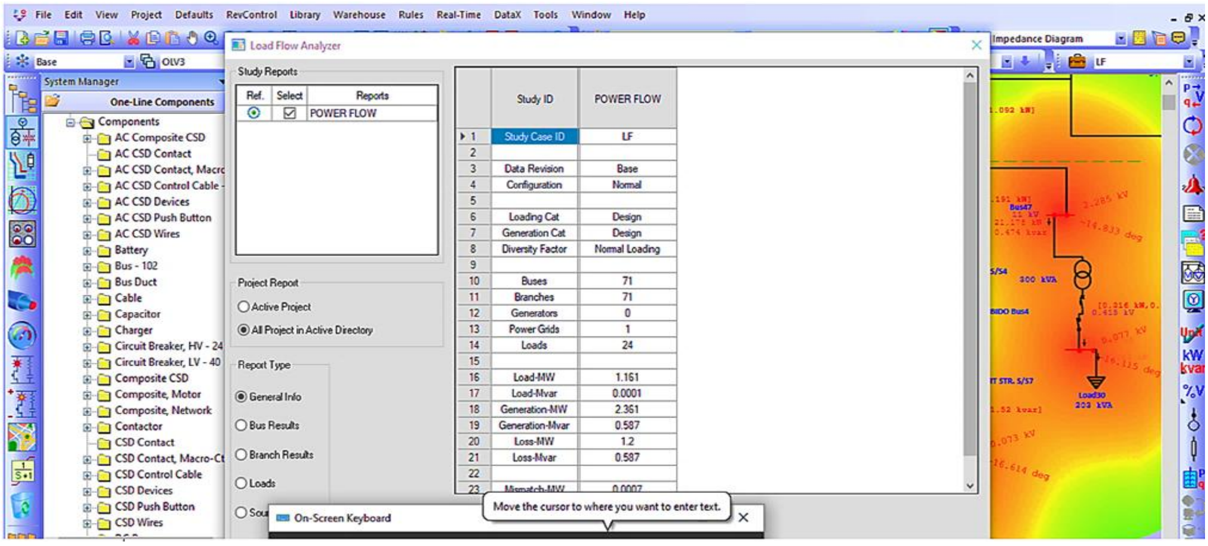

Fig. 2. ETAP load flow profile.

4 | Results and Discussion

Load flow simulation and results

The replacement time for transformers within a given zone was determined based on a variety of factors, including the age of the transformer, its load history, and the manufacturer's recommendations. When a transformer reaches the end of its operational life or begins to show signs of wear and tear, it is important to replace it promptly to prevent potential failures that could disrupt the power supply to consumers. *Fig. 3* indicated that the active substation Abak road2 S/S and slot10 s/s had the highest frequency of replacement time; hence, Peter Uboh S/S4 and Mpkong street s/s had the lowest frequency of replacement time, which also indicates that the population sizes and load centers vary.

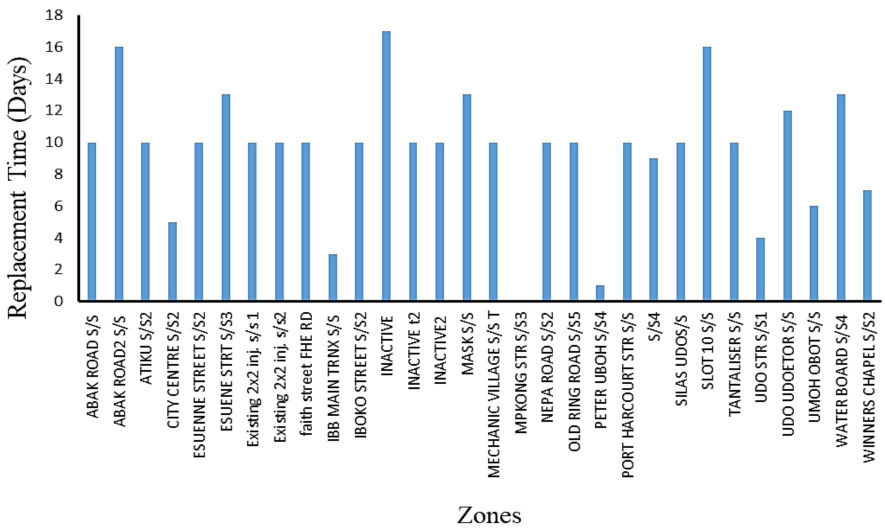

Fig. 3. Replacement time and the full load current (A) of the transformers within the zones.

