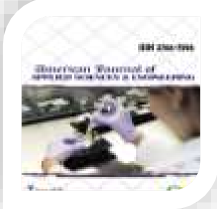

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Research Article

Optimizing Voltage and Reactive Power Compensation in a Distribution Grid Using Metaheuristic Technique

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Abstract

The availability of consistent, reasonably priced, and efficient power is a key determinant for the development and sustainability of every society's economy. However, the distribution grid is affected by persistent voltage collapse and power losses. Power losses are caused by various challenges, including reactive power burden, unbalanced loading, and harmonic distortions due to non-linear loads and technical inefficiency. This study uses metaheuristic method, a simple yet effective optimization solution to determine the optimal sizing and placement locations of reactive power compensators (RPC) for voltage optimization and power loss reduction in the distribution grid. It also examined the power distribution network in southeast Nigeria, while the scope covered the New Haven 33kV/11kV distribution grid, modelled with 40 buses, 43 branches, and 26 loads. The study demonstrated average losses of 40.3% (comprising 3.1% active and 37.2% reactive) at the buses, with branch losses accounting for 2.5% active and 3.8% reactive losses, and transformers contributing significantly with 19.7% active and 89.8% reactive power losses. Implementation of Reactive Power Compensators (RPCs) resulted in a voltage improvement of 5.43% for 11 kV and 3.16% for 33 kV, along with an enhanced power factor from 89.19% to 99.15%. This optimization increased the system's maximum loading capacity from 73.54 MW to 103.44 MW and reduced the reactive power burden from 37.29 Mvar to 13.55 Mvar. The cost-benefit analysis indicates potential annual cost savings of approximately $1,933,500 (over 773.4 million naira at $/N400) within the proposed 5-year planning period, with a payback period of less than 11 months.

Keywords	Optimizing Voltage; Reactive Power Compensation; Distribution Grid; Metaheuristic Technique
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Introduction

The distribution grid is exposed to reactive power burden, unbalanced loading, voltage collapse, harmonic distortions, and losses due to non-linear loads and technical inefficiencies. Voltage variations are typically caused by an inadequate reactive power supply from generation to the load side. Besides, due to long radial feeders especially in rural areas, the transmission of reactive power from supply to end users may be impossible, Stanelyte & Radziukynas (2020). This significantly leads to a high voltage drop at the end users.

Excessively low voltages on buses could lead to poor service quality, unstable voltage, and power losses, Kavitha & Neela (2018). This is because modern electrical equipment is designed to operate within specific voltage ranges and tolerance to fluctuations. Voltage collapses when reactive power is reduced, and rises when reactive power is increased, (Parmar, 2011). Voltage collapse happens when there is an increase in load or a decrease in power generation – this further reduces reactive power from the capacitor and line charging. If the problem persists, voltage reduction will cause an increase in current and losses in the distribution system accordingly.

The consequences are presumably higher in developing countries like Nigeria, as the distribution systems experience increased current and losses due to voltage regulation problems. For instance, in southeast Nigeria, the technical report shows a reliability index of 664 cases per year, i.e., voltage collapse occurs in the network approximately twice daily (EEDC, 2021). Moreover, the southeast region imports an average of 180 million units (kWh) per month, where over 66 million units are lost to technical inefficiencies (EEDC, 2022). These losses are technical, amounting to over 3.5 billion naira ($7.6 million), monthly, and do not include the commercial and collection losses in the sector, and they affect the performance of the distribution company and its customers who suffer higher tariffs without a reliable power quality. Therefore, the distribution sector, both the 33kV/11kV and 415V, i.e., medium voltage (MV) and low voltage (LV) levels, arguably, experience more technical losses in the electricity business value chain.

These power system issues are classical cases of non-linear, multi-modal, and multi-objective problems that require metaheuristic optimization techniques for the optimal sizing and placement of reactive power compensation (RPC) devices. Other techniques such as the analytical and conventional have many constraints. Power system optimization problems could be solved with evolutionary algorithms (Biswas, 2019).

Literature Review

Optimal Location and Sizing Techniques

There are several reactive power compensation (RPC) techniques, which can be grouped into four categories: analytical-based approach, conventional-based approach, metaheuristic-based approach, and hybrid-based approach (analytical-metaheuristic, conventional-metaheuristic, and metaheuristic-metaheuristic). The analytical approach or sensitive-based approach could provide an optimal or near-optimal global solution but lacks computation accuracy in dealing with both optimal location and sizing simultaneously. It requires extensive computational burden and storage to provide high calculation precision, Ismail et al. (2020).

In traditional or conventional optimization techniques like linear programming, non-linear programming, dynamic programming, sequential quadratic programming (SQL), and Newton Raphson (NR), there is no guarantee that the final solution obtained will be globally optimal because they depend on the value of initial randomly chosen parameters. In addition, traditional optimization techniques are incompetent to solve the multi-objective nonlinear problem and have more chances to trap into local optimum, hence, metaheuristic algorithms were introduced to compensate for these problems (Rajpurohit et al., 2017).

Metaheuristic Optimization

In today's world, metaheuristics are mostly preferred above other optimization algorithms, because they are more adaptable than precise techniques in two key aspects. Firstly, since metaheuristic frameworks are defined broadly, the algorithms can fit into the requirements of most real-world optimization problems in terms of expected solution quality and computing time (Kizielewicz & Sałabun, 2020). Secondly, there are no requirements placed on the formulation of the optimization problem by metaheuristics, like requiring constraints or objective functions to be expressed as linear functions of the decision variables, (Abhishek et al., 2022). The trade-off for this flexibility is that it necessitates significant problem-specific customization to attain high performance. Another advantage of many metaheuristics is that they can be used in conjunction with more rigorous methods through a process that we might call "*hybridization*" thus improving their performance when needed (Chopard & Tomassini, 2018). Amongst the proven metaheuristic algorithms for solving reactive power optimization problems, is the Genetic algorithm (GA).

Review of Related Literature

There are several related works, including Moghadam et al. (2020) which used a non-dominated sorting genetic algorithm (NSGA-II) technique, and Saddiquea et al. (2020) which used a hybrid of conventional approach and metaheuristic technique, all agree that metaheuristics are very effective when dealing with a multimodal, multi-objective, and discrete system, such as in sizing and placement of various FACTS device types in power systems. According to Ahmad & Sirjani (2020), the use of analytical methods or traditional optimization approaches combined with metaheuristic optimization techniques significantly reduces the search space for the proposed meta-heuristic optimization technique. Arithmetic programming approaches are frequently ineffective in managing constrained optimization problems.

