

Optimal Placement Of Thyristor-Controlled Series Compensator [TCSC] In The 330kv Southern Nigerian Transmission Network Using Genetic Algorithm

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Abstract—This study addresses power flow congestion issues in Nigeria's 330kV transmission system, which leads to reduced power flow, increased losses, and voltage instability. Using a model of the Nigerian transmission network and simulating it with Power System Analytical Tool [PSAT] in Matlab, I investigated the impact of Thyristor-Controlled Series Compensator [TCSC] Flexible AC Transmission System [FACTS] devices on power quality. A genetic algorithm optimization technique was employed to determine the optimal placement of TCSC, with a 5th degree polynomial objective function derived from curve fitting analysis. Simulation results show significant improvements in voltage profile [39%], active power flow [43.27%], reactive power flow [38.44%], and power losses {38.44% active, 48.31% reactive} when TCSC was placed on Benin TS- Onitsha TS transmission line. The study highlights the importance of optimal FACTS placement for maximizing power system performance.

1. Introduction

Power interruptions and failures remain major problems that act as impediments to economic growth in a country. These issues are primarily driven by the increasing demand for electricity, which is a result of the growing number of residential, commercial, and industrial consumers. Given the current rate of growth in electricity demand, the power system was originally designed to function under near-stable operating conditions (Adedokun, R. F., 2024).

The infrastructure of the power system has been considered as one of the most complex engineering systems ever designed. It is composed of three main subsystems: generation, transmission, and distribution. Both conventional and renewable energy sources are harnessed to generate power. Traditional generation consists of gas-based plants, thermal power plants and nuclear power plants. On the other hand, renewable energy sources used in the generation of electricity are solar photovoltaic (PV) panels, wind machinery, and hydroelectric energy plants (Babatunde et al., 2023).

The normal voltage output of the power generation units is between 250V to a maximum of 500V. Transformers then increase this voltage to a level between 330kV and 750kV, allowing for efficient long-range transmission. Afterwards, the voltage is lowered at different transmission substations using step-down transformers towards a level that would be applicable to end-users (Breyer et al., 2022).

In case the power flow is congested, it is common to find that replacing the affected properties is often expensive. The resolution of this traffic jam, which is linked to Flexible AC Transmission Systems (FACTS), can thus be the answer to this money-saving solution. (Chanchangi et al., 2023).

In this paper, the Thyristor-Controlled Series Capacitor (TCSC) is used to minimise the circuit power losses and also enhance power flow through the 330kV Nigerian power system. The case study in the analysis is the southern part of Nigeria's power system. With the Power System Analysis Toolbox (PSAT), the network is modelled, and the genetic algorithm is deployed to give the best positioning of the TCSC. The percentage of efficiency achieved in the performance of a power system is then compared and analysed with the known results that are available in other literature.

By 2005, the cumulative capacity in all the Power Holding Company of Nigeria (PHCN) stations totalled 6,656.40 MW, with an average available capacity of 3,736.55 MW, which translated to an availability factor of 56.13% (Olabode & Oluwabamise, 2022). This figure has declined over the years due to multiple factors, including the ageing of generating units.

One of the worrying problems with the Nigerian power system is age, together with poor maintenance of the transmission line systems. As an example, the Ikorodu-Ayede-Osogbo 132 kV line, which was built circa 1964, has remained poorly maintained in recent years. On the same note, we have the AkangbaOjo 132 kV line, which is a sign of bad maintenance. Moreover, some of the transmission lines are excessively long, and this results in a sharp drop in voltages. The Gombe-Maiduguri 132 kV transmission line is about 310 km long, and the New Haven-Oturkpo-Yandev 132 kV line has a length of 330 Km with the 20kV drop over the stretch New Haven-Yandev (Olusanya et al., 2024).

A further weakness lies in lack of redundancy or alternative transmission routes. The Benin–Onitsha–Alaoji 330 kV line, for instance, presents a single-line contingency risk. A fault on this line could have severe consequences. The same risk applies to the Aba–Itu 132 kV line, which supplies Aba, Itu, Calabar, and Eket. An outage on this line would affect all these areas simultaneously (Olusanya et al., 2018).