Rated power on a transformer is a crucial parameter that determines the maximum amount of power that the transformer can handle efficiently. The manufacturer typically specifies the rated power of a transformer, which is an important factor to consider when designing power distribution systems. The implications of minimum, mid-range, and maximum power ratings on a transformer are discussed in this section. At the minimum power rating, a transformer is operating at a level where it is not being fully utilized. This can lead to inefficiencies in the system, as the transformer is not operating at its optimal capacity. In addition, running a transformer at a lower power rating than its rated capacity can result in increased losses and reduced efficiency. Therefore, it is important to ensure that the transformer is operating at or near its rated power to maximize efficiency and performance.

On the other hand, operating a transformer at its maximum power rating can lead to overheating and potential damage to the transformer. Transformers are designed to operate within a certain range of power ratings, and exceeding this range can result in overheating and insulation breakdown. It is important to carefully monitor the power levels in a system to ensure that the transformer is not being overloaded and is operating within its rated capacity. Operating a transformer at a mid-range power rating is ideal for maximizing efficiency and performance. This allows the transformer to operate at a level where it is being fully utilized without being overloaded. By operating the transformer at a mid-range power rating, the system can achieve optimal efficiency and performance, as shown in *Table 2*, while ensuring the longevity of the transformer.

Table 2. Rated power on the transformers within the zones (Transformers, 2W).

ABAK ROAD S/S6	Primary kV	Primary kA	Rated Max. S
ABAK ROAD2 S/S2	11	0.394	300
ATIKU S/S2	11	0	300
CITY CENTRE S/S2	11	0	300
ESUENNE STREET S/S3	11	0.394	300
ESUENNE STREET S/S1	11	0.345	300
ESUENNE STREET S/S2	11	0.656	500
EXISTING 2X 11/33KV INJT	11	0.394	300
EXISTING 2X 11/33KV INJT	11	0.394	300
FAITH STREET S/S3	33	2.62	150
FHE RD S/S	33	0	150
IBB MAIN TRX INJ S/S	11	0	300
IBOKO STR S/S2	11	0.656	500
INACTIVE	132	1.09	25
INACTIVE T2	11	0	300
INACTIVE 2	11	0	0
MASK S/S	11	0	0
MECHANIC VILLAGE S/S T	11	0.262	200
MKPONG STREET S/S3	11	0.131	100
NEPA ROAD S/S2	11	0.262	200
OLD RING ROAD S/S5	11	0.394	300
PETER UBOH S/S4	11	0.394	300
PORT HARCOURT STR. S/S	11	0.656	500
S/S4	11	0.656	500
SILAS UDO S/S	11	0.656	500
SLOT 10 S/S	11	0.394	300
TANTALISER	11	0.066	50
UDO STREET S/S1	11	0.131	100
UDO UDOETOR S/S	11	0.131	100
UMOH OBOT S/S	11	0.656	500
WATER BOARD S/S4	11	0.394	300
WINNERS CHAPEL S/S2	11	0.656	500

Power transformers play a crucial role in the transmission and distribution of electrical energy. One of the key parameters that need to be closely monitored and controlled in power transformers is the bus voltage [11]. Bus voltage refers to the voltage level at the output terminals of the transformer, which is then supplied to the load. In order to ensure the safe and efficient operation of the transformer, it is essential to regulate the bus voltage within specified limits. The bus voltage of a power transformer is typically regulated in two phases. The first phase involves the initial setting of the voltage level at the transformer's output terminals.

This is done by adjusting the tap changer, which is a device that allows for the adjustment of the transformer's turn ratio [12]. By changing the turns ratio, the output voltage of the transformer can be increased or decreased as needed. This initial setting is crucial in ensuring that the transformer is operating at the desired voltage level.

mkT000he second phase of bus voltage regulation involves continuously monitoring and adjusting the voltage level to maintain it within specified limits. This is typically done using a voltage regulator, which is a device that automatically adjusts the tap changer based on the measured voltage level at the transformer's output terminals [13]. The voltage regulator ensures that the bus voltage remains stable and within the acceptable range, even in the presence of fluctuations in the load or the incoming voltage. Proper regulation of the bus voltage is essential for the safe and efficient operation of power transformers. Overvoltage or undervoltage conditions can lead to overheating of the transformer, insulation breakdown, and, ultimately, transformer failure. By regulating the bus voltage within specified limits, the transformer can operate at its optimal efficiency and reliability (see *Table 3*).