Methodology

Characterization of the Distribution Grid

Firstly, the distribution grid was characterized to determine the parameters required for modelling. The parameters include the network design, power grid data (132kV, operating in swing mode), bus data in nominal kV (33kV and 11kV busses), and branch data, i.e., transformers (MVA), transmission lines (km), peak load (MW), etc. Secondly, the feeder performance data (ATC&C %) was obtained from the power distribution company, Enugu Electricity Distribution Company (EEDC) for a comparative analysis of the impact of the modelled network. Modelling and simulations were done using the Electrical Transient Analyzer Program (ETAP) version 19.0.1, installed in a Windows 10 Pro laptop, HP Intel Core i5 2.6GHz 8GB RAM.

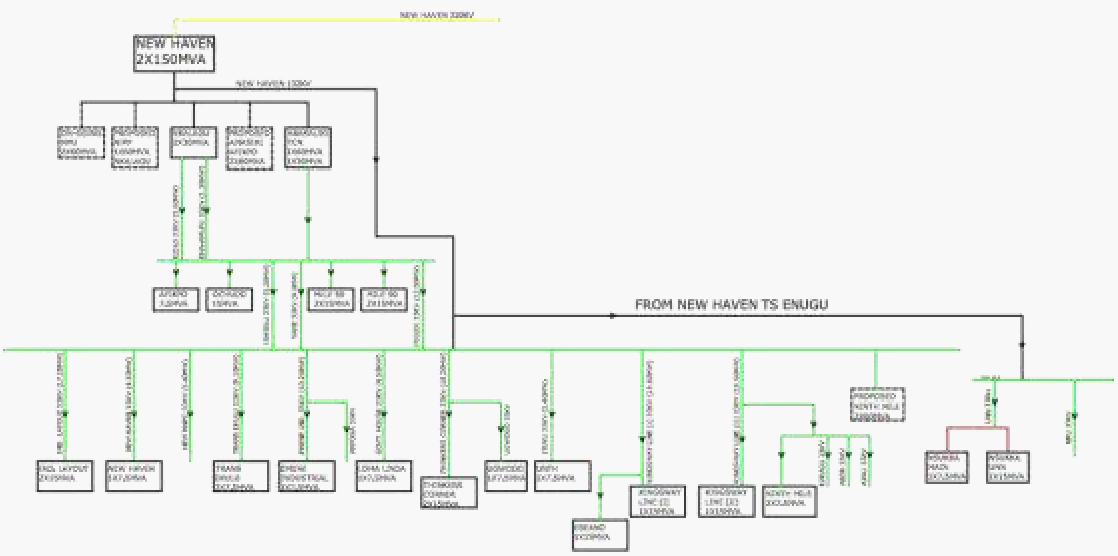

Figure 1: Single-line diagram of New Haven 132kV Transmission Grid

Technical Feasibility for Modelling:

The technical feasibility survey of the study area shows power transformers at the transmission substations: 2 x 60 MVA 132/33kV, step-down transformers at the distribution feeders: 5 x 15, 8 x 7.5, 2 x 5, and 2 x 2.5 (MVA). There are 29 connected 11kV feeders, with a combined peak load of 102.8 MW, the total route length of the 11/33kV feeders from the source was 599.7 km, average daily availability at 17.04 hours, outage 6.96 hours, average losses, 145.2 kWh daily, and 4.356 MWh monthly.

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Financial Analysis

The financial viability of the distribution grid (EEDC, 2021) was subject to a six (6) months analysis of the feeder performance: energy import (MW) and total losses (kWh). The report shows that the New Haven substation (area of research) lost an average of 22% of the energy imported between April and September 2021, amounting to about N55.8M, monthly ($139,500, at $/N400). This report is important for the post-simulation comparative analysis.

Optimization Problems and Applied Principles

The optimal location and sizing of reactive power compensators (RPC) in the power distribution grid, is a non-linear, multi-modal, multi-objective, mixed-integer, and highly constrained optimization problem. The power system's constraints and objective functions exhibit non-linearity, resulting in optimization solutions with multiple local optima, making it a multi-modal optimization challenge. Addressing the simultaneous goals of minimizing power losses, improving voltage profiles and power factor, and enhancing system load capacity constitutes a multi-objective optimization task, while determining the optimal location and sizing involves mixed-integer optimization problems.

The study utilizes the Electrical Transient Analyzer Program (ETAP), for the design, analysis, and optimization of electrical power systems to ensure reliability, stability, and efficiency. ETAP simplifies the optimization process by utilizing its built-in genetic algorithm (GA) for capacitor sizing and placement. This streamlined approach minimizes the extensive external coding and integration, thereby increasing accessibility for power engineers. The economic analysis was conducted using the Present Worth Method (PWM) to assess the cost implications.

To determine the extensive optimization coding process, an integration of ETAP and MATLAB can be employed. This integration involves data collection, the development of a GA-based optimization algorithm with a defined objective function, configuration of GA parameters, execution of the optimization, transmission of optimized parameters to the power system model, and validation of outcomes to enhance overall system performance. Genetic algorithms (GA) serve as a population-based metaheuristic, evaluating the solution's objective function value and/or feasibility, ensuring pure evolution by enhancing local search operators.

Furthermore, the objective function is influenced by operational constraints such as bus voltage, power flow, and power factor, as well as capacitor-related constraints, including the number of capacitors, their sizes, and the total reactive power. The optimization aims to address operating constraints such as branch and transformer overloading, bus voltage deviations, and power losses in the network while achieving goals like identifying optimal capacitor locations and sizes, enhancing system voltage and power factor, minimizing installation and operation costs, determining branch capacity release, and analyzing loading parameters.

The calculation methods include:

Load flow analysis

Newton-Raphson method formulates and solves iteratively the following load flow equation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta V \\ \Delta \delta \end{bmatrix} \tag{1}$$

where ΔP and ΔQ are bus real power and reactive power mismatch vectors between specified value and calculated value, respectively; ΔV and Δδ represent bus voltage magnitude and angle vectors in an incremental form; and J1 through J4 are called Jacobian matrices.

Using ETAP, Newton Raphson's load flow method was also compared with Adaptive Newton Raphson, and Fast-Decoupled methods.

