

# Investigation of Flexible Alternating Current Transmission Systems for Power Loss Mitigation On 33kv Feeders in Akure

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**Abstract-** *A stable operation of transmission lines is critical for achieving optimal transmission, stability of the voltage, and minimizing losses in a developing power system. However, the Akure 33 kV transmission feeders experiences under-voltage conditions, high technical losses, and feeder overloading due to high reactive power demand and insufficient compensation. In this study, a FACTS (Flexible AC Transmission System) technique was used where the efficiency of an optimally designed Static VAR Compensator (SVC) for minimizing losses and improving voltage profiles was assessed. The operational data of the transmission lines were collected and modeled using ETAP, and an optimization model based on a genetic algorithm (GA) was formulated using MATLAB. Load-flow simulations were conducted for two operating conditions: the existing network without compensation (base case) and the improved network with the GA-optimized SVC. Network performance was evaluated using voltage profile, voltage drop, active power losses, and branch loading indices. The base-case results showed significant voltage depression at the Akure Main feeder (91.28%), marginal voltage levels at IJU (95.98%) and Owena (94.50%), and high real power losses concentrated along heavily loaded branches, particularly Line 4 with 8.86 MW. The GA optimization selected the Akure Main feeder as the critical compensation bus and introduced a 20 MVar SVC rating. After SVC integration, feeder voltages improved from 0.68% to 8.1%, with the Akure Main feeder recovering from 91.28% to 98.70%. Total network real power losses reduced substantially from 89.35% to 6.37%. The highest line losses reduction is noticed on line 4 from 8.86MW to 1.051MW (88.14%) and lowest reduction from 2.517MW to 0.268MW (89.35%). This research concludes that introduction of FACTS-base reactive power compensator (SVC) when properly sized and located using AI-driven techniques provides improved nominal voltage and reduces power losses to accepted limits in 33 kV feeders in Akure transmission corridor. It is advisable to use SVC on a network that is experiencing lower nominal voltage and high power losses.*

**Keywords:** *Powerless, Static Var Compensator, Voltage, Genetic Algorithm.*

## I. INTRODUCTION

In today's world, it can never be over emphasized that the socio-economic growth, educational/technological advancement and industrialization of any country rely on reliable electricity supply [3]. It has been asserted that access to reliable and efficient electricity supply is a key driver of all round development in modern societies. The future economies rely on the sufficient supply of electrical electricity that plays a significant role in alleviating poverty, reducing infant mortality, increasing life expectancy, and accelerating urbanization in the developing countries [4]. Strength transmission networks can be explained as a service of electrical circuits that transmit bulk power over long distances. While, delivering the main objective of the electric utility company is to achieve certain sufficient levels of cost, peak load, efficiency, and dependability [5].

The efficiency of transmission networks strongly influences total system losses and security of supply. Therefore, the reliable transmission of electrical energy from generation centers to load centers is a fundamental requirement and very crucial for proper planning and smooth operation of the power system. In the Nigerian context, the transmission network is a mix of 330 kV, 132 kV and 33 kV lines connecting generation plants to distribution substations. The Nigerian power sector has been plagued with several challenges ranging from high proportion of transmission line losses, voltage instability, and insufficient supply to meet the ever-growing demand of consumers. Transmission grid is considered to be the backbones through which bulk power is transferred from the generation plants to the distribution entities. Unfortunately, this grid has increasingly become inefficient due to its ageing nature, high technical losses, and inability to expand [17]. It has been reported in various researches that voltage stability problem exists in the transmission

grid in Nigeria, especially in the 330 kV grid where some buses consistently operate at voltages above the threshold limit [16][18].

Transmission losses not only reduce system efficiency and increase operational cost, but also limit the available capacity for additional generation dispatch, thereby constraining growth and reliability. Power losses in transmission systems arise from resistive losses ( $I^2R$ ) in conductors and transformers, reactive power flows that increase currents, suboptimal power dispatch (including loop flows and non-ideal phase angles), and flows due to network configuration and constraints. As system loads increase, these losses escalate nonlinearly because currents rise, voltage regulation becomes more stressed, and reactive power balancing becomes more demanding [6].

In order to address the aforementioned technical challenges without the enormous capital cost of building new transmission lines, traditional approaches, such as the installation of shunt capacitors and reactors which offer static compensation, but limited in adaptability are employed for reactive power support. Nowadays, due to advancement in power electronics technology and global trends toward intelligent grid modernization, modern power systems increasingly rely on reactive power compensation through the deployment of Flexible AC Transmission System (FACTS) technologies. FACTS device such as: Static Var Compensator (SVC), that allow dynamic control of voltage magnitude, line reactance, and phase angle. This flexibility leads to benefits such as decongestion, voltage regulation, increased transfer capacity, damping of oscillations, and in particular, reduction of transmission losses.

The idea behind this is that by regulating the reactive power flows and optimal voltage levels using SVCs, the amount of current in the line is minimized, hence reducing the  $I^2R$  losses. Also it improve the voltage margins at remote nodes [9]. In order to yield significant benefits of FACTS device, installation in transmission network, optimal placement and sizing is paramount [10]

In Nigeria, the Akure 132/33 kV sub transmission station is one of the crucial substations carrying significant loads especially during peak periods, and feeding parts of Ondo State distribution systems and radiating another 132kv transmission line to Ekiti state. Field observations and internal operational

records suggest that the Akure 33 kV feeders suffers nontrivial real and reactive losses and occasional voltage drops at remote points under heavy loading or contingencies. Ensuring optimal performance of these feeders is perhaps vital for sustaining socio-economic activities in these states [15] [17].

Thus, the adoption of FACTS device for power loss mitigation on the Akure 33 kV feeders is both timely and strategic. This research seeks to adopt flexible AC transmission system for power loss mitigation techniques along Osogbo-Akure 132kV line, quantifying the extent of loss reduction, and to provide technical recommendations for Nigeria's power sector.

## II. METHODOLOGY

The method employed in this research is based on analysis and simulation. The investigation of power loss and mitigation along 33 kV feeders in Akure transmission station through the deployment of Static Var Compensator (SVC) using Genetic Algorithm optimization technique for its optimal value sizing and placement. This will be achieved by performing load flow analysis and investigating technical losses under existing conditions, size and simulating the integration of Static VAR Compensator (SVC) into the transmission network and assess its impact on voltage stability, reactive power compensation, and power loss , and conducting a comparative evaluation of the network's performance before and after the SVC integration.

### *A. Compilation of Operational Data*

All necessary technical data for the 33 kV feeders in Akure transmission station are collected. The technical data which are line parameters comprising resistance, reactance, line length; bus data comprising voltage levels, load demand, injections; transformer ratings, and conductor characteristics. Microsoft Excel computational ltd is used to format and validate these datasets before importing into Electrical Transient Analyzer Program (ETAP) and Matrix Laboratory (MATLAB) software for modelling.

### *1. Detailed Description of the Existing Akure 132 /33 kV Transmission Station*

The Akure 132/33 kV transmission station is a critical component of Nigeria's electric power transmission

network, providing a bulk power to most parts of Ondo state. The transmission station radiates power through nine 33 kV feeders. It plays a key role in regional power evacuation and system reliability in the southwestern part of the country.

The corridor receives power from Osogbo 132 kV station at a nominal voltage level of 132 kV and is equipped with 132 kV gas circuit breakers (GCBs) at both the Osogbo and Akure transmission substations. These circuit breakers provide essential protection, switching, and isolation functions, ensuring safe and reliable operation of the line under normal and fault conditions.