To mitigate such challenges, distributed generation (DG) is gaining traction. DG refers to electricity production from numerous small-scale energy sources, also called on-site or decentralised generation. While most industrialised nations rely on large, centralised power stations, DG offers a local, efficient alternative. By generating power near the point of use, DG reduces transmission losses and minimises the need for extensive power lines (Remy & Chattopadhyay, 2021).

Despite its advantages, such as low maintenance, reduced pollution, and high efficiency, DG adoption is hampered by high capital costs, with micro-hydropower being a notable exception (Rajesh et al., 2022). Since the mid-1980s, as competition has risen, utilities have increasingly adopted the premise that they should no longer be concerned with building large plants, but should focus instead on demand-side management (DSM) programs that will enhance energy efficiency (Shari & Moumouni, 2020).

The DG systems can be basic backup generators to complex grid-connected environments, which possess energy storage as well as energy control and waste. DG can be utilised when combined with the central grid, mainly during peak demand, and increase resilience to the grid when implemented correctly (Tambari et al., 2020; Ugwoke et al., 2020).

Besides, interconnected distributed energy resources (DERs) are capable of giving useful functions, including control of voltages, improving the power, neighbourhood emergency power supply, and the capability of purchasing surplus energy to the grid (Xianyong & Zixuan, 2022). DERs are most often modular systems of between 3 to 50MW in capacity that are in close vicinity to the end user to enhance reliability and efficiency (Yetano et al., 2020).

2.1 Flexible AC Transmission Systems (FACTS): An Overview

The general increased demand for energy in Nigeria, both because of the development of technology and the increase in population (Zhang et al., 2022), also needs an upgrade and modernisation of the power infrastructure. Nevertheless, unique load characteristics, especially due to inductive load, such as induction motor, principally used within the residential and industrial sectors, adversely affect power grid frequency dynamic response and voltage profile stability (Yuguda et al., 2023).

In order to cope with these issues and enhance the operation of systems, modern solutions, which demand the application of Flexible Alternating Current Transmission Systems (FACTS), have been suggested. FACTS are power electronics units introduced in the electrical framework to regulate the power flow and increase the possibilities of the AC systems to convey the power. They improve voltage regulation, transient stability, reliability and thermal loading capacity of transmission lines when they are pumped.

Prior to power electronics, the power flow regulation was done by switching mechanical devices like capacitors, reactors, and synchronous generating devices. These traditional methods suffered from slow response times and mechanical wear. The advent of high-voltage power electronic switches, particularly thyristors, enabled the development of FACTS controllers capable of fast and precise network control (Yohanandhan et al., 2022).

Given the real-time nature of electric power systems—where electricity is generated and delivered instantly—coordination between supply and demand is crucial. As demand escalates, optimizing every component of the system becomes imperative (Yetano et al., 2020). The balance between capacitive and inductive reactive power is an important constituent of system stability, which can be achieved by suitable compensation methods (Ugwuanyi et al., 2024).

A classification is made based on FACTS devices by elimination of connection type and purpose, often as series compensators or shunt compensators (Tambari et al., 2020; Shari & Moumouni, 2020):

- i. Series Compensators: Some devices are used in series with transmission lines to boost the available transfer capability (ATC). They also decrease the phase difference between current and voltage and it increases stability and power transfer. (Refer to Figure 2.7 for a schematic representation of a series compensated transmission line.)

Other types of FACTS controllers include:

- ii. Shunt Compensators (e.g., SVC – Static Var Compensator, STATCOM)
- iii. Unified Power Flow Controllers (UPFC)
- iv. Thyristor Controlled Series Capacitors (TCSC)

The implementation of FACTS in the grid offers more control, quicker response, better power quality, thus a stable and efficient system of power.

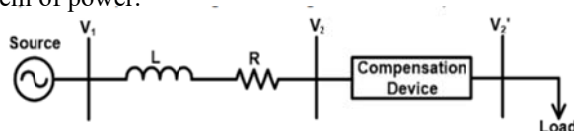


Figure 2.1: Line diagram of series compensator (Remy & Chattopadhyay, 2021)

Shunt Compensator

Shunt compensation methods are used on overloaded transmission networks to maintain voltage levels by injecting or absorbing reactive power as required. The reactive power requirement in a transmission line is affected by the capacitance of the line. Once the demand for reactive power exceeds the limit, especially during heavy loads, the voltage at the receiving line terminals drops tremendously. To ameliorate the same, capacitor banks are placed in shunt at the receiving end to increase the voltage and stabilise the voltage at the receiving end.