Table 3. Phase and regulated bus voltages of the transformers within the zones (Transformers, 2W).

Zones	LTC Pri. Reg. Bus Voltage	Phase	Pri. Earthing
ABAK ROAD S/S2	100	2	IT-Individual
ABAK ROAD S/S6	100	2	IT-Individual
ABAK ROAD2 S/S	100	2	IT-Individual
ATIKU S/S2	100	2	IT-Individual
CITY CENTRE S/S2	100	2	IT-Individual
ESUENNE STREET S/S3	100	2	IT-Individual
ESUENNE STREET S/S1	100	2	IT-Individual
ESUENNE STREET S/S2	100	2	IT-Individual
EXISTING 2X 11/33KV INJT	100	2	IT-Individual
EXISTING 2X 11/33KV INJT	100	2	IT-Individual
FAITH STREET S/S3	100	2	IT-Individual
FHE RD S/S	100	2	IT-Individual
IBB MAIN TRX INJ S/S	100	2	IT-Individual
IBOKO STR S/S2	100	2	IT-Individual
INACTIVE	100	2	IT-Individual
INACTIVE T2	100	2	IT-Individual
INACTIVE 2	100	2	IT-Individual
MASK S/S	100	2	IT-Individual
MECHANIC VILLAGE S/S T	100	2	IT-Individual
MKPONG STREET S/S3	100	2	IT-Individual
NEPA ROAD S/S2	100	2	IT-Individual
OLD RING ROAD S/S5	100	2	IT-Individual
PETER UBOH S/S4	100	2	IT-Individual
PORT HARCOURT STR. S/S	100	2	IT-Individual
S/S4	100	2	IT-Individual
SILAS UDO S/S	100	2	IT-Individual
SLOT 10 S/S	100	2	IT-Individual
TANTALISER	100	2	IT-Individual
UDO STREET S/S1	100	2	IT-Individual
UDO UDOETOR S/S	100	2	IT-Individual
UMOH OBOT S/S	100	2	IT-Individual
WATER BOARD S/S4	100	2	IT-Individual
WINNERS CHAPEL S/S2	100	2	IT-Individual

The fault frequency of buses and their individual tap-in power transformers is a critical aspect of power system analysis and maintenance. Buses are the points in a power system where different electrical components are connected, and faults at these locations can have significant impacts on the overall system performance. Power transformers, on the other hand, play a crucial role in voltage regulation and power distribution within the system. The fault frequency of buses can vary depending on the size and complexity of the power system [14]. In larger systems with multiple buses and interconnected components, the likelihood of faults occurring at any given bus is higher compared to smaller, simpler systems. This is due to the increased number of potential fault sources and the complexity of the system topology. Individual tap-in power transformers also play a key role in system performance and fault management. The tap settings on a transformer determine the voltage level at which the transformer operates, and incorrect tap settings can lead to voltage instability and potential faults in the system [15]. Regular monitoring and maintenance of tap settings are essential to ensure optimal transformer performance and prevent potential faults. Power system operators need to prioritize the monitoring and maintenance of buses and individual tap settings in power transformers to ensure the reliability and stability of the system [16]. By implementing proactive maintenance strategies and utilizing advanced fault detection technologies, as shown in *Table 4*, operators can minimize the risk of system failures and ensure continuous and reliable power supply to consumers.

Table 4. Fault frequency of the buses and their individual tap within the zone (Transformers, 2W).