Power is transmitted primarily from the Osogbo 132 kV Transmission Station to the Akure 132 kV Transmission Station. In addition, the line incorporates a turn-in–turn-out (TITO) configuration that facilitates a connection to the Ado-Ekiti 132 kV Transmission Station in Ekiti State. This arrangement allows the Osogbo-Akure line to supply multiple load centers while enhancing network flexibility and redundancy without the need for a dedicated radial line

### 2. Load and Line data Used.

Load data for this study was obtained from the Akure 132/33 kV Transmission Station. All loads are connected at the 33 kV level through distribution feeders supplied by the 132/33 kV transformers

Table 1a: Load Feeder Connected to Transformer AKR-TR1 60MVA

S/N	Feeder Name	Nominal Voltage (kV)	Load (MVA)
1	FMPI Feeder	33	11.3
2	OWO Feeder	33	9.0
3	IJU Feeder	33	13.4
4	Akure Main Feeder	33	15.8

Table 1b: Load Feeder Connected to Transformer AKR-TR2 60MVA

S/N	Feeder Name	Nominal Voltage (kV)	Load (MVA)
5	Elizade Feeder	33	11.5
6	FUTA Feeder	33	9.2
7	Oba-Ile Feeder	33	10.8

Table 1c: Load Feeder Connected to Transformer AKR-TR2 30MVA

S/N	Feeder Name	Nominal Voltage (kV)	Load (MVA)
8	Owena Feeder	33	10.9
9	Igba-Oke Feeder	33	11.3

### 3. Line Data

For this study, an ACSR/1350 (Coyote, 151.8 mm<sup>2</sup>) conductor was adopted to model the existing Akure 33 kV feeders within the ETAP software environment. The conductor selection reflects typical Transmission Company of Nigeria (TCN) practice for medium-voltage transmission corridors of comparable length and loading characteristics.

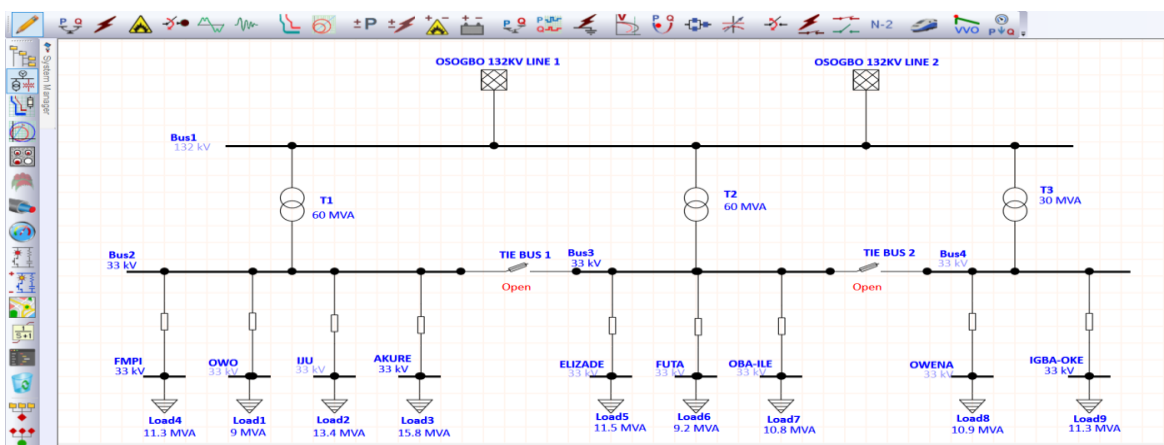


Figure 1: Single-Line Diagram of the Akure 33 kV feeder Network

Using ETAP, as illustrated in Figure 1. The positive- and zero-sequence resistance and reactance parameters of Akure 33 kV feeders were extracted

directly from the network model. The software automatically includes those of the conductor material properties, cross-sectional area, geometric mean

radius (GMR), and phase spacing, as well as taking into consideration ambient operating conditions, including a reference temperature of 25°C. Based on the modeled conductor characteristics, ETAP will compute a positive-sequence resistance and a positive-sequence reactance. The corresponding zero-sequence resistance and reactance were obtained. These parameters will form the basis for the steady-state load flow analysis, power loss evaluation, and subsequent assessment of the impact of Static Var Compensator (SVC) integration on voltage regulation and loss mitigation in Akure 33 kV feeders.

Feeder ID	Length (km)	R (Ω)	X (Ω)
FMPI	4.7	1.052	1.814
OWO	8.2	1.835	3.164
IJU	6.6	1.477	2.547
Akure Main	16.5	3.693	6.367
Elizade	8.0	1.790	3.087
FUTA	10.6	2.372	4.090
Oba-Ile	11.3	2.529	4.361
Owena	7.6	1.701	2.933
Igbara-Oke	4.8	1.074	1.852

#### 4. Resistance of the conductor

The resistance of the conductor represents the opposition to current flow along the phase conductors under balanced operating conditions. It is primarily determined by the material resistivity and the cross-sectional area of the conductor given by [13].

$$R = \frac{\rho}{A} \times 1000 \text{ } \Omega/\text{km} \quad (1)$$

Where:

$\rho$  is resistivity of the conductor for ACSR  $\approx 0.032 \text{ } \Omega \cdot \text{mm}^2/\text{m}$

A is cross-sectional area of the conductor  $151.8 \text{ mm}^2$

#### 5. Inductance of the Conductor

The inductance quantifies the self and mutual inductive effects of the distribution line under balanced load flow depends on the geometric arrangement of conductors and the geometric mean radius (GMR), including any bundling effects. As presented in contemporary power system analysis literature [19], the conductor radius is giving by

$$r = \sqrt{\frac{A}{\pi}} \quad (2)$$

The GMR for a single Bison ACSR  $158.1 \text{ mm}^2$  conductor is giving by

$$\text{GMR} = r' = 0.778 \quad (3)$$

$$L = 2 \times 10^{-7} \ln \left( \frac{D_{eq}}{r'} \right) \Omega/k \quad (4)$$

$$X_L = 2\pi fL \quad (5)$$

Where:

$D_{eq}$ : Equivalent spacing between phase conductors (3m)

f: system frequency (Hz), typically 50 Hz

$r'$ :  $0.778 \cdot r$  is the geometric mean radius

r: physical radius of conductor (m)

Table 2: Line Parameters of the 33kV Akure Feeders

#### 6. Voltage Deviation Index (VDI)

The Voltage Deviation Index (VDI) is employed to quantify the cumulative voltage deviation across all buses of the Akure 33 kV feeders under base-case operating conditions. The index provides a quantitative measure of how far individual bus voltage magnitudes deviate from their nominal values and serves as a key VDI indicator used to detect voltage-weak and reactive power deficient buses.

The higher the value of VDI, the more vulnerable the bus is to experiencing voltage collapse. This makes such buses excellent candidates for locating SVCs because it allows dynamic reactive power control at these critical weak-voltage buses to improve their voltage levels.

By deploying the VDI technique in detecting voltage weakness in buses, there is technical justification for implementing SVCs in buses with high VDI values [1][8].

$$VDI_k = \sum_{i=1}^{N_b} \left( \frac{V_i^{(k)} - V_i^{ref}}{V_i^{ref}} \right)^2 \quad (6)$$

Where:

$V_i^{(k)}$  :- voltage at bus I under contingency k in p.u

$V_i^{ref}$  :- nominal voltage at bus i usually 1p.u

$N_b$  :- total number of buses

#### 7. Line Overload Index (LOI)

The Line Overload Index (LOI) measures the degree to which transmission lines operate close to or exceed their thermal loading limits under base-case conditions. It is determined by comparing the actual line power flow or current magnitude to the rated thermal capacity of each 33 kV feeder transmission line within Akure 132/33 kV station.

Feeder lines exhibiting high LOI values are identified as critical or congested corridors, where excessive current flow leads to increased real power losses and voltage drops. These lines are prime candidates for

reactive power support through SVC installation at nearby buses. Incorporating the LOI into the candidate bus selection process ensures that SVCs are placed at locations where they can most effectively reduce line current, alleviate congestion, minimize losses, and improve voltage stability of the transmission network [14].

$$LOI_k = \sum_{l=1}^{N_l} \left( \frac{|S_l^{(k)}| - S_l^{max}}{S_l^{max}} \right)^2 \quad (7)$$

Where:

$|S_l^{(k)}|$  is apparent power flow on the line l under contingency k in MVA

$S_l^{max}$  is thermal capacity of the line l MVA

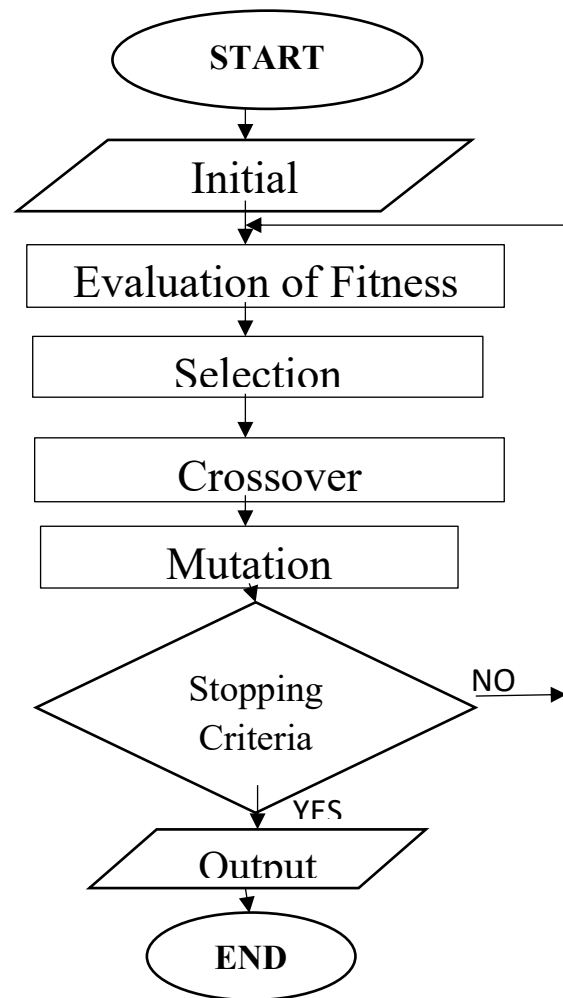
$N_l$  is total number of lines

### B. Develop AI Algorithm for Optimal SVC Sizing and Location

Genetic Algorithm (GA) is used to determine the optimal SVC location and size. The transmission feeders are modelled in MATLAB using the data from (A). The optimization problem is formulated with SVC size and location as decision variables. GA operators such as selection, crossover and mutation are applied until convergence to the optimal solution.

1. The Optimization Method of Genetic Algorithms (GA) and Its Choices A subfield of evolutionary programming addressing optimization issues across continuous domains is called genetic algorithms (GA). In order to describe the characteristics of each search space, the genetic algorithm first generates a wide range of solutions. Positive traits are chosen and passed on to the following generation through crossover and mutation. It is used in this study due to its resilience, speed, simplicity, and convenience of use. Additionally, it is among the finest evolutionary algorithms for addressing real-value variable problems. Genetic algorithms are highly useful design tools that are readily available and simple to include into suitable software for real-world use. In this work, a genetic algorithm is employed to decide the optimal size and location of a fixed variable to compensate reactive power loss after a successful load flow analysis using the Newton Raphson method and subsequent system voltage upgrading. The goal of the selection procedure is to keep the population size constant above the generations. Typically, the selection process is used to choose which of the parent and child vectors will be kept and which will be replaced in the following generation. Any of the child vector or parent vector with higher fitness value is retained. As seen in Figure 2, the GA algorithm bases its selection procedure on the survival of the fittest.

Figure 3: Flowchart of Genetic Algorithm [7]



### 1. Determination of Candidate Bus Suitable for SVC Placement

Potential locations for Static Var Compensator (SVC) installation were identified based on system performance indicators obtained from the base-case load flow analysis of the Akure 132/33 kV transmission station network. Buses (feeders) exhibiting significant voltage deviations below 0.95 p.u., high reactive power demand, increased line loading, elevated real power loss sensitivity, and indications of weak voltage support were flagged as suitable candidate buses for SVC deployment.

Such a placement guarantees that the SVC is installed at sensitive buses where the effects of dynamic reactive power compensation have a maximum positive impact on improving voltage profiles, reducing transmission currents, minimizing losses in real power, and alleviating the loading of critical lines and transformers.

The selected candidates were used as the inputs in further analysis of the placement and sizing of the SVC in Akure 132 kV Transmission Station.

### 3 Optimal Placement and Sizing of Static Var Compensator (SVC) Using Genetic Algorithm (GA)

In the process of reinforcing an existing transmission network with reactive power compensation devices, there must be proper placement and sizing of these devices. This is because if they are improperly placed or oversized/undersized, they will not give the intended voltage improvement or loss reduction or alleviate the loading of lines and transformers. On the other hand, properly placed and sized SVCs would contribute immensely towards enhancing voltage profiles, minimizing losses, mitigating line congestion, and improving the performance of the transmission network as a whole.

In this research work, a genetic algorithm (GA), which is a nature-based stochastic search algorithm, was used to find out the optimal placement and reactive power rating of SVC devices in Akure 132 kV transmission station. The fact that the GA can solve nonlinear, non-convex and multi-objective optimization problems inherent to power system planning makes the GA particularly well suited to the task.

The GA is an iterative search to find the best solution by evolving a population of candidate solutions through the processes of selection, crossover and mutation. Each candidate solution is a particular combination of SVC location(s) and reactive power capacities, which are determined using load flow results provided by ETAP. The fitness of a solution is determined by how well it minimizes voltage deviations, reduces transmission losses, and or alleviates line and transformer overloading, and fits all the operational constraints.

The optimization problem is formulated to minimize a composite objective function subject to system constraints such as bus voltage limits, thermal limits of transmission lines and transformers, and SVC reactive power operating limits. The general mathematical formulation of the optimization problem is expressed as follows [23].

$$F = w_1 \sum_{i=1}^{n_{bus}} |V_i - V_{ref}| + w_2 \sum_{i=1}^{n_{l,ne}} \left( R_{ij} \frac{P_{ij}^2 + Q_{ij}^2}{V_i^2} \right) \quad (7)$$

Subject to

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (8)$$

$$Q_i^{min} \leq Q_i^{SVC} \leq Q_i^{SVC} \quad (9)$$

$$S_{ij} \leq S_{ij}^{max} \quad (10)$$

Where:

F is total objective function to be minimized

$V_i$  is Voltage magnitude at bus i

$V_{ref}$  is Nominal / reference voltage magnitude

$w_1, w_2$  are Weighting factors assigned to each performance index in the objective function

$V_i^{min}$  is minimum permissible bus voltage limit

$V_i^{max}$  is maximum permissible bus voltage limit

$$Q_i^{min} \leq Q_i^{SVC} \leq Q_i^{SVC}$$

#### C. Evaluate Performance of the Algorithm

In order to achieve the above, a baseline load flow is first performed in ETAP without SVC. The optimized SVC size and bus location from MATLAB are then integrated into the ETAP model. Post-compensation load flow is conducted and key performance indices are evaluated, including real and reactive power losses, bus voltages, and line loading. The MATLAB and ETAP results are compared to validate the reliability of the developed algorithm.

#### 1. Comparative Performance Evaluation Before and After SVC.

In order to achieve this, Newton–Raphson load flow results are compared for two cases: (i) the existing network without SVC, and (ii) the network with optimally sized and placed SVC. Performance parameters such as total real/reactive power loss, voltage deviation, and voltage stability margin are extracted highlighting the improvements achieved through SVC installation.

### III. RESULTS AND DISCUSSION

The analyses were carried out for two operating conditions: the existing network without compensation and the improved network with an optimally sized Static Var Compensator (SVC) installed at the selected candidate bus.

#### 1. Network Modeling and Base-Case Load Flow Analysis.

The result of the voltage profile of Akure 33 kV feeders before SVC integration is presented in figure 4.

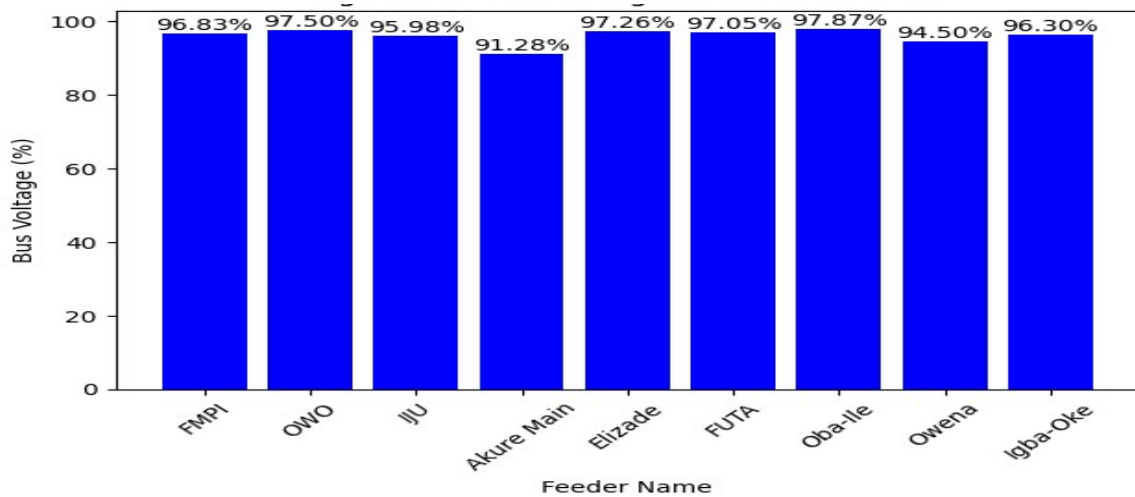


Figure 4. Voltage Profile of the Existing Akure 33kV feeders before SVC Integration

Figure 4. Is a composite bar chart illustrating the bus voltage profile of the Akure 33 kV feeders under existing operating conditions. The results indicate noticeable voltage variations across the feeders, with bus voltage magnitudes ranging from a minimum of 91.28% at the Akure Main feeder to a maximum of 97.87% at the Oba-Ile feeder. While most feeders operate within the acceptable statutory voltage limit of 0.95-1.05 p.u.