On the other hand, with light loads, the reactive power delivered by the line can be too much, which means an increase in voltage and results in an imbalance between the sending and receiving end voltages. When it happens, a shunt reactor is introduced to the system to absorb any excess reactive power, thus preventing the voltage from exceeding safe levels.

A shunt-compensated power system network provides voltage support, improves **power factor**, and enhances **system stability**. Figure 2.8 indicates the schematic representation of a shunt-compensated transmission line.

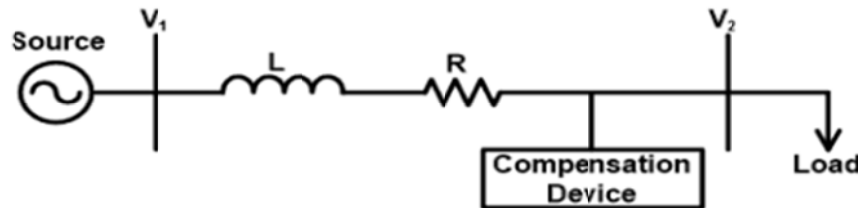


Figure 2.2: Shunt Compensator Line diagram (Remy & Chattopadhyay, 2021)

3.1 Materials

The study used as its materials mainly simulation and software applications, that is:

- i. The determination of power flow of the power system network was done using PSAT.
- ii. MATLAB was used for the optimum FACTS placement determination, generation of graphs and charts, where necessary.
- iii. Microsoft Excel: This application was used in the arrangement of the data.
- iv. Microsoft Word: used for the arrangement of the study.

3.2 Methods

This section describes the patterns and the processes that were followed to upgrade the 330kV power system network in Nigeria, such as the study procedure that was followed and the end game, which was the most suitable location of FACTS.

3.2.1 Research Procedure

Chronic bottlenecks in the Nigerian 330 kV transmission system caused a serious imbalance of power flow and a voltage profile shift component. Using Flexible AC Transmission Systems (FACTS), this research sliced transmission losses and reduced the efficiency of current and voltage signal transmission by the power quality, greatly boosting the stability and performance of the grid as a whole.

This study was conducted in the region of the southern part of the Nigerian power network. In a bid to have an improvement in power transfer, the Thyristor Controlled Series Capacitor (TCSC) was established as the FACTS device to be added to the system.

Modelling of the power system was carried out using the Power System Analysis Toolbox (PSAT), whereby both without the application of FACTS and with FACTS were simulated. Comparison of power flows studies was also carried out to appreciate, how the system works under condition one and two.

In order to find the best place to install the TCSC, we used a Genetic Algorithm (GA) optimisation tool to find the optimal spot where the FACTS equipment should be installed in the network.

The whole modelling process and the results are detailed in the following sections, whereas the results analysis will be given in Chapter Four. As Figure 3.1 shows, an overview of the workflow of the research is depicted.

3.2.4 Power System Network Modelling

The process of the power system model took the first step by starting the Power System Analysis Toolbox (PSAT) environment. This gave the basis for simulating the system under investigation. Figure 3.4 provides a pictorial depiction of the PSAT interface.