Optimal Capacitor Placement using ETAP

The objective of optimal capacitor placement is to minimize the cost of the system. This cost is measured in four ways (fixed capacitor installation cost, capacitor purchase cost, capacitor bank operating cost (maintenance and depreciation), and cost of real power losses. This can be represented mathematically as:

Min objective function =

$$\sum_{i=1}^{N_{bus}} (x_i\, C_{0i} + Q_{ci}\, C_{1i} + B_i\, C_{2i}\, T) + C_2 \sum_{l=1}^{N_{load}} T_l\, P_L^l \qquad (2)$$

N_{bus} = number of candidate buses
C_{0i} = number of capacitors installed at bus *i*
C_{1i} = per kVar cost of capacitor banks
Q_{ci} = capacitors bank size in kVar
B_i = number of capacitor banks
C_{2i} = operating cost per bank, per year
T = planning period (years)
C_2 = cost of each kWh loss, in $/kWh
l = load levels, maximum, average, and minimum
T_l = time duration, in hours, of load level l
$x_i = \frac{0}{1}$, 0 means no capacitors installed at bus *i*
P_L^l = total system loss at load level l

Modelling of the Distribution Grid

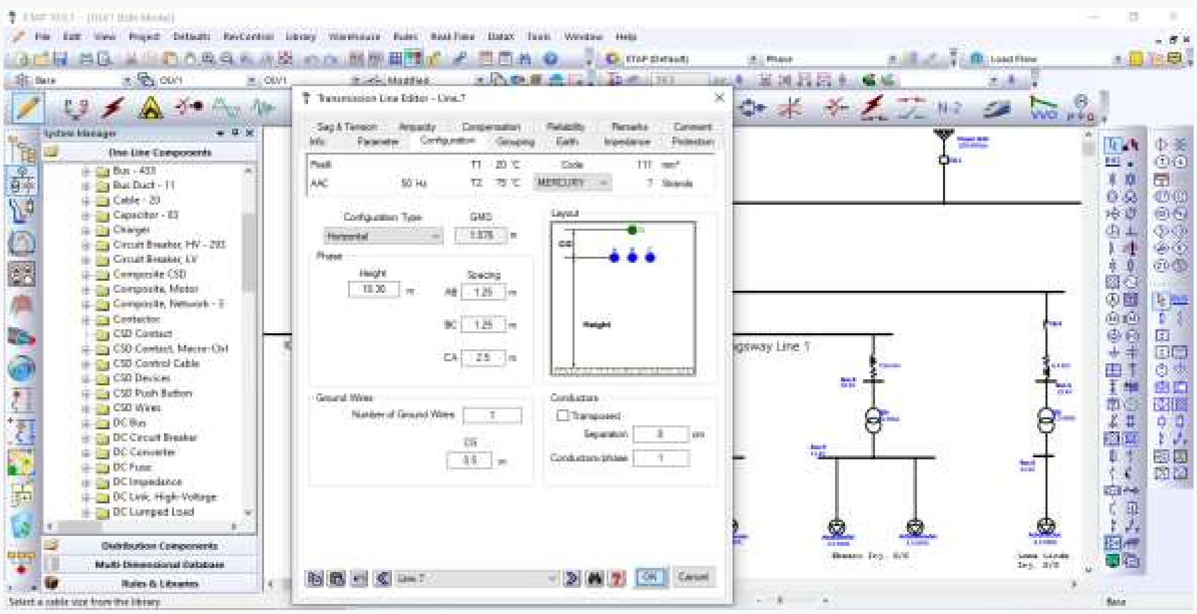

Figure 2: Configuring the transmission line parameters in ETAP

After modelling the power grid and parameters as characterized, with buses and branches, the conductors were configured to mercury all aluminium conducts (AAC) Pirelli 111mm^3, 7 strands, while the poles were set at 10.36 m, and spacing AB and BC at 1.25m respectively, to match the actual distribution grid. Other details are presented in Tables 1 and 2 below.

Table 1: Transformer impedance, reactance, and resistance values

Transformer rating	+ve sequence impedance (% Z)	+ve sequence X over R ratio (X/R)	+ve sequence R over X ratio (R/X)	+ve sequence reactance (%X)	+ve sequence resistance (%R)
60 MVA	12.5	45	0.022	12.497	0.278
15 MVA	10	20	0.050	9.988	0.499
7.5 MVA	8.35	13	0.077	8.325	0.640

Table 2: Phase Conductor Parameters

Conductor Type	AC resistance at system frequency in ohms per unit length, per conductor		Inductive reactance due to both the internal and external flux in ohms per unit length, per conductor	
	R-T1 (20 ºC)	R-T1 (75 ºC)	Xa ohms/1km	Xa[1] Xa megaohms/1km
Aluminum	0.257	0.314	0.26	0.218

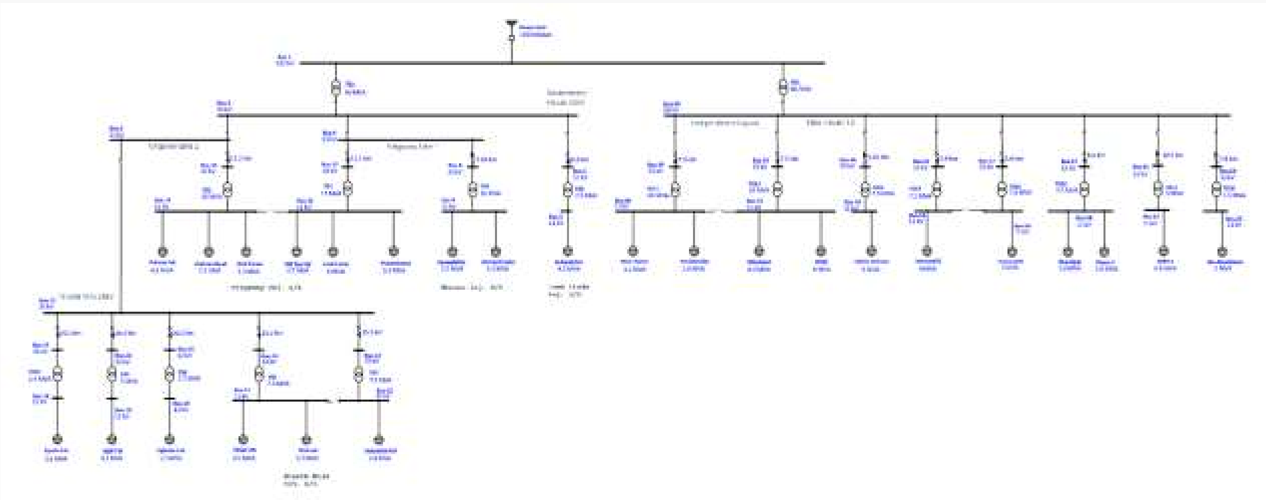

Figure 3: The New Haven 132KV distribution grid (modelled)

The New Haven 132KV distribution grid was modelled using ETAP. It has a power grid, 40 buses, 43 branches, and 26 loads of 82.201 MW and 27.018 Mvar.