In particular, the Akure Main feeder (91.28%) and the Owena feeder (94.50%) operate below the lower permissible limit, indicating weak voltage support at these locations. The IJU feeder (95.98) has a narrow

operating margin (close to 95%), indicating a marginal operating condition. The attribution of such conditions of undervoltage can be linked to the long network feeder lengths, the high loading points, combined with the insufficient support of reactive power, which all help contribute to the increased voltage drops along the network. These operating conditions can have a negative effect on power quality, technical losses can increase, and the reliability of the system may be undermined.

Figure 5 shows the ETAP load flow model of the 33kV feeders of the existing Akure transmission station prior to SVC Integration.

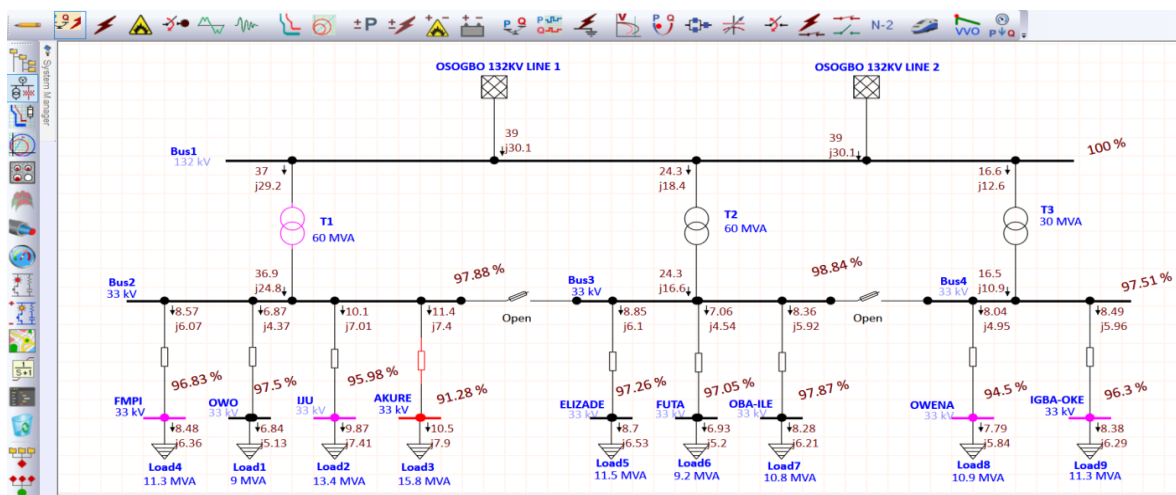


Figure 5 ETAP Load Flow Model of the Existing 33 kV feeders Before SVC Integration

A. Voltage Drop on the Existing Network without SVC.

The voltage drop profile of existing Akure 33kV transmission corridor before SVC integration is presented in figure 6

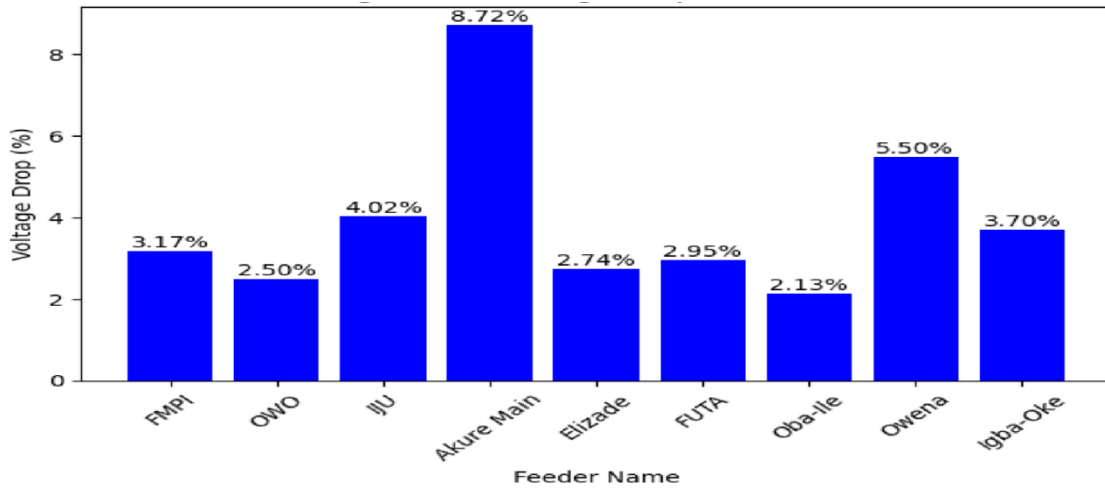


Figure 6. Voltage Drop Profile of the 33kV feeders in Akure before SVC Integration

Figure 6 shows a composite bar chart that shows voltage drop between the source bus and the load end of each feeder in the current Akure 132/33kV transmission station operating under base-case operating conditions. Voltage drops along most feeders such as FMPI, OWO, Elizade, FUTA and Oba-Ile are less than 3.2% indicating reasonably satisfactory voltage regulation along the feeders.

The Akure Main feeder, however, suffers a very high voltage drop of 8.72% which is well above the acceptable limits and corresponds with its severely depressed load-end voltage of 91.28. This means that there is a high voltage degradation due to heavy loading with the lack of support of the reactive power along this feeder. Likewise, the Owena feeder has a relatively high voltage drop of 5.50% and the IJU feeder has a moderate voltage drop of 4.02%,

suggesting marginal voltage regulation conditions. The excessive voltage drop observed on the Akure Main feeder confirms it as the weakest section of the network and aligns with the earlier findings on voltage profile, power losses, and branch loading.

The severe voltage drop recorded along the Akure Main feeder agrees with the findings of [18][16], who reported that remote feeders and long transmission corridors in Nigeria experience substantial voltage decline due to high loading and insufficient reactive power reinforcement

*B. Power Flow and Line Losses on the Existing Network without SVC*

Figure 7 presents active power loss profile on Akure 33kV feeders before the integration of SVC

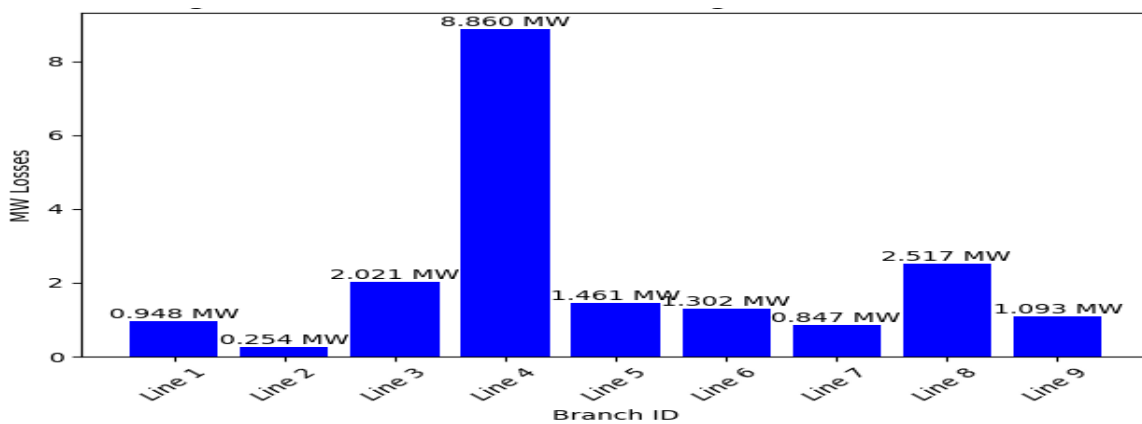


Figure 7 Active Power Loss Profile on the Existing Akure 33kV feeders Before SVC Integration

Figure 7 is a composite bar chart of losses of active power in the network of the current study.