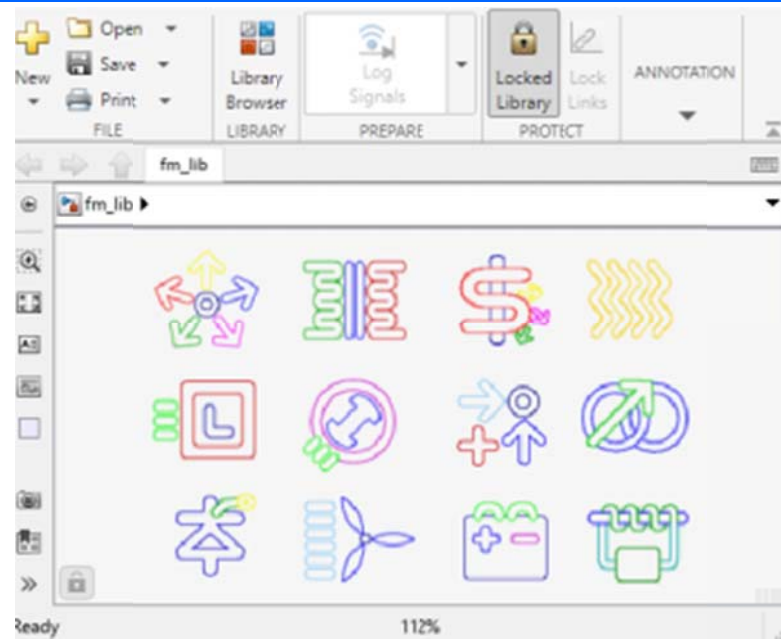


Figure 3.4: PSAT Modelling Environment



Figure 3.5: Modelled 330 kV Network Without FACTS Integration

The next step, after the introduction of the PSAT application, was putting together the different parts of the power system and connecting them. These components were configured by the schematic layout previously illustrated in Figure 3.3. The resulting environment, where the system elements were placed and configured, is displayed in Figure 3.4

The complete 330 kV transmission network model representing the southern region of Nigeria is shown in Figure 3.5. In this model, the reference bus was designated at the Egbin Transmission Station (TS). This location was chosen due to its strategic significance and the anticipated impact of its performance on the wider grid.

Within the modelled network, seven stations functioned as generation stations, while the remaining nodes were transmission and load stations, all accurately represented in the simulation. The network has the major components connected like the transmission lines, generating units, and load centres.

To have a better view and analysis, Figure 3.5 has been subdivided into Figure 3.5a and Figure 3.5b, each displaying different sections of the full network.

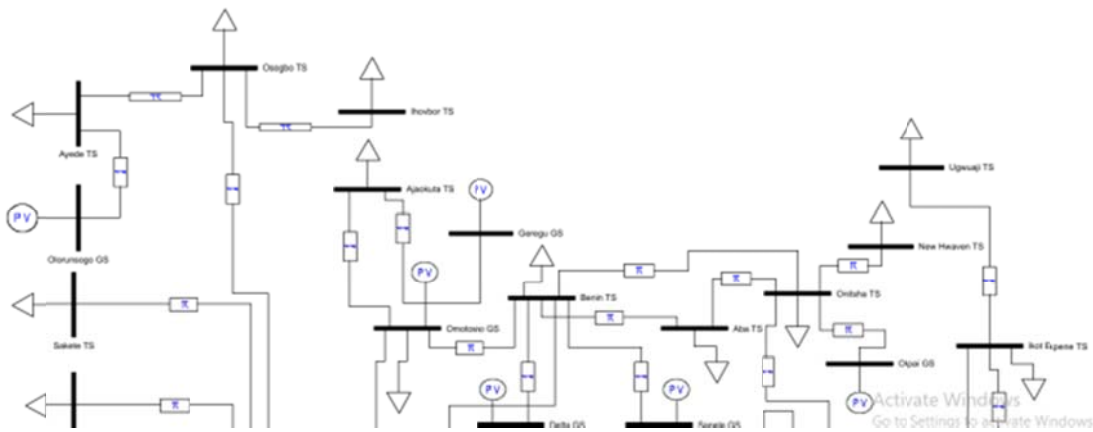


Figure 3.5a: Part of the power system network

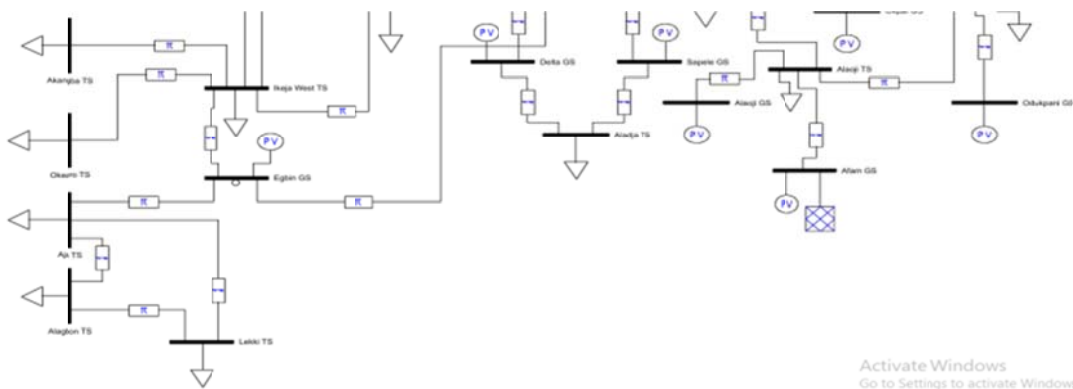


Figure 3.5b section 2 of the power system network model in PSAT

Figure 3.6 indicates the power system model that includes the TCSC.