Zones (From Bus)	Fault Frequency	Fixed Tap Pri. Setting	Fixed Tap Sec. Setting
ABAK ROAD FEED LINE Bus	35	11	0.415
Bus 44	32	11	0.415
Bus 53	23	11	0.415
ATIKU Bus 34	24	11	0.415
CITY CENTRE 53	23	11	0.415
Bus 24	22	11	0.415
Bus 12	20	11	0.415
Bus 20	21	11	0.415
Bus 5	19	33	0.415
Bus 5	16	33	0.415
OLD RING ROAD Bus 40	22	11	0.415
Bus 18	12	11	0.415
Bus 4	4	132	0.415
IBOKO Bus 54	17	11	0.415
Bus 38	24	11	0.415
Bus 17	2	11	0.415
Bus 25	7	11	0.415
Bus 52	15	11	0.415
Bus 51	2	11	0.415
Bus 45	25	11	0.415
Bus 41	2	11	0.415
Bus 49	28	11	0.415
Bus 47	2	11	0.415
Bus 10	23	11	0.415
Bus 27	12	11	0.415
Bus 13	27	11	0.415
Bus 39	21	11	0.415
Bus 35	21	11	0.415
UMOH OBOT S/S Bus 16	12	11	0.415
WATER BOARD	22	11	0.415
WINNERS CHAPEL 47	2	11	0.415

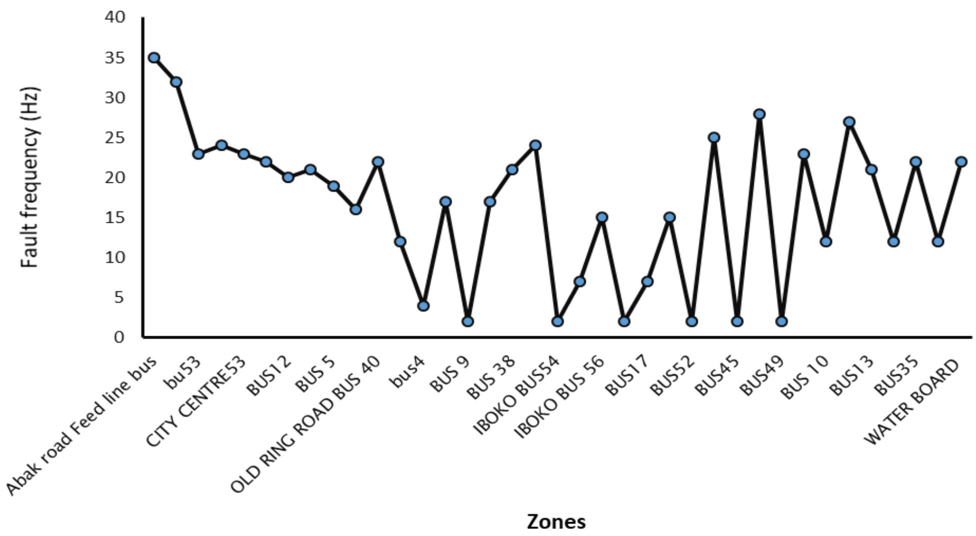

Fig. 4. Fault frequency of the buses and their individual tap within the zone.

The Fault Frequency of buses is a critical aspect of power distribution systems, as it directly impacts the reliability and efficiency of the system. Fault frequency refers to the rate at which faults occur in a particular component or section of the power distribution system. In the case of buses, fault frequency is a measure of how often faults occur at a specific bus within the system. *Table 4* and *Fig. 4* clearly show that Abak Road Feed Line Bus was overloaded and had the highest fault frequency, 35%, within that tap zone, while Bus 51, bus 41, bus 47 and Winners' Chapel had the lowest fault frequencies of 2%. It should also be noted that bus 4, with a fault frequency of 4%, used a 132kV transmission line. Load flow efficiency data is crucial for understanding the performance of power systems in different zones. This data provides valuable insights into how effectively electricity is being transmitted and distributed within a given area. The implications of minimum, mid-range, and maximum efficiency in load flow data for different zones are explored in this section.

Firstly, consider the implications of minimum efficiency in load flow data. When a zone is operating at minimum efficiency, it indicates that there are significant losses in the transmission and distribution of electricity. This could be due to factors such as outdated infrastructure, overloading of lines, or inadequate maintenance. In such cases, there is a risk of power outages, voltage fluctuations, and increased costs for consumers. Utilities need to address these issues promptly to improve the overall reliability and affordability of electricity supply in the affected zone.