Power flow distribution indicates that the largest part of the load is supplied via Transformer T1 which has the greatest power transfer and is critical in providing the downstream network with power. Line 4 (Bus 2-

Akure Main feeder) has the highest real power loss of 8.86 MW, which implies that there is extreme stress and inefficient power transfer along this passage. Likewise, it can be seen that Lines 3 and 8 also exhibit somewhat high losses of 2.021 MW and 2.517 MW, respectively, which corresponds to the IJU and Owena feeders. This high level of losses can be related to the high loading and long feeder distances in the network. The power flow and loss profile so offers a good reason in support of targeted reactive power compensation, particularly through SVC installation, to improve power transfer efficiency, reduce losses, and enhance voltage stability in the network

The concentration of real power losses along the heavily loaded Akure Main corridor is consistent with the observations of [21][22], who reported that high line current and excessive reactive power flow significantly increase I<sup>2</sup>R losses in congested transmission lines.

*C. Branch Loading on the Existing Network without SVC*

Figure 8 is the branch loading profile of Akure 33 kV feeders before SVC integration

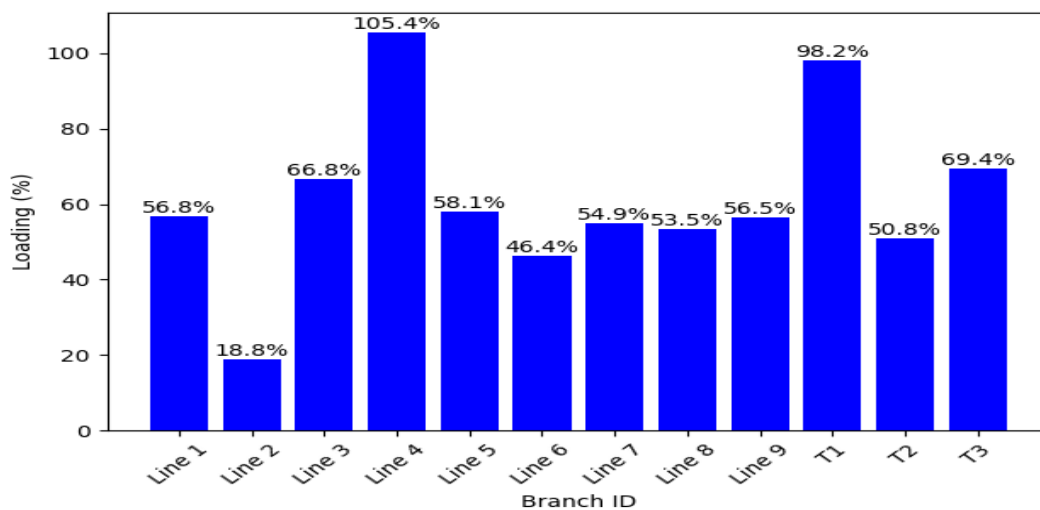


Figure 8. Branch Loading Profile of the Existing Akure 33kV Feeders Transmission before SVC Integration

Figure 8. shows the load of the existing Akure 33kV feeders in base-case operating conditions. The findings demonstrate that there is an imbalance in the loading of the network components with a number of lines and transformers working near their specified capacities. Table 3 presents a corresponding table. It is worth noting that the Line 4 supplying the Akure Main feeder has been severely overloaded with a loading level of 105.4% indicating that it is operating beyond its thermal limit and significant risk to system reliability. Moreover, Transformer T1 can be loaded at about 98.2 percent of its full loading capacity (60MVA), which does not leave much room to take into consideration the increase in load or the presence of contingency conditions.

The other network elements, Line 3 and Line 9, have a moderate loading of 66.8% and 56.5% respectively, whereas the rest of the lines are well within the acceptable limits. Transformer T3 also has a relatively high utilization of 69.4, with Transformer T2 having a much more moderate utilization level of 50.8. The observed overloading of Line 4, along with the near capacity operation of Transformer T1, confirm the existence of congestion on the Akure Main feeder corridor.

The overloading of Line 4 and the near-thermal operation of Transformer T1 is consistent with the results presented by [20][15], who found feeder congestion and stress on Transformers as main operational challenges in transmission networks operating close to capacity limits.

*D. Candidate Bus Selection by ETAP.*

Line	Feeder	Bus Voltage (%)	Voltage Drop (%)	Max Line Loading (%)	MW Losses (Dominant Branch)	Transformer Loading (%)	Candidate Priority
Line 1	FMPI	96.83	3.17	56.8	0.948	98.2	Non Candidate
Line 2	OWO	97.50	2.50	18.8	0.254	98.2	Non Candidate
Line 3	IJU	95.98	4.02	66.8	2.021	50.8	Marginal
Line 4	Akure Main	91.28	8.72	105.4	8.86	98.2	Critical
Line 5	Elizade	97.26	2.74	58.1	1.461	50.8	Non Candidate
Line 6	FUTA	97.05	2.95	46.4	1.302	50.8	Non Candidate
Line 7	Oba-Ile	97.87	2.13	54.9	0.847	50.8	Non Candidate
Line 8	Owena	94.50	5.50	53.5	2.517	69.4	Marginal
Line 9	Igba-Oke	96.30	3.70	56.5	1.093	69.4	Non Candidate

Table 3 Summary of Candidate Bus Classification Based on Network Performance Indices

The table above, gives an overview of the candidate bus classification, based on key network performance indicators, such as the magnitude of the bus voltage, voltage drop, line loading, real power losses, and transformer loading. The results show that Akure Main feeder is the most critical point in the existing network with a severely depressed voltage of 91.28, maximum voltage drop of 8.72 and feeder overloading of 105.4 with maximum real power loss of 8.86 MW. Secondly, the supplying transformer is working near its rated capacity of 98.2% loading, indicating high operational stress and reliability issues. As a result, the Akure Main feeder was declared as a Critical candidate bus that needed urgent compensation.

The Owena and IJU feeders were categorized as Marginal candidate buses, since they exhibit moderate voltage deviation 94.50% and 95.98%, respectively and also a relatively higher voltage drop and losses compared to the other feeders, but without serious line or transformer overloading. These conditions are indicative of weakened voltage support, which can be degraded with increased loading. All other feeders have acceptable voltages, moderate loading and lower losses and were therefore categorized as Non-candidate buses.

This classification of the Akure Main feeder as a critical compensation bus is consistent with the approaches to candidate-bus selection that have been reported by [22][12] when locating FACTS devices. Their research revealed the FACTS placement can be most effective when it is directed to weak buses with high operational loads.

*E. Optimal Sizing of SVC Using Genetic Algorithm*

Table 4 presents the SVC sizing and placement results for the Akure Main feeder.

Bus Location	Optimal SVC Size (MVar)
Akure Main feeder	20

Table 4: Optimal Sizing of SVC for Voltage Support on the Akure Main Feeder

A Genetic Algorithm (GA) was employed to determine the optimal placement and reactive power rating of Static Var Compensator (SVC) in the network. The Akure Main feeder bus, identified as the critical bus with a base-case voltage of 0.9128 p.u. was selected for installation. The GA iteratively evaluated candidate SVC solutions using load flow analyses in ETAP, adjusting reactive power ratings through selection, crossover, and mutation operations to minimize voltage deviation, reduce feeder losses, and alleviate network congestion. Considering the high feeder loading of 105.4%, significant reactive power demand, and large real power losses 8.86 MW, a 20 MVAR SVC provides sufficient reactive power support to restore voltage within acceptable limits of 0.95-1.0 p.u. without causing overcompensation. The optimized configuration was validated through post-installation load flow studies, confirming its effectiveness in improving voltage profiles, reducing losses, and maintaining system parameters within permissible limits

*F. Post-Compensation Load Flow Analysis Result*

The post SVC integration voltage profile is presented in figure 9.

