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Optimal Placement and Sizing of STATCOM for Loss Reduction and Voltage Profile Enhancement Using Genetic Algorithm

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Abstract

Electric power distribution networks frequently experience significant power losses and voltage profile deterioration due to increasing load demand and inadequate reactive power compensation. This study investigates the enhancement of the Eleme distribution network in Rivers State through voltage upgrading and optimal deployment of a Static Synchronous Compensator (STATCOM). The existing network consists of a 5.56 km, 11 kV radial distribution system supplying seventeen distribution transformers with a cumulative load demand of 3.87 MW. EasyPower software was used to do load flow analysis in order to assess the current network's operational performance. Subsequently, the network voltage level was upgraded from 11 kV to 33 kV, and a Genetic Algorithm (GA) implemented in MATLAB software was utilized to determine the optimal location and size of the STATCOM for reactive power compensation. The study employed per-unit system calculations to obtain the line parameters of the upgraded 33 kV network. Simulation results revealed substantial reductions in system losses following network upgrading and STATCOM integration. Real power losses decreased from 168.8 kW in the existing network to 79.0 kW after voltage upgrading, representing a 43.24% reduction. Further incorporation of the optimally located STATCOM reduced losses to 39.3 kW, yielding an additional 38.83% reduction. Reactive power losses also declined significantly from 320 kVAr to 129.3 kVAr following voltage upgrading and subsequently to 126 kVAr after STATCOM deployment. The Genetic Algorithm identified Bus 16 as the optimal STATCOM location with a compensation capacity of 33.5 kVAr. The findings demonstrate that voltage upgrading combined with intelligent reactive power compensation can significantly improve distribution system efficiency, reduce losses, and enhance overall network performance.

Keywords: Distribution network, STATCOM, genetic algorithm, voltage profile improvement, power loss reduction

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INTRODUCTION

Electrical energy distribution systems constitute the final stage of power delivery from generation stations to end users. The efficiency and reliability of these systems significantly influence the quality of the power supplied to consumers. However, distribution networks are commonly characterized by high power losses, poor voltage regulation, and inadequate reactive power support, particularly in developing countries, where rapid urbanization and increasing electricity demand place additional stress on existing infrastructure. These challenges often result in reduced system efficiency, increased operating costs, and poor service quality [1–3]. Power losses within electrical distribution networks arise primarily from the flow of current through transmission and distribution conductors, which possess inherent electrical resistance and reactance. As consumer demand for electricity increases, the amount of current flowing through the network also increases, resulting in greater real (active) and reactive power losses. These losses reduce the overall efficiency of the power system, increase operational costs, and limit the amount of useful power delivered to the end users. In addition, distribution systems are commonly designed as long radial feeders, which are highly susceptible to voltage drops as electrical power is transmitted over long distances. Excessive voltage drops can lead to poor power quality, equipment malfunctions, and reduced system reliability. Therefore, maintaining acceptable voltage profiles while minimizing power losses has become a fundamental objective in modern power system planning and operations. To address these challenges, advanced technologies such as reactive power compensation devices, network reconfiguration, and optimization algorithms are increasingly employed to enhance voltage stability, improve energy efficiency, reduce technical losses, and ensure a reliable and sustainable electricity supply to consumers [4, 5].

Several techniques have been developed to address these challenges, including network reconfiguration, capacitor placement, feeder reinforcement, voltage upgrading, and the deployment of Flexible AC Transmission System (FACTS) devices. Among these approaches, voltage upgrading is recognized as an effective strategy because it reduces the line current for the same power transfer level, thereby minimizing power losses and improving voltage regulation. Upgrading distribution systems from lower to higher voltage levels can significantly enhance the power transfer capability while reducing the thermal stress on network components [6, 7].

In recent years, Flexible AC Transmission System technologies have gained widespread attention for their ability to improve power system performance. One of the most effective FACTS devices for distribution networks is the Static Synchronous Compensator (STATCOM). A STATCOM is a voltage-source converter-based device that can provide fast and continuous reactive power compensation. Unlike conventional capacitor banks, STATCOMs offer dynamic voltage support and respond rapidly to changing network conditions. Their application contributes to improved voltage stability, enhanced power factors, and reduced system losses [8, 9].