Results and Discussion

The Findings

Load flow analysis using ETAP

The comparative analysis of Newton Raphson, Adaptive Newton Raphson, and Fast-Decoupled load flow methods for the kW and kvar losses in the network is presented below.

Table 3: Comparative analysis of NR, ANR, and FD load flow methods

Method of Solution	Newton Raphson	Adaptive Newton Raphson	Fast-Decoupled
Precision of Solution	0.0001000	0.0020000	0.0001000
System Frequency	50.00 Hz	50.00 Hz	50.00 Hz
Number of Iterations	3	92	3
Losses kW	2,269.6	2,269.6	2,269.6

Losses kvar	13,860.4	13,860.4	13,860.4

From the outcomes presented above, it was observed that the Adaptive Newton-Raphson method required more iterations and provided a less precise solution, while the Fast-Decoupled method, although may sacrifice some accuracy in comparison to the Newton-Raphson method, was still deemed acceptable. Consequently, the Newton-Raphson method was favoured due to its recognized robustness, accuracy, and capability to handle a broader spectrum of power system scenarios. The additional computational demands posed by the Newton-Raphson method were considered negligible, especially given the widespread availability of high-speed processors and substantial RAM capacity in modern laptop computers.

In addition to other findings, the Newton-Raphson load flow analysis showed an average of 40.3% losses (3.1% active and 37.2% reactive) at the buses. These losses are distributed at 2.5% active and 3.8% reactive from the branches, while the transformers accounted for 19.7% and 89.8% active and reactive power losses, respectively. This is tabulated below.

Table 4: Summary of active and reactive power losses

	MW	**Mvar**
Power	73.544	37.287
Losses	2.27	13.86
Losses %	3.1%	37.2%
Losses %	MW	Mvar
Branch	2.5%	3.8%
Transformer	19.7%	89.8%

Typically, high Mvar losses in a transformer are caused by overloading, low power factor loads, poor voltage regulation, harmonics, high magnetic flux density, ageing or poor condition, and frequency variations. Please refer to the branch losses report in Appendix 1 for details.

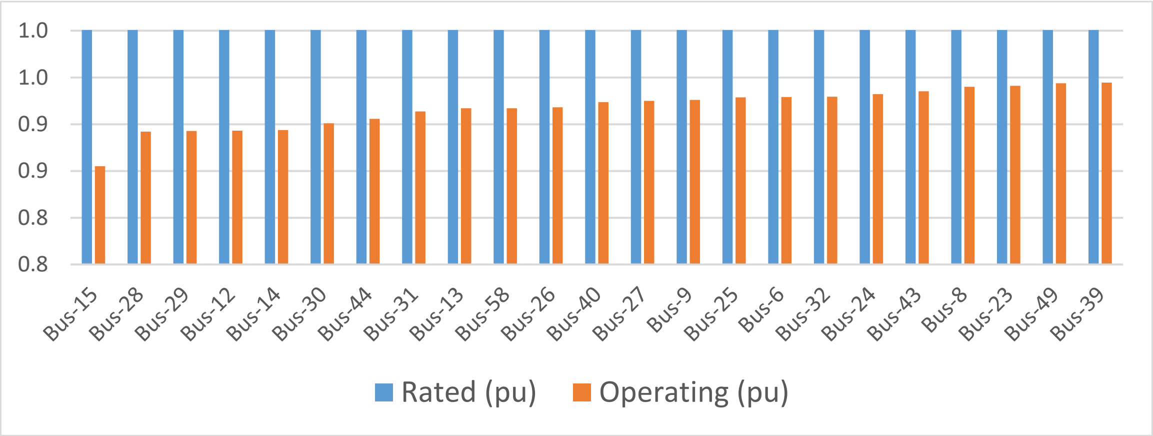

Figure 4: Rated and operating voltage magnitudes of the buses in per unit (pu)

Figure 4 above shows that 23 out of the 40 11/33kV buses in the distribution grid reported under voltages, operating below the IEEE acceptable range of 0.95pu to 1.05pu for healthy buses. The most critical buses include bus 15 at 0.85 per unit (pu) and buses 28, 29, 12, and 14, at roughly 0.89 pu. The details of the bus loading and critical report (under-voltage buses) are tabulated in Appendix 2.

Optimal Capacitor Sizing and Placement (OCP)

The objectives of the OCP are voltage support and PF correction, with a global constraint of 95 > % V< 105.

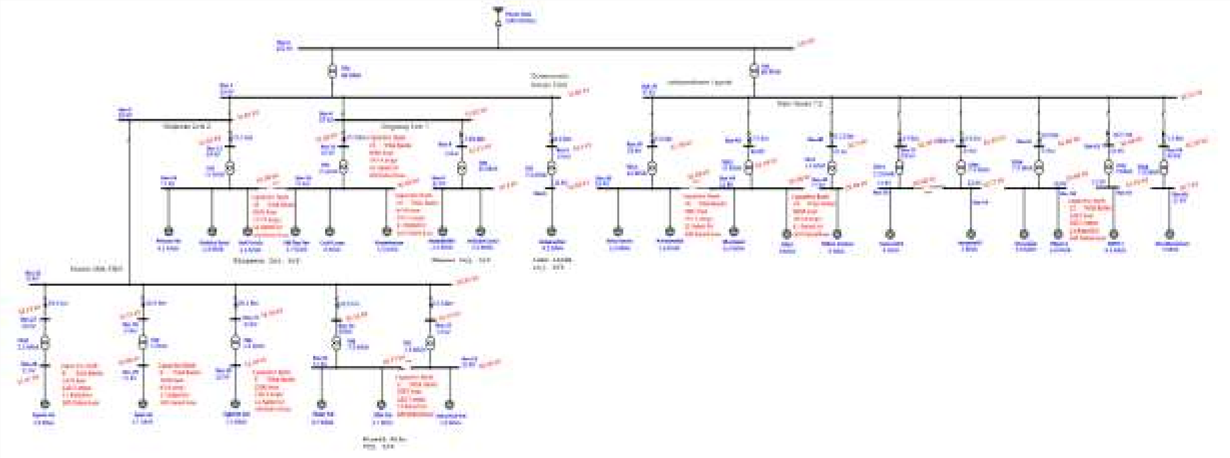

Figure 5: Optimal Capacitor Placement in the power grid

Please refer to Appendix 3a and 3b for a more extensive perspective.