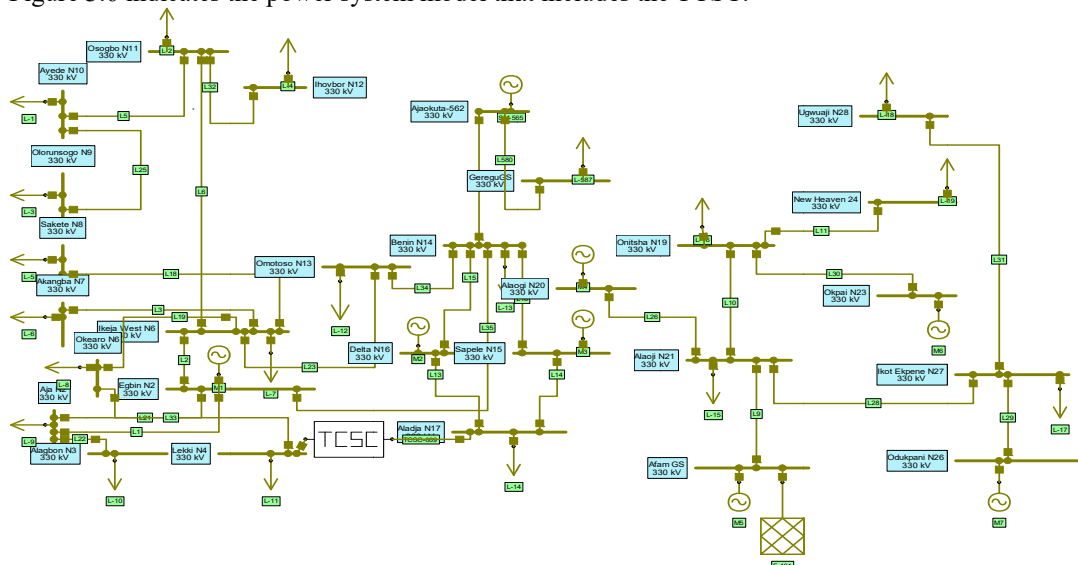


Figure 3.6: Power system network model with TCSC

Strategy Series FACTS device- The Thyristor Controlled Series Capacitor (TCSC) it was installed in strategic position on the transmission of a pair of the buses in the network. Its placement was carried out between two stations (buses) situated at an optimal distance along the transmission path. To ensure that the TCSC device delivered maximum improvement in power quality, it was essential to first determine the optimal location for installation. This preliminary step helped in achieving effective compensation and enhanced system performance on the selected transmission line.

3.2.5 Optimal FACTS Placement Using Genetic Algorithm

To determine the most effective location for deploying the FACTS device, a Genetic Algorithm (GA) optimisation method was employed. This procedure started by calculating cumulative sum of the transmission lines. The shortest path transmission line was identified and chosen to be analysed.

For the placement strategy, the FACTS device was positioned at equal intervals along the identified transmission segment. A linear mathematical model was drafted then to indicate the correlation between the line distance (D) and the actual power flow (PF). This relationship is described by Equation (3.1):

$$PF = \sum_{i=0}^n a_i D_i^n$$

Equation (3.1)

Where: PF = Real Power Flow, D = Distance of the transmission line segment (in km) and a_i = Coefficient associated with each distance segment, calculated using the Least Squares Method in MATLAB. The flow chart presented below in Figure 3.7 depicts the entire optimisation procedure of using GA in order to place FACTS.