The effectiveness of a STATCOM depends largely on its placement and compensation capacity. Improper sizing or installation on unsuitable buses may lead to suboptimal performance and increased investment costs. Therefore, optimization techniques are essential for identifying the most suitable location and rating of devices. Artificial intelligence and evolutionary algorithms have been extensively employed for this purpose because of their capability to solve complex nonlinear optimization problems. Among these methods, the Genetic Algorithm (GA) has emerged as a powerful optimization tool because of its robustness, flexibility, and ability to obtain near-optimal solutions within a reasonable computational time [10, 11].

This study focused on the Eleme distribution network in Rivers State, Nigeria. The existing network operates at 11 kV and comprises 17 distribution transformers with a total load demand of approximately 3.79 MW. The network experiences considerable power loss and voltage profile challenges, making it an ideal candidate for system enhancement. This study investigated the impact of upgrading the network voltage level from 11 to 33 kV and subsequently integrating an optimally placed STATCOM [12].

Load flow simulations were conducted using EasyPower software to evaluate the operational performance of the distribution network under different loading and compensation scenarios. The simulations provided detailed information on bus voltages, line currents, power flow distribution, and real and reactive power losses across the network. These analyses enabled a comprehensive assessment of the existing network conditions, voltage-upgraded network, and network integrated with a STATCOM device. To determine the most effective placement and sizing of the STATCOM, a MATLAB-based Genetic Algorithm (GA) optimization technique was employed. The optimization process iteratively searched for the optimal solution by minimizing system losses while satisfying the network operating constraints, including voltage limits and reactive power requirements. The optimized STATCOM parameters obtained from the Genetic Algorithm were incorporated into the EasyPower simulation model to validate their effectiveness. Comparative analyses were then performed to quantify the improvements in system performance in terms of voltage profile enhancement, reduction in real and reactive power losses, improved power factors, and increased network stability. The simulation results demonstrated that the optimized STATCOM significantly enhanced the operational efficiency and reliability of the distribution system compared with existing and voltage-upgraded networks. Furthermore, the integration of advanced optimization techniques with flexible AC transmission system (FACTS) devices has proven to be an effective strategy for addressing voltage regulation challenges and minimizing transmission losses. Overall, the findings highlight the potential of combining Genetic Algorithm optimization with reactive power compensation technologies to achieve a more efficient, reliable, economically viable, and sustainable electrical power distribution network capable of meeting growing energy demands [13].

MATERIALS AND METHOD

Materials Used

The materials used include the following:

1. Line input data of the study case network
2. Single line diagram of the network
3. Bus input data of the network
4. Conductor cross sectional area and route length of the network
5. Input data of the transformers in the network
6. EasyPower software
7. Excel computer application software

Existing Eleme Distribution Network

The electrical distribution network selected for this study is located in Eleme and spans approximately 5.56 km in length. The system operates at an incoming voltage level of 11 kV and consists of seventeen (17) distribution transformers rated at 11/0.415 kV, supplying a combined load demand of 3.79 MW. Among these transformers, sixteen (16) have a capacity of 500 kVA each, while one (1) is rated at 300 kVA. Detailed information on the bus load characteristics and line parameters of the Eleme 11 kV distribution network is presented in Table 1. The corresponding single-line representation of the network configuration prior to the simulation is illustrated in Figure 1.