Report on Voltage and Power Factor Optimization

Table 5: OCP Voltage Optimization Report

		Initial Conditions			**After Optimization**		**% Improvement**	
ID	Rated voltage (kV)	Voltage (pu)	Condition	Power (MVA)	Voltage (pu)	MVA	Voltage	MVA
Bus-1	132	0.99	Normal	82.46	1.00	104.32	1%	27%
Bus-2	33	0.96	Normal	45.06	1.00	60.86	4%	35%
Bus-3	33	0.96	Normal	22.50	1.00	30.52	4%	36%
Bus-4	33	0.96	Normal	18.81	1.00	26.05	4%	38%
Bus-5	33	0.95	Normal	3.72	0.98	4.99	4%	34%
Bus-6	11	0.93	Under Voltage	3.65	0.96	4.87	3%	33%
Bus-8	33	0.94	Under Voltage	5.26	0.98	7.03	4%	34%
Bus-9	11	0.93	Under Voltage	5.19	0.96	6.90	3%	33%
Bus-12	33	0.89	Under Voltage	12.60	0.96	19.23	7%	53%
Bus-13	33	0.92	Under Voltage	8.22	0.96	11.07	5%	35%
Bus-14	11	0.89	Under Voltage	8.01	0.96	12.08	8%	51%
Bus-15	11	0.85	Under Voltage	12.06	0.95	18.78	11%	56%
Bus-22	33	0.96	Normal	13.95	1.00	19.27	4%	38%
Bus-23	33	0.94	Under Voltage	2.47	0.98	3.30	4%	34%
Bus-24	33	0.93	Under Voltage	3.78	0.98	5.56	5%	47%
Bus-25	33	0.93	Under Voltage	1.86	0.98	2.71	5%	45%
Bus-26	33	0.92	Under Voltage	3.40	0.97	4.82	6%	42%
Bus-27	33	0.92	Under Voltage	2.17	0.97	2.86	5%	31%
Bus-28	11	0.89	Under Voltage	2.10	0.95	2.95	7%	41%
Bus-29	11	0.89	Under Voltage	3.31	0.97	4.85	8%	47%
Bus-30	11	0.90	Under Voltage	1.81	1.00	3.16	11%	75%
Bus-31	11	0.91	Under Voltage	3.71	1.00	6.52	9%	76%
Bus-32	11	0.93	Under Voltage	2.44	0.96	3.25	3%	33%
Bus-39	33	0.94	Under Voltage	7.74	0.96	9.59	1%	24%
Bus-40	11	0.92	Under Voltage	7.57	0.95	10.02	3%	32%

Bus-43	33	0.94	Under Voltage	10.53	0.95	13.36	2%	27%
Bus-44	11	0.91	Under Voltage	10.20	0.95	14.47	5%	42%
Bus-45	33	0.97	Normal	34.24	0.98	42.96	1%	25%
Bus-48	33	0.97	Normal	4.60	0.98	5.87	1%	28%
Bus-49	11	0.94	Under Voltage	4.48	0.95	5.68	1%	27%
Bus-51	33	0.97	Normal	1.86	0.98	2.37	1%	28%
Bus-52	33	0.97	Normal	1.40	0.98	1.79	1%	28%
Bus-53	11	0.96	Normal	1.84	0.97	2.34	1%	28%
Bus-54	11	0.96	Normal	1.39	0.97	1.77	1%	28%
Bus-57	33	0.95	Normal	5.62	0.97	7.28	2%	29%
Bus-58	11	0.92	Under Voltage	5.44	0.97	8.11	6%	49%
Bus-61	33	0.97	Normal	0.47	0.98	0.60	1%	28%
Bus-62	11	0.96	Normal	0.47	0.98	0.60	1%	28%
Bus-64	33	0.97	Normal	1.39	0.98	1.79	1%	28%
Bus-65	11	0.96	Normal	1.38	0.97	1.77	1%	28%

Table 6: Summary of OCP Voltage Optimization Report

	Initial Conditions		**Optimized**	
Rated (kV)	Avg. Vol.	Avg. MVA	Avg. Vol.	Avg. MVA
11	0.92	4.41	0.97	6.36
33	0.95	9.62	0.98	12.90
132	0.99	82.46	1.00	104.32
AVG.	0.94	9.23	0.97	12.41

Table 5 is summarized in Table 6 above, and it shows that voltage was optimized for the 11 kV, from an initial operating average of 0.92 pu to 0.97 pu, while the 33 kV increased from an initial operating average of 0.95 pu to 0.98 pu. In addition, the average of the apparent power in the network increased in 11 kV from 4.41 MVA to 6.36 MVA, and in 33 kV from 9.62 MVA to 12.90 MVA. Voltage optimization resulted in improved power quality with voltage levels for both 11 kV and 33 kV networks reaching higher and more stable values. Furthermore, there was a significant increase in apparent power, enhancing the overall network capacity.

Table 7: Summary of total generation, loading & demand (max. loading)

	Before optimization					**After optimization**				
	MW	Mvar	MVA	% PF		MW	Mvar	MVA	% PF	
Total Demand:	73.54	37.29	82.46	89.19	Lag	103.44	13.55	104.32	99.15	Lag
Total Motor Load	4.29	1.41	4.52	95.00	Lag	5.37	1.76	5.65	95.00	Lag
Total Static Load	6.98	22.02	70.51	95.00	Lag	94.15	-11.40	94.84	99.27	Lead

Table 7 shows some of the significant improvements in the network as discussed below.

Improved Power Factor: The power factor increased from 89.19% to 99.15% after the capacitor placement. This indicates improved efficiency in power transmission and distribution. A higher power factor reduces the burden on the electrical system, decreases line losses, and enhances voltage stability.

Increased Maximum Loading: The maximum loading capacity of the system increased from 73.54 MW to 103.44 MW. This means that the power system can now accommodate a higher electrical load, allowing for future growth in demand without requiring costly infrastructure upgrades.

Reduced Reactive Power (Mvar): The reduction in reactive power from 37.29 Mvar to 13.55 Mvar signifies a decrease in the system's reactive power demand. This reduction not only lowers energy losses but also reduces the need for additional compensation equipment, leading to cost savings.