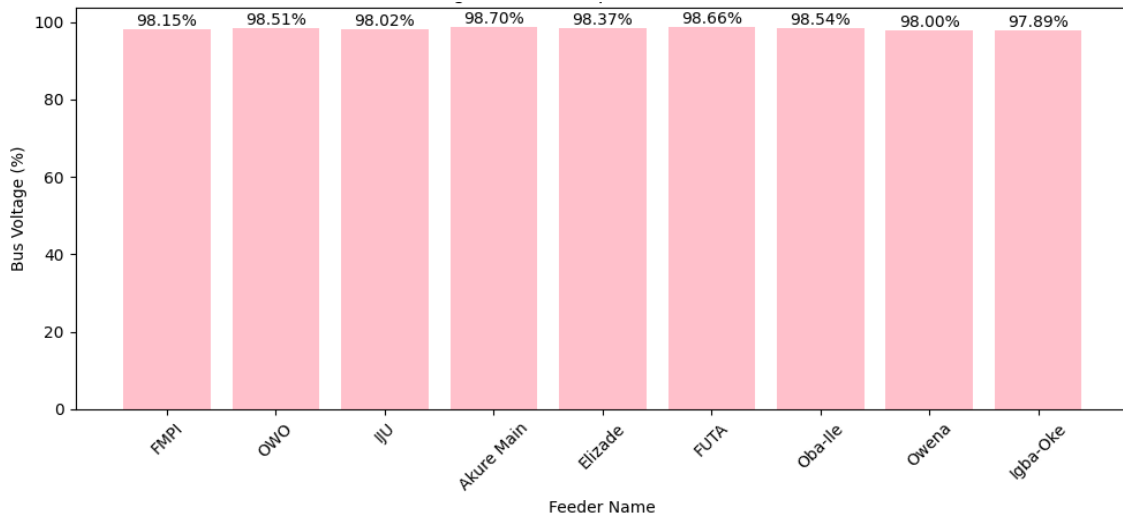


Figure 9. Voltage Profile of Akure 33kV Feeders after SVC

Figure 9 is bar chart presenting the bus voltage profile of the improved Akure 33kV feeders following the integration of a Genetic Algorithm optimized 20MVar Static Var Compensator (SVC). The results demonstrate a significant enhancement in voltage regulation across all feeders compared to the base-case scenario. All buses now operate comfortably within the statutory voltage limits of 0.95-1.05 p.u., with voltage magnitudes ranging from 97.89% to 98.70%.

Notably, the Akure Main feeder, which previously exhibited the most severe under voltage condition at 91.28%, shows a remarkable voltage improvement to 98.70% after SVC installation. Similarly, the Owena and IJU feeders, earlier identified as marginal

candidates, record improved voltage levels of 98.00% and 98.02%, respectively, indicating effective reactive power support and voltage stabilization. The remaining feeders also experience uniform voltage enhancement, reflecting improved power flow distribution and reduced reactive power demand across the network.

The significant improvement in bus voltage levels after SVC integration is consistent with the results obtained by [2] whose studies showed that SVCs provide effective dynamic reactive power support and enhance voltage stability at weak buses.

Figure 4.7 is the ETAP load flow model of the Akure 33kV feeders after SVC Integration

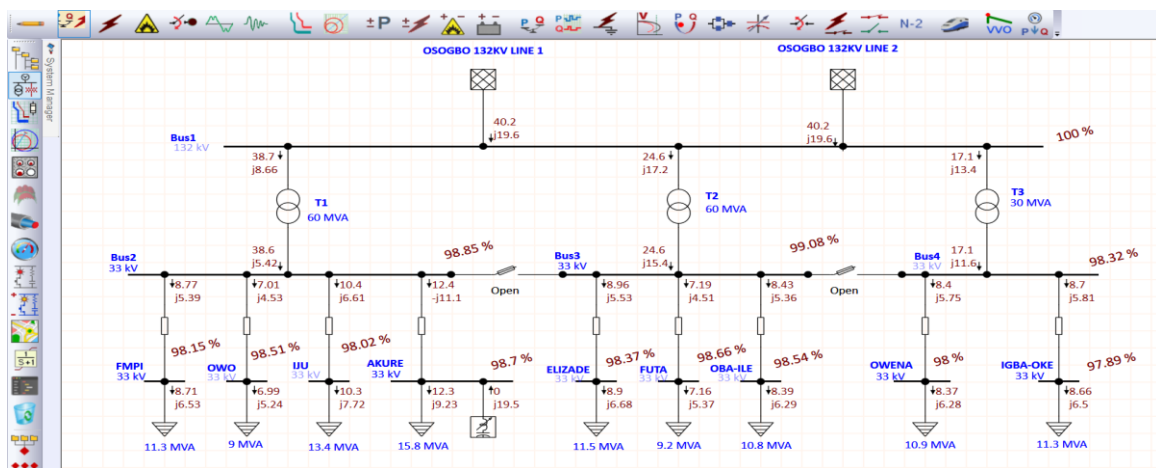


Figure 10. ETAP Load Flow Model of Akure 33 kV Transmission network After SVC Integration

Figure 10 illustrates the ETAP load flow model of Akure 33 kV feeders after the integration of SVC

G. Voltage Drop on the Improved Network with SVC

Figure 11 presents the voltage drop profile of the improved Akure 33 kV feeders after SVC integration

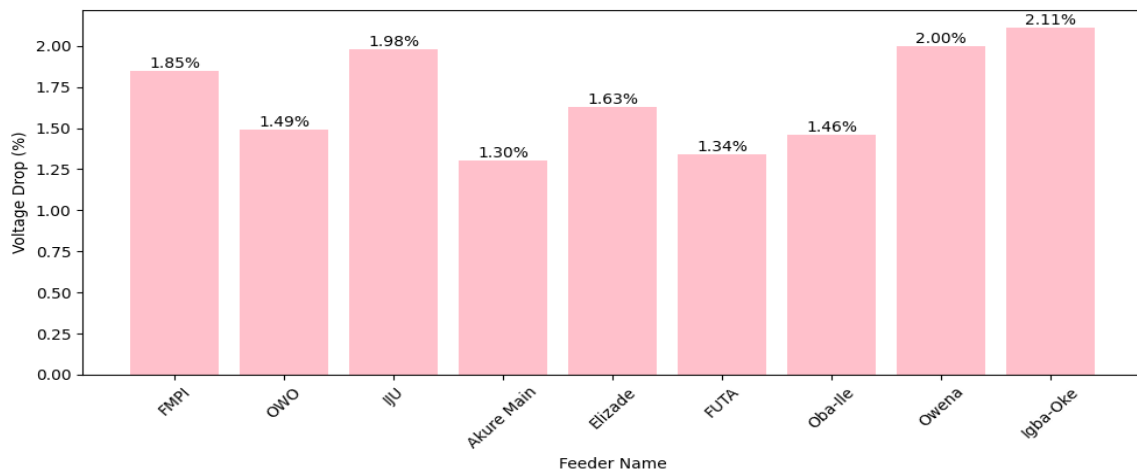


Figure 11. Voltage Drop Profile of the Improved Akure 33kV transmission Feeders after SVC Integration.

Figure 11 is a bar chart that presents the voltage levels at the load ends of the various feeders on the improved Akure 33 kV transmission feeders following the integration of GA optimized 20 MVar SVC. The results show a marked enhancement in voltage performance across all feeders, with load-end voltages ranging between 97.89% and 98.70%, corresponding to voltage drops of only 1.30% to 2.11%. This indicates that the network now operates well within acceptable voltage regulation limits, reflecting the effectiveness of the SVC in supplying localized reactive power support and minimizing line voltage depression along the distribution corridors.

Among the feeders, the Akure Main feeder records the highest voltage level of 98.70% with a corresponding drop of 1.30%, representing a significant improvement compared to the base-case condition where severe voltage decline was previously observed. Similarly, the OWO, FUTA, and Oba-Ile

feeders maintain load-end voltages above 98.5%, indicating strengthened voltage stability and reduced sensitivity to loading effects. Although the Owena and Igba-Oke feeders exhibit slightly higher voltage drops of 2.00% and 2.11%, respectively, these values remain within permissible operational limits and do not indicate any critical voltage weakness.

Therefore, the reduction in voltage drop across all feeders confirms that the SVC has substantially improved network voltage support, reduced reactive current flow, and enhanced power delivery quality to the downstream loads.