On the other hand, mid-range efficiency in load flow data signifies a relatively stable and balanced operation of the power system. While there may still be room for improvement, the zone is generally able to meet the demand for electricity without major disruptions. This level of efficiency is desirable as it ensures a reliable supply of power to consumers while keeping costs in check. Utilities should continue to monitor and optimize their operations to maintain this level of efficiency and potentially improve it further. Lastly, maximum efficiency in load flow data indicates that the zone is operating at its peak performance. This means that electricity is being transmitted and distributed with minimal losses, resulting in lower costs and higher reliability for consumers. Achieving maximum efficiency requires a combination of modern infrastructure, advanced technology, and effective management practices. Utilities that consistently operate at this level of efficiency are able to provide high-quality service to their customers and contribute to the overall sustainability of the power system (see *Fig. 5*).

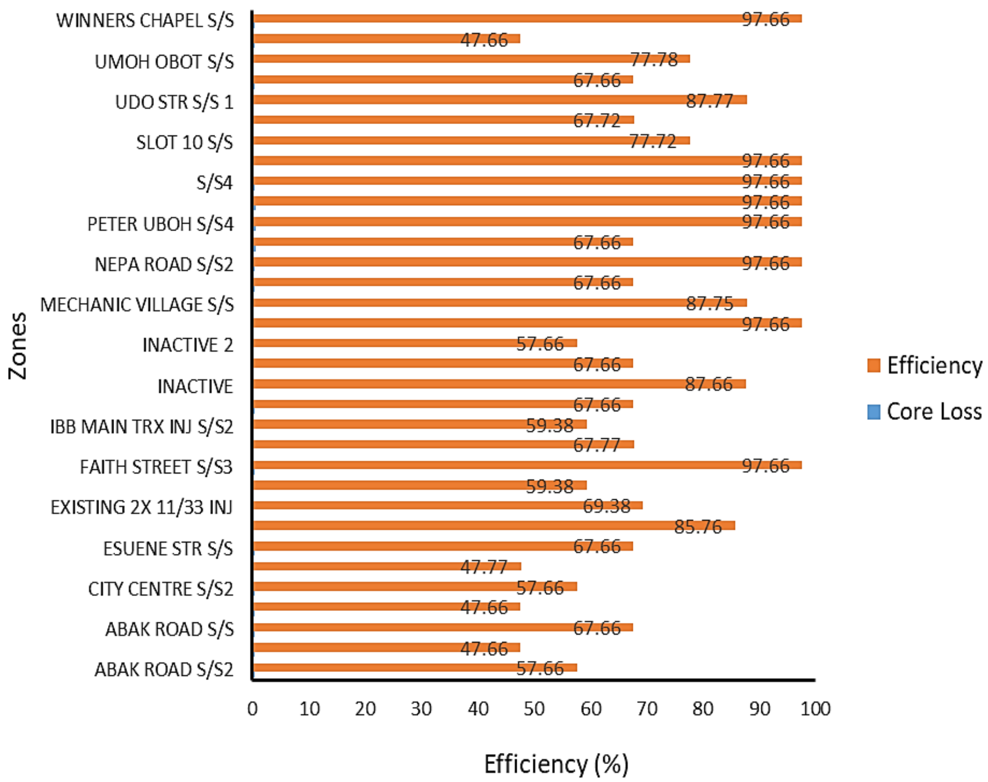

Fig. 5. Plot of load flow efficiency data for various zones.

Power transformers are essential components in electrical power systems, responsible for stepping up or down voltage levels to facilitate efficient transmission and distribution of electricity [17]. The replacement time and full load current of a power transformer are crucial parameters that need to be carefully considered in order to ensure the reliable and safe operation of the transformer. The replacement time of a power transformer refers to the period after which the transformer needs to be replaced due to aging, wear and tear, or failure. This time can vary depending on factors such as the design, construction, and operating conditions of the transformer. In general, power transformers are designed to have a long service life, typically ranging from 20 to 40 years. However, factors such as overloading, poor maintenance, and environmental conditions can accelerate the aging process and shorten the replacement time of the transformer. The full load current of a power transformer is the maximum current that the transformer can safely carry at its rated voltage and frequency. This parameter is important for determining the capacity and performance of the transformer, as well as for ensuring that the transformer is not overloaded. The full load current of a power transformer is typically specified by the manufacturer and is expressed in terms of amperes. In various zones, the replacement time and full load current of power transformers can vary based on factors such as the level of electrical demand, the quality of the power supply, and the maintenance practices in place. For example, in urban areas with high population density and heavy industrial activity, power transformers may be subjected to higher loads and more frequent maintenance, leading to a shorter replacement time and higher full-load current. On the other hand, in rural areas with lower electrical demand and less industrial activity, power transformers may have a longer replacement time and lower full-load current. The replacement of transformers during scheduled maintenance periods is a critical aspect of ensuring the reliability and efficiency of power distribution systems (see *Table 5*).