Optimal Capacitor Placement Cost Analysis

Table 8: Summary of OCP Cost Implications

Nominal kV	kvar/ Bank	Number of Banks	Total kvar	Cost of Purchase ($)	Cost of Installation ($)	Operation Cost/Year ($)
11	300	116	34,800	1,044,000	7,200	34,800
33	400	27	10,800	432,000	4,800	10,800
Total		143	45,600	1,476,000	12,000	45,600

The summary of the OCP optimization outcome indicates the necessity of 143 capacitor banks, comprising 116 units of 300 kvar and 27 units of 400 kvar, with a total cost of $1,533,600 covering procurement, installation, and operational expenses for the initial 5-year period. Please refer to Table 9 below for the candidate buses.

Table 9: Capacitor Sizing and Placement per Candidate Buses

Candidate Buses		**Capacitor Information**			**Cost ($)**		
ID	Nominal kV	kvar/ Bank	No. of Banks	Total kvar	Installation	Purchase	Oper./Year
Bus-12	33	400	21	8,400	1,200	336,000	8,400
Bus-13	33	400	1	400	1,200	16,000	400
Bus-14	11	300	18	5,400	800	162,000	5,400
Bus-15	11	300	25	7,500	800	225,000	7,500
Bus-26	33	400	4	1,600	1,200	64,000	1,600
Bus-27	33	400	1	400	1,200	16,000	400
Bus-28	11	300	3	900	800	27,000	900
Bus-29	11	300	6	1,800	800	54,000	1,800
Bus-30	11	300	6	1,800	800	54,000	1,800
Bus-31	11	300	13	3,900	800	117,000	3,900
Bus-40	11	300	11	3,300	800	99,000	3,300
Bus-44	11	300	21	6,300	800	189,000	6,300
Bus-58	11	300	13	3,900	800	117,000	3,900
Total			143	45,600	12,000	1,476,000	45,600

Table 9 presents the details of capacitor bank specifications (sizing and placement) for various candidate buses in the distribution grid.

The project's financial viability is justifiable, considering the enhancements presented in Tables 6 and 7, alongside the project expenses outlined in Table 8 above. The annual savings in energy costs due to reduced losses are determined, based on the average energy cost (AEC) valued at $0.12/kWh (≈ N50/kWh), the planning period proposed for 5 years, with an interest rate of 12%.

Annual Savings = (Initial Losses - New Losses) × AEC
Initial Losses = Initial Maximum Loading (73.54 MW) × (1 - Initial Power Factor (89.19%))
New Losses = New Maximum Loading (103.44 MW) × (1 - New Power Factor (99.15%))

Now, the annual savings:
Annual Savings = (73.54 MW × (1 - 0.8919)) - (103.44 MW × (1 - 0.9915)) × $0.12/kWh
Annual Savings ≈ $1,933,500 per year

The payback period:
Payback Period = Optimal Capacitor Placement Cost / Annual Savings
Payback Period = $1,533,600 / $1,933,500 ≈ 0.79 years

The payback period is approximately 0.79 years (9.48 months), which means that the project will become viable for power loss reduction in less than one year. The assumed cost savings due to reduced losses amount to approximately $1,933,500 per year once the project is implemented.

Summary of Findings

The research findings are discussed below.

The technical feasibility observed that some of the 33 kV feeder lines exceeded the maximum length stipulated by the International Electrotechnical Commission (IEC) standard. The length of the distribution lines and the sizes of the conductors are the major reasons for technical losses (Nationalgrid, 2022). According to IEC3 600384, the standardized conductor size for a medium voltage (1 kV - 35 kV) is All Alloy Aluminum Conductors, 120 mm^2 to 200 mm^2 (AAAC7). However, the field survey shows that some of the 11kV distribution lines have aluminium conductor sizes of 35 mm^2.

In ETAP, Newton Raphson's load flow method is mostly preferred. According to the report, the distribution grid experiences substantial losses, with 40.3% of total power being dissipated as heat. These losses were further broken down into 3.1% for active power and a staggering 37.2% reactive power burden. This burden is particularly significant, with transformers being the primary source, contributing a notable 89.8%. High power losses, especially in the form of reactive power, can strain the distribution system, leading to reduced overall efficiency and increased operational costs.

The research findings indicate a successful optimization of voltage levels within the 11 kV and 33 kV networks. Notably, the power factor improved from 89.19% to 99.15%, increasing the system's maximum loading capacity from 73.54 MW to 103.44 MW, and simultaneously decreasing the reactive power burden from 37.29 Mvar to 13.55 Mvar. These changes not only reduce energy losses but also lower the requirement for additional compensation equipment, resulting in cost savings.

The metaheuristic technique proves to be very reliable and cost-effective for optimal capacitor sizing and placement in the distribution network. The expenditure of $1,533,600 on optimal capacitor placement, encompassing procurement, installation, and the initial 5-year operational period, constitutes a sound and feasible investment. If implemented, the project yields an annual cost savings of approximately $1,933,500, with a projected payback period of 9.48 months. Therefore, the cost of actual power losses in the study area projected at $139,500 per month could fund the cost for the OCP project in about 11 months ($1,533,600/$139,500).

Conclusion

In conclusion, the research findings revealed technical feasibility challenges, particularly related to the length of 33 kV feeder lines and conductor sizes, which contribute significantly to technical losses. These losses, particularly in the form of reactive power, can adversely impact system efficiency and operational costs. Furthermore, the research demonstrated the successful optimization of voltage levels within the 11 kV by 5.43% and 33 kV by 3.16%. Also, the apparent power increased by approximately 44.22% for the 11 kV network, and 34.21% for the 33 kV network, amongst others. The enhancements in voltage, apparent power, and power factor represent substantial improvements in both power quality and network capacity.

ETAP uses a genetic algorithm (GA) – a metaheuristic technique to optimize the sizing and placement of capacitors. The investment of $1,533,600 in optimal capacitor placement, covering procurement, installation, and the initial 5-year operation, is well-justified, with anticipated annual cost savings of approximately $1,933,500 and a projected payback period of less than 11 months.