H. Power Flow and Line Losses of the Improved Network with SVC.

Figure 12. Presents active power loss profile of the improved Akure 33 kV Transmission Feeders after SVC integration

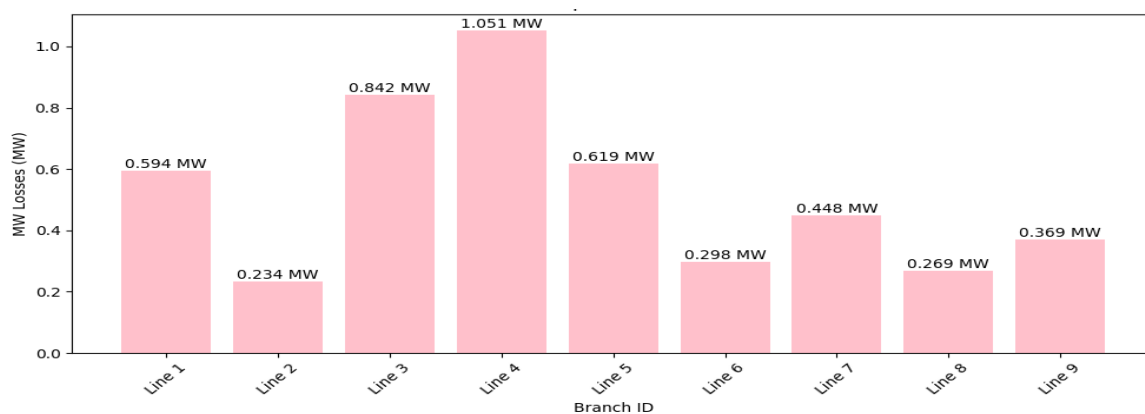


Figure 12. Active Power Loss Profile of the Improved Akure 33kV Feeders after SVC Integration

Figure 12 is a bar chart illustrating the active power losses after the integration GA optimized SVC into the study case network. The post-compensation power flow distribution indicates a more balanced loading pattern across the transformers and outgoing feeders, with Transformer T1 still carrying the largest share of power transfer but now operating under improved reactive support conditions. Among the distribution lines, Line 4 (Bus 2 – Akure Main feeder) records the highest real power loss of 1.051 MW, although this value is significantly lower than in the uncompensated case, indicating a marked reduction in corridor stress and improved power transfer capability. Other feeders such as Lines 3 and 5 also exhibit moderate losses, but

these remain within acceptable operational limits under the improved voltage profile.

The notable decline in reactive power losses and the stabilization of feeder loading patterns confirm the effectiveness of the SVC in supplying local reactive power support, thereby minimizing voltage drops and mitigating unnecessary reactive power flows along the network.

#### I. Branch Loading of the Improved Network with SVC

Figure 13 presents branch loading profile of the improved Akure 33kV Feeders after SVC integration

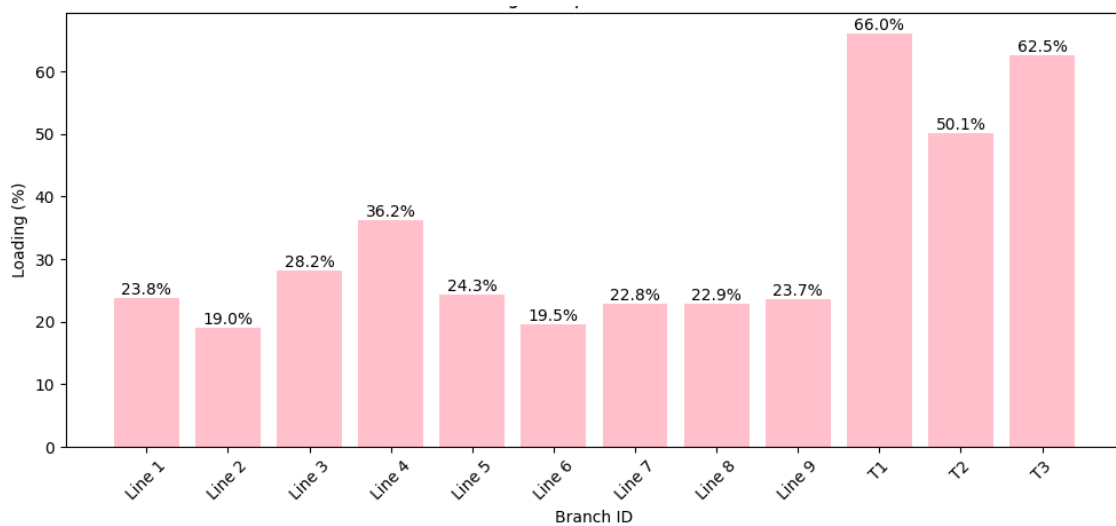


Figure 13. Branch Loading Profile of the Improved Akure 33kV Feeders after SVC Integration.

The Figure above is a composite that presents the branch loading levels of Akure 33 kV feeders following the integration of GA optimized, 20 MVar SVC. The results indicate a significant improvement in network loading conditions, with all lines and transformers now operating comfortably within their thermal limits. The highest loading is recorded on Line 4 (Akure Main feeder) at 36.2%, which represents a substantial reduction compared to the overloaded condition observed in the base-case scenario. This reduction reflects the positive impact of reactive power support in relieving corridor stress and improving the distribution of power flow across the network.

Similarly, the transformer loading profile shows enhanced operating margins, with Transformers T1, T2, and T3 recording loading levels of 66.0%, 50.1%, and 62.5%, respectively. These values indicate adequate spare capacity and improved operational flexibility, thereby enhancing the network's ability to

withstand load variations and potential contingency events. The remaining feeders exhibit relatively low loading levels, generally ranging between 19% and 28%, confirming a more balanced and stable load distribution across the downstream network.

The reduction in feeder and transformer loading levels after SVC integration agrees with the results reported by [15][11], who observed that FACTS devices relieve corridor congestion and improve system loading margins by supplying localized reactive power.

#### J. Comparison of the Network's Voltage Profile With and Without SVC.

Figure 14. Shows comparative bar chart illustrating voltage profile of Akure 33 kV Feeders with and without SVC integration

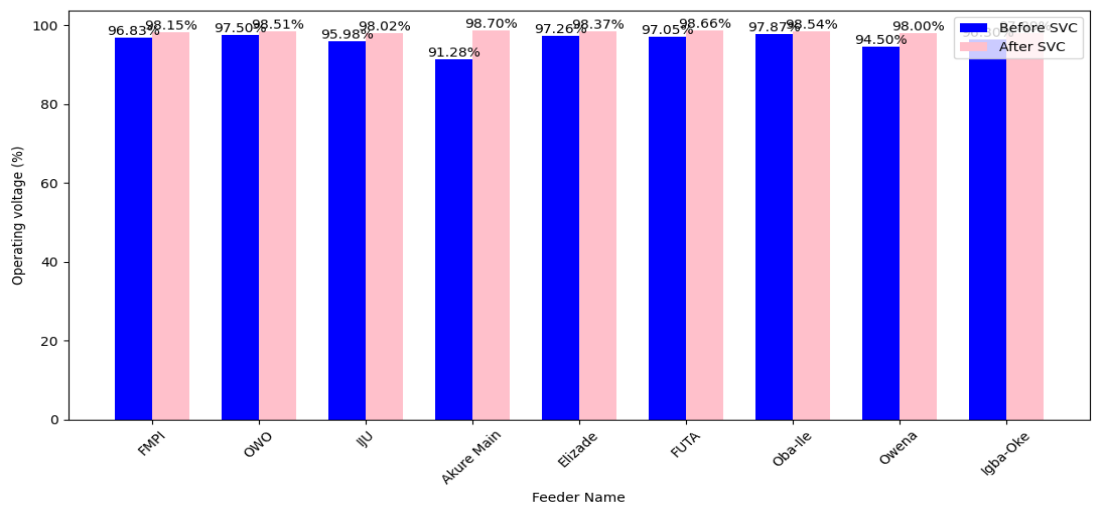


Figure 14: Comparative Bar Chart Illustrating Voltage Profile of Akure 33kV Feeders with and Without SVC Integration.