Table 5. Replacement time and the full load current (A) of the transformers within the zones during scheduled maintenance periods.

Zones	Secondary kV	Secondary kA	Switching Time	Temp. Rise
ABAK ROAD FEED LINE Bus	0.415	10.43	200	60
Bus 44	0.415	10.85	200	90
Bus 53	0.415	10.56	200	55
ATIKU Bus 34	0.415	10.43	200	70
CITY CENTRE 53	0.415	14.56	200	55
Bus 24	0.415	17.39	200	55
Bus 12	0.415	10.43	200	67
Bus 20	0.415	10.43	200	90
Bus 5	11	7.87	200	55
Bus 5	11	145	200	59
OLD RING ROAD Bus 40	0.415	136	200	78
Bus 18	0.415	17.39	200	56
Bus 4	33	4.37	200	78
IBOKO Bus 54	0.415	0	200	55
Bus 38	0.415	0	200	88
Bus 17	0.415	0	200	65
Bus 25	0.415	6.96	200	55
Bus 52	0.415	3.48	200	59
Bus 51	0.415	6.96	200	55
Bus 45	0.415	10.43	200	55
Bus 41	0.415	10.43	200	76
Bus 49	0.415	17.39	200	68
Bus 47	0.415	17.39	200	55
Bus 10	0.415	17.39	200	58
Bus 27	0.415	10.43	200	86
Bus 13	0.415	1.74	200	55
Bus 39	0.415	3.48	200	82
Bus 35	0.415	3.48	200	56
UMOH OBOT S/S Bus 16	0.415	17.39	200	55
WATER BOARD	0.415	10.43	200	59
WINNERS CHAPEL 47	0.415	17.39	200	75

5 | Conclusion

The application of ETAP algorithmic power flow equations for load flow analysis has been extensively studied in this research paper. One of the key conclusions drawn from this study is that the ETAP algorithmic power flow equations are highly effective in analyzing load flow in power systems. These equations have been shown to be effective in modeling the behavior of power systems under various operating conditions, allowing for the prediction of voltage levels, power flows, and system losses. One of the findings derived from this study is that the ETAP algorithmic power flow equations are versatile and can be applied to a wide range of power system configurations. Additionally, this study has highlighted the computational efficiency of the ETAP algorithmic power flow equations. Despite the complexity of power system analysis, the ETAP algorithm is able to solve load flow problems quickly and efficiently. This efficiency is essential for conducting real-time analysis and for performing multiple simulations to assess different scenarios. Based on the findings from this study, it is evident that the application of ETAP algorithmic power flow equations for load flow analysis is a valuable tool for power system analysis. The effectiveness and computational efficiency of these equations make them an essential component of modern power system analysis tools. As power systems continue to evolve and become more complex, the ETAP algorithmic power flow equations will play a crucial role in ensuring the reliable and efficient operation of these systems.

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Author Contributaion

Eyo Sunday Abia contributed to the conceptualization, methodology design, and overall direction of the study. He also took the lead in writing the manuscript.

Kelechi Nworah was responsible for data analysis and interpretation of results and assisted with manuscript revisions.

Eko Akpama contributed to the literature review, prepared the figures and tables, and supported the editing and proofreading of the manuscript. All authors discussed the results and contributed to the final manuscript.

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Data Availability

We encourage all authors to make their research data available. Please indicate where the data supporting the reported findings can be found, including links to publicly archived datasets that were analyzed or generated during the study. If no new data were generated or if data are not available due to privacy or ethical restrictions, an explanation is still required. The suggested Data Availability Statements were collected in the DAS file.

Conflicts of Interest

There is no Conflict of Interest to declare concerning the content of this manuscript.

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