This study confirms that reactive power compensation and voltage optimization are central to power system quality, and the GA-based OCP approach helps to improve system-level reliability, reactive power compensation (Legha & Torkestani, 2016, Abadia, 2019), net-maximum economic benefits, and operational risk mitigation (Alvarez-Alvarado, 2020). To further mitigate losses in transmission and distribution lines, it is advisable to adhere to standard cable size and length, conduct harmonic analysis with the implementation of filters, consider the addition of parallel feeders, and strategically position distribution transformers. Lastly, further research is recommended in the integration of harmonic studies with reactive power compensation and voltage optimization, using metaheuristics.

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Appendix 1: Newton Raphson load flow (Branch Losses Report)

	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd %Drop in Vmag
Branch ID	kW	Kvar	MW	Mvar	kW	kvar	From	To	
Line.19	3.61	1.38	(3.54)	(1.34)	73.51	35.36	95.64	93.21	2.44
Line.2	3.51	1.32	(3.49)	(1.31)	28.11	12.03	95.64	94.68	0.96
Line.20	2.35	0.82	(2.32)	(0.84)	30.60	(14.38)	95.64	94.09	1.55
Line.27	1.77	0.63	(1.73)	(0.70)	41.03	(66.74)	95.64	92.86	2.78
Line.28	3.26	1.30	(3.16)	(1.26)	104.29	37.10	95.64	91.82	3.83
Line.31	2.06	0.79	(2.00)	(0.84)	54.01	(46.37)	95.64	92.50	3.15
Line.4	5.01	1.88	(4.94)	(1.83)	69.24	55.10	95.64	93.99	1.66
Line.7	12.17	5.80	(11.52)	(5.09)	643.24	704.69	95.64	89.31	6.33
Line.8	7.90	3.30	(7.64)	(3.04)	259.45	263.07	95.64	91.70	3.94
Line-29	(7.21)	(2.81)	7.36	2.95	145.46	142.69	94.46	96.86	2.40
Line-32	(9.73)	(4.03)	10.00	4.32	274.57	291.21	93.52	96.86	3.34
Line-35	4.27	1.70	(4.27)	(1.70)	0.98	0.62	96.86	96.83	0.03
Line-37	1.75	0.61	(1.75)	(0.62)	4.15	(8.18)	96.86	96.57	0.29
Line-38	1.32	0.45	(1.32)	(0.46)	2.35	(10.26)	96.86	96.64	0.21
Line-41	5.27	2.24	(5.19)	(2.16)	87.09	71.96	96.86	94.85	2.01
Line-44	0.44	0.12	(0.44)	(0.15)	0.69	(34.10)	96.86	96.67	0.19
Line-46	1.32	0.45	(1.32)	(0.46)	3.24	(14.21)	96.86	96.56	0.30
T010	2.00	0.84	(1.99)	(0.65)	14.13	183.74	96.86	89.20	3.30
T011	7.21	2.81	(7.19)	(2.36)	22.37	447.42	96.86	92.36	2.10
T012	9.73	4.03	(9.69)	(3.18)	42.22	844.36	96.86	90.56	2.96
T013	4.27	1.70	(4.26)	(1.40)	15.01	300.17	96.86	94.38	2.45
T014	1.75	0.62	(1.75)	(0.57)	2.46	49.16	96.86	95.62	0.95
T015	1.32	0.46	(1.32)	(0.43)	1.39	27.82	96.86	95.93	0.71
T016	5.19	2.16	(5.16)	(1.70)	23.38	467.58	96.86	91.72	3.13
T017	0.44	0.15	(0.44)	(0.15)	0.23	4.67	96.86	96.32	0.35
T018	1.32	0.46	(1.32)	(0.43)	1.39	27.77	96.86	95.85	0.71
T02	7.64	3.04	(7.61)	(2.50)	26.73	534.62	96.86	89.39	2.32
T03	11.52	5.09	(11.46)	(3.77)	66.24	1,324.82	96.86	85.50	3.81
T04	4.94	1.83	(4.93)	(1.62)	10.44	208.89	96.86	92.58	1.41
T05	3.49	1.31	(3.47)	(1.14)	13.21	171.74	96.86	92.92	1.77
T06	3.54	1.34	(3.52)	(1.16)	14.08	183.00	96.86	91.38	1.83
T07	2.32	0.84	(2.32)	(0.76)	5.87	76.35	96.86	92.93	1.16
T08	1.73	0.70	(1.72)	(0.56)	10.30	133.86	96.86	90.09	2.78
T09	3.16	1.26	(3.14)	(1.03)	17.59	228.73	96.86	89.26	2.56
TR1	31.81	15.44	(31.75)	(12.84)	57.86	2,603.53	96.86	96.86	3.14
TR2	41.74	21.85	(41.64)	(17.22)	102.72	4,622.57	96.86	95.64	4.36
Total	184.18	81.88	(181.91)	(68.02)	2,269.63	13,860.41	3,470.23	3,364.49	77.18

Appendix 2: Bus loading and Critical report (under-voltage buses)