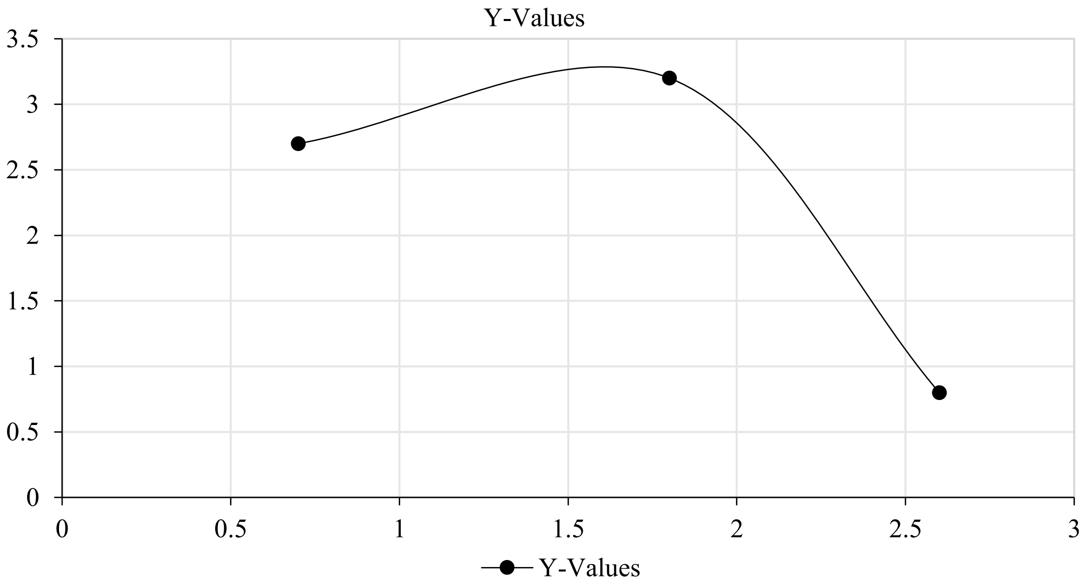

Figure 1. Real power losses in the three network scenarios.

Table 1. Network line parameter.

Line ID	From Bus	To Bus	Line Impedance (p.u)	
			R	***X***
1	PCC	1	0.0114	0.0168
2	1	2	0.0075	0.0111
3	2	3	0.0073	0.0108
4	3	4	0.0071	0.1104
5	4	5	0.0119	0.0418
6	5	6	0.0078	0.0114
7	6	7	0.0071	0.0104
8	7	8	0.0082	0.0121
9	8	9	0.0119	0.0418
10	9	10	0.0087	0.0128
11	10	11	0.0073	0.0108
12	11	12	0.0069	0.0101
13	12	13	0,0073	0.0108
14	13	14	0.0078	0.0114
15	14	15	0.0080	0.0080
16	15	16	0.0080	0.0118
17	16	17	0.0082	0.0121

Source: PH Electricity Distribution Company (2025)

Determination of Distribution Line Parameter for 33 kV Lines

The line parameters for the proposed network were evaluated using a per-unit (p.u.) system, which provides a standardized approach for power system analysis. A base power value of 10 MVA was selected for the 33 kV distribution network to facilitate the computation of the normalized electrical quantities. Using this base value, the corresponding base impedance was calculated using Equation (1). The derived base impedance was subsequently used to determine the per-unit resistance and reactance values of the distribution lines.

$$V_{base} = V_{line} = 33\text{kV}$$

$$Z_{base} = \frac{(V_{base})^2}{MVA_{base}} \quad (1)$$

The per-unit values for resistance and reactance are obtained using eqns. (2) and (3), respectively.

$$R_{p.u} = \frac{Rpu\ on\ 11kv}{Z_{base}}; \quad (2)$$

$$X_{p.u} = \frac{Xpu\ on\ 11kV}{Z_{base}}; \quad (3)$$

For the Line from Point of Common Coupling (PCC) to Bus 1

Substituting values into equations (1), (2) and (3)

$$Z_{base} = \frac{(33{,}000)^2}{10\ x\ 10^6} \quad (4)$$

$$Z_{base} = 108.9\Omega \quad (5)$$

$$R_{p.u} = \frac{0.0114}{108.9} \quad (6)$$

R (p.u) = 0.00105

$$X_{p.u} = \frac{0.0168}{108.9} \quad (7)$$

X (p.u) = 0.000154

The calculations were repeated for all other segments of the line, and the calculated per-unit values of the line parameters were generated for the proposed 33 kV system.