Figure 14 is a comparative bar illustrating the bus voltage magnitudes on the Osogbo–Akure 33 kV feeders before and after the installation of the optimally sized 20 MVAR SVC at the Akure Main feeder. The results show a significant improvement in the voltage profile across all feeders after compensation.

Before SVC installation, several feeders operated below the statutory lower voltage limit, with the Akure Main feeder recording the lowest voltage magnitude of 91.28%, indicating a severe undervoltage condition. The Owena feeder also exhibited marginal voltage weakness at 94.50%, while the IJU feeder operated close to the threshold at 95.98%. These results reflect insufficient reactive power support and high loading stress along the corridor.

After the integration of the SVC, all feeder voltages increased to acceptable operating limits between 97.89% and 98.70%. The most remarkable improvement occurred at the Akure Main feeder, where the voltage rose from 91.28% to 98.70%, representing a substantial enhancement in voltage stability and regulation. The Owena and IJU feeders also improved to 98.00% and 98.02%, respectively, eliminating the previously observed marginal voltage

conditions. The remaining feeders experienced uniform and stable voltage enhancement, indicating improved system support and reduced sensitivity to voltage drop.

The improvement in the voltage profile after installing the SVC agrees with the findings of previous researchers who reported that SVCs help to supply reactive power, stabilize weak buses, and improve voltage levels in transmission networks. Studies such as [15] [2] also showed that SVC installation leads to better voltage regulation under heavy loading conditions. Similar results were reported in Nigerian grid studies, where FACTS devices were found to improve voltage stability and reduce undervoltage problems [17]; [11]. The results of this study therefore agree with these works, confirming that SVC integration is an effective method for improving voltage profile on stressed transmission feeders.

#### *K. Comparison of Active Power Loss With and Without SVC*

Figure 15 presents a comparative bar chart illustrating active power loss on Akure 33 kV feeders with and without SVC integration

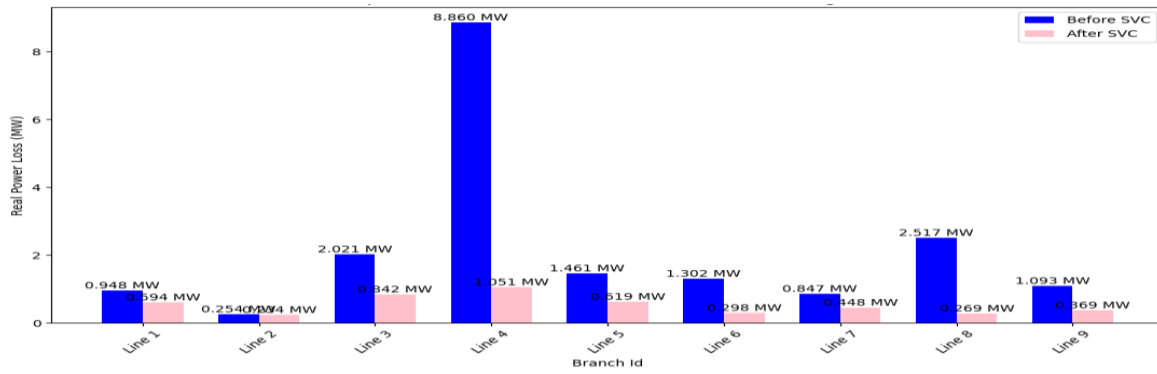


Figure 15: Comparative Bar Chart Illustrating Active Power Loss on Akure 33kV Feeders with and Without SVC Integration

Figure 15 is a comparative bar illustrating the of the real power losses along the transmission branches before and after the installation of the SVC. The results show a significant reduction in active power losses across most feeders in the improved network.

In the base-case condition without compensation, the highest loss was recorded on Line 4 (Akure Main feeder) with 8.86 MW, indicating severe corridor stress and inefficient power transfer. Other notable losses occurred along Line 3 (2.021 MW), Line 8 (2.517 MW), and Line 6 (1.302 MW). These high loss values are attributed to excessive line current, high reactive power flow, and feeder overloading.

After SVC installation, the losses along these critical feeders decreased substantially. The loss on Line 4 reduced to 0.594 MW, representing a major improvement in transmission efficiency along the

Akure Main corridor. Losses on Lines 3 and 8 also decreased to 0.408 MW and 0.619 MW, respectively, while other feeders recorded moderate reductions. The overall decline in active power loss indicates improved voltage support, reduced line current magnitude, and enhanced reactive power compensation. Although a slight increase in losses occurred on a few low-loading branches, the total network losses were significantly reduced, confirming that the SVC redistributed power flow and minimized technical loss accumulation along highly stressed feeders.

The reduction in active power losses after SVC installation is similar to what was reported in earlier studies where FACTS devices were used to reduce transmission line losses and improve power flow efficiency. Researchers such as [21][22][12] found that SVCs help to reduce line current and  $I^2R$  losses

*L. Bus Voltage and Real power losses Summary.*

Table 5: Bus Voltage Magnitude Before and After SVC integration

S/N	FEEDER NAME	VOLTAGE BEFORE SVC (KV)	VOLTAGE AFTER SVC (KV)	NOMINAL VOLTAGE	IMPROVEMENT (KV)	% IMPROVEMENT
1	FMPI Feeder	31.95	32.39	33	0.44	1.36
2	OWO Feeder	32.18	32.51	33	0.33	1.02
3	IJU Feeder	31.67	32.35	33	0.68	2.10
4	Akure Main Feeder	30.12	32.57	33	2.45	7.52
5	Elizade Feeder	32.09	32.46	33	0.37	1.14
6	FUTA Feeder	32.03	32.56	33	0.53	1.63
7	Oba-Ile Feeder	32.3	32.52	33	0.22	0.68
8	Owena Feeder	31.19	32.34	33	1.15	3.56

9	Igba-Oke Feeder	31.78	32.3	33	0.52	1.61
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Table 5 is the summary of the voltage before and after introduction of SVC. It is a summary of voltage improvement at a glance. It clearly shows improvement in the Bus voltage magnitude after SVC introduction.

Table 6 presents the Real Power Losses Before and After SVC Penetration

Table 6: Real Power Losses Before and After SVC Penetration

BRANCH ID	FROM	TO	LOSSES	LOSSES	POWER LOSS REDUCTION	%
			BEFORE SVC (MW)	AFTER SVC (MW)	SVC <sub>B</sub> -SVC <sub>A</sub> (MW)	
T1	Bus1	Bus2	0.958	0.719	0.239	24.95
T2	Bus1	Bus3	0.409	0.397	0.012	2.93
T3	Bus1	Bus4	0.408	0.382	0.026	6.81
Line 1	Bus2	FMPI-FDR	0.948	0.594	0.354	37.34
Line 2	Bus2	OWO-FDR	0.254	0.234	0.02	7.87
Line 3	Bus2	IJU-FDR	2.021	0.842	1.179	58.34
Line 4	Bus2	AKURE-MAIN FDR	8.86	1.051	7.809	88.14
Line 5	Bus3	ELIZADE-FDR	1.461	0.619	0.842	57.63
Line 6	Bus3	FUTA-FDR	1.302	0.298	1.004	77.11
Line 7	Bus3	OBA-ILE-FDR	0.847	0.448	0.399	47.11
Line 8	Bus4	OWENA-FDR	2.517	0.268	2.249	89.35
Line 9	Bus4	IGBA-OKE-FDR	1.093	0.369	0.724	66.24

Table 6 is the summary of power losses before and after the introduction of SVC.

It shows reduction of real power losses after SVC introduction to the bus ranges from 2.93% to 89.35.1%

## VI. CONCLUSION

The effectiveness of an optimally sized Static VAR Compensator (SVC), as a Flexible AC Transmission System (FACTS) device, for mitigating power losses and improving voltage performance in Akure 33 kV transmission feeders is established in this research work.

The following conclusions are listed below

- i. Introduction of SVC provided adequate voltage improvement from 0.68%, 32.52 kV, (minimum) to 7.52%, 32.57, (maximum) with Akure main 33 kV feeder recovering from 91.28% to 98.70% (above minimum standard of 94%, 31.02 kV).
- ii. All 33 kV feeders in this research work meet 94% of the required minimum standard.
- iii. The percentage power loss reduction ranges from 2.93% to 89.35% across all feeders.
- iv. The results provided clear quantitative evidence that SVC integration improved transmission

efficiency, mitigate losses, enhanced voltage magnitude.

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