Bus		**Directly Connected Load**				**Total Bus Load**			**Critical Report**	
		Constant kVA		Constant Z						
ID	*kV*	*MW*	*Mvar*	*MW*	*Mvar*	*MVA*	*%PF*	*Amp*	Operating (PU)	Condition
Bus-1	132.000					82.456	89.2	360.7	0.99	Normal
Bus-2	33.000					45.058	92.4	824.2	0.96	Normal
Bus-3	33.000					22.505	93.1	411.7	0.96	Normal
Bus-4	33.000					18.811	91.3	344.1	0.96	Normal
Bus-5	33.000					3.724	93.6	68.8	0.95	Normal
Bus-6	11.000	0.200	0.066	3.272	1.076	3.655	95.0	206.4	0.93	Under Voltage
Bus-8	33.000					5.264	93.8	98.0	0.94	Under Voltage
Bus-9	11.000	0.285	0.094	4.641	1.526	5.186	95.0	294.0	0.93	Under Voltage
Bus-12	33.000					12.598	91.5	246.8	0.89	Under Voltage
Bus-13	33.000					8.217	92.9	156.8	0.92	Under Voltage
Bus-14	11.000	0.470	0.155	7.139	2.346	8.010	95.0	470.3	0.89	Under Voltage
Bus-15	11.000	0.770	0.253	10.688	3.513	12.060	95.0	740.4	0.85	Under Voltage
Bus-22	33.000					13.951	93.6	255.2	0.96	Normal
Bus-23	33.000					2.468	94.1	45.9	0.94	Under Voltage
Bus-24	33.000					3.784	93.5	71.0	0.93	Under Voltage
Bus-25	33.000					1.862	92.7	35.1	0.93	Under Voltage
Bus-26	33.000					3.403	92.9	64.8	0.92	Under Voltage
Bus-27	33.000					2.173	92.3	41.1	0.92	Under Voltage
Bus-28	11.000	0.124	0.041	1.867	0.614	2.095	95.0	123.3	0.89	Under Voltage
Bus-29	11.000	0.195	0.064	2.948	0.969	3.308	95.0	194.5	0.89	Under Voltage
Bus-30	11.000	0.105	0.034	1.611	0.530	1.806	95.0	105.2	0.90	Under Voltage
Bus-31	11.000	0.209	0.069	3.316	1.090	3.710	95.0	213.1	0.91	Under Voltage
Bus-32	11.000	0.133	0.044	2.182	0.717	2.437	95.0	137.6	0.93	Under Voltage
Bus-39	33.000					7.743	93.2	143.4	0.94	Under Voltage
Bus-40	11.000	0.418	0.137	6.774	2.227	7.571	95.0	430.3	0.92	Under Voltage
Bus-43	33.000					10.531	92.4	197.0	0.94	Under Voltage
Bus-44	11.000	0.584	0.192	9.104	2.992	10.198	95.0	591.1	0.91	Under Voltage
Bus-45	33.000					34.245	92.7	618.6	0.97	Normal
Bus-48	33.000					4.597	92.9	83.1	0.97	Normal
Bus-49	11.000	0.238	0.078	4.019	1.321	4.481	95.0	249.2	0.94	Under Voltage
Bus-51	33.000					1.856	94.2	33.6	0.97	Normal
Bus-52	33.000					1.397	94.4	25.3	0.97	Normal
Bus-53	11.000	0.095	0.031	1.650	0.542	1.837	95.0	100.8	0.96	Normal
Bus-54	11.000	0.071	0.023	1.246	0.410	1.386	95.0	75.9	0.96	Normal
Bus-57	33.000					5.620	92.3	103.7	0.95	Normal
Bus-58	11.000	0.304	0.100	4.859	1.597	5.435	95.0	311.0	0.92	Under Voltage
Bus-61	33.000					0.467	94.7	8.5	0.97	Normal
Bus-62	11.000	0.024	0.008	0.419	0.138	0.466	95.0	25.4	0.96	Normal
Bus-64	33.000					1.395	94.4	25.3	0.97	Normal
Bus-65	11.000	0.071	0.023	1.244	0.409	1.384	95.0	75.8	0.96	Normal

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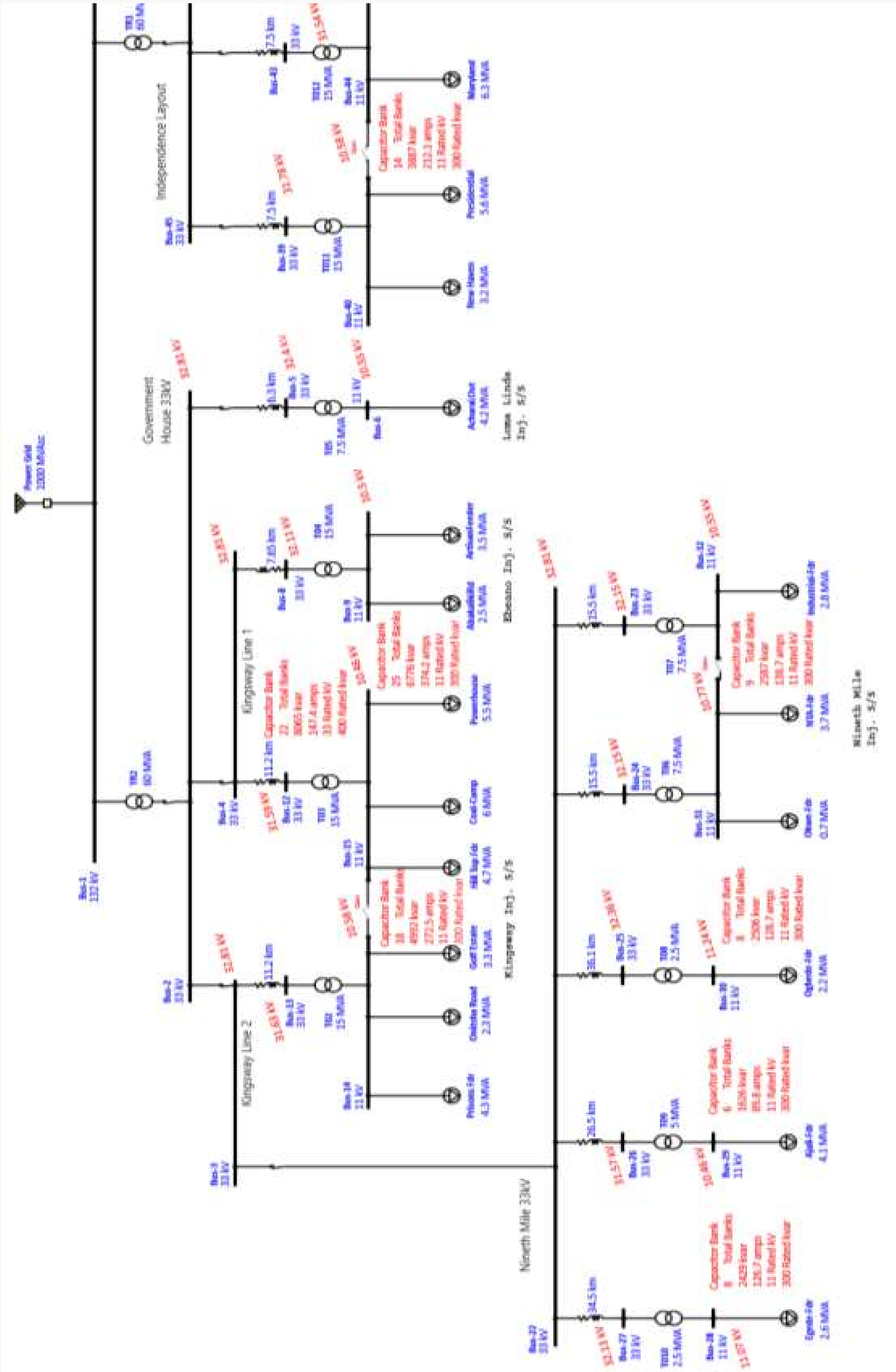
Appendix 3a: Optimal Capacitor Placement in the power grid



Appendix 3b: Optimal Capacitor Placement in the power grid (continuation)