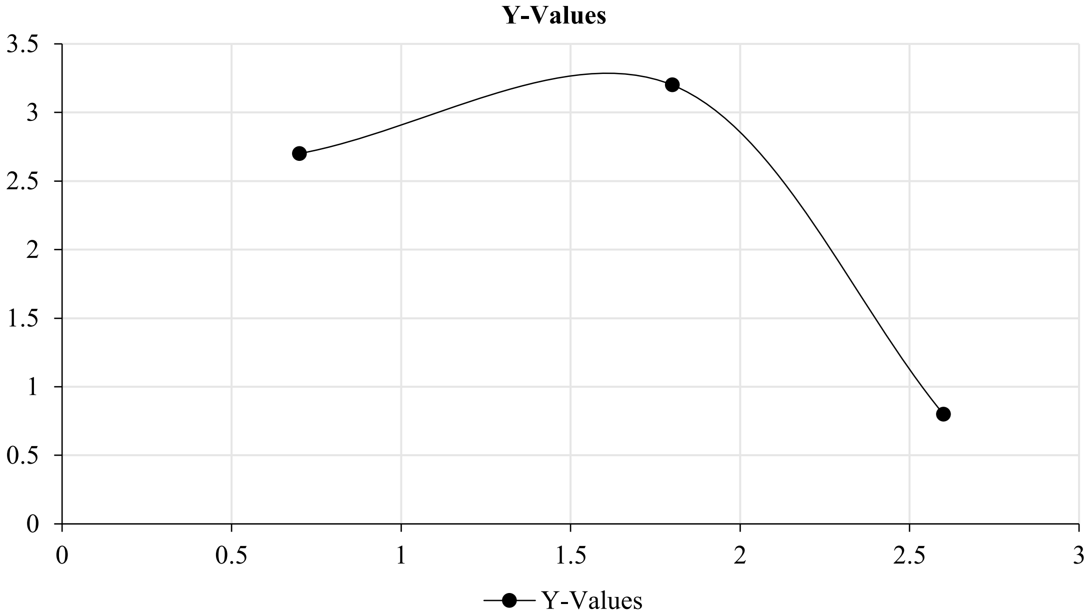

Figure 2. Reactive power losses in the three network scenarios.

RESULTS AND DISCUSSION

Figure 1 shows the total real power losses recorded under three operating conditions: the existing distribution network, voltage-upgraded network, and upgraded network integrated with a STATCOM. The simulation results indicate a substantial improvement in the system performance after implementing the proposed modifications. Upgrading the network voltage level reduced the real power losses from 157.9 to 86.0 kW, corresponding to a reduction of 45.54%. Furthermore, the installation of an optimally placed STATCOM in the upgraded network led to an additional decrease in losses from 86.0 to 48.3 kW, representing a further reduction of 43.83%. These findings are consistent with established power system principles, which indicate that reductions in line current and improvements in the power factor contribute significantly to minimizing transmission and distribution losses [14].

Figure 2 presents the total reactive power losses obtained for the three network configurations: the existing distribution network, voltage-upgraded network, and upgraded network incorporating a STATCOM. The results demonstrated a noticeable decrease in reactive power losses following both network enhancement measures. Specifically, upgrading the network voltage level reduced the reactive power losses from 330 to 139.3 kVAr, representing a reduction of approximately 58%. The subsequent integration of an optimally sized and strategically located STATCOM further lowered the reactive power losses from 139.3 to 137 kVAr, corresponding to an additional reduction of 1.65%. These results highlight the effectiveness of voltage upgrading and reactive power compensation in improving network efficiency and reducing the losses associated with reactive power flow within the distribution system [15].

CONCLUSION

This study evaluated the performance enhancement of the Eleme distribution network through voltage upgrading and optimal deployment of a STATCOM using a genetic algorithm optimization technique. The existing 11 kV distribution system was analyzed and subsequently upgraded to a 33 kV network to investigate its impact on the system losses and operational efficiency. Load flow simulations conducted using EasyPower and MATLAB demonstrated that voltage upgrading significantly improved the network performance by reducing both the real and reactive power losses.

The results showed that upgrading the network voltage level reduced the real power losses from 157.9 to 86.0 kW, representing a reduction of 45.54%. Further improvement was achieved by installing an optimally located STATCOM, which reduced the real power losses to 48.3 kW. Similarly, reactive power losses decreased substantially from 330 kVAr in the existing system to 139.3 kVAr after voltage upgrading, and further to 137 kVAr following STATCOM integration. The Genetic Algorithm successfully identified Bus 16 as the optimal location for the STATCOM with a compensation capacity of 34.6 kVAr.

The findings confirm that the combined application of voltage upgrading and intelligent reactive power compensation provides an effective solution for improving voltage stability, reducing system losses, and enhancing the overall reliability and efficiency of electrical distribution networks.

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