RESULTS AND DISCUSSION

4.1 Results of the Power Flow analysis without FACTS

Table 4.1 Voltage profile of power system network without TCSC

Bus location	Voltage profile (pu)
1	0.9870
2	0.7707
3	0.7906
4	0.8202
5	0.8653
6	0.8661
7	0.7773
8	0.8668
9	0.8653
10	0.8134
11	0.8480
12	0.7756
13	0.8064
14	0.8607
15	0.8471
16	0.8655
17	0.8321
18	0.7639
19	0.8534
20	0.8627
21	0.8347
22	0.8434
23	0.8417
24	0.8031
25	0.8321
26	0.7788
27	0.8377
28	0.7635

The power system network comprised 28 buses, which were divided into two sections to enhance clarity in analysis and presentation. Section 1 included buses 1 to 14, while Section 2 included buses 15 to 28. Figure 4.1 shows the voltage profile bar chart of Section 1 of the network.

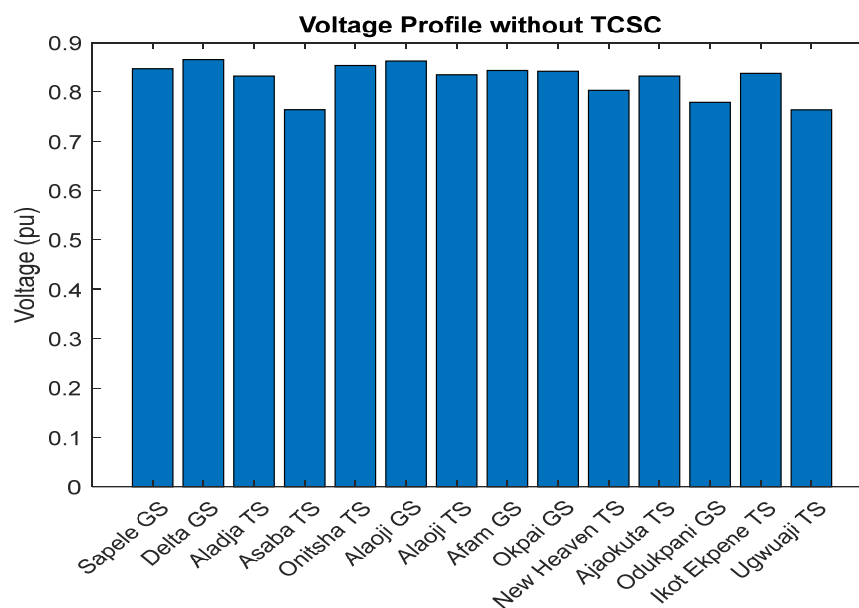


Figure 4.1: Voltage profile for section 1

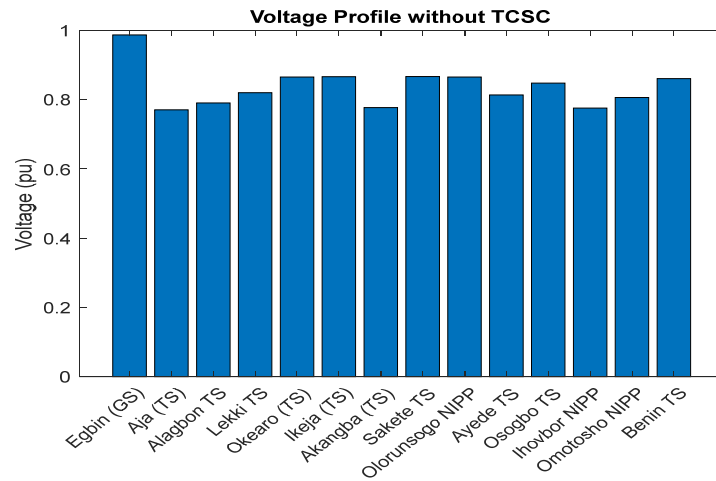


Figure 4.2: Voltage profile for section 2

Table 4.2: Power flow analysis of the system without TCSC

Transmission line number	Power flow (pu)		Power loss (pu)	
	Active flow	Reactive flow	Active loss	Reactive loss
1	1.4059	2.2329	0.0824	0.3067
2	1.0605	2.2533	0.1073	0.3316
3	1.2343	2.3502	0.0817	0.3445
4	1.1107	2.4272	0.0829	0.4174
5	1.1749	2.0387	0.1009	0.3019
6	1.2343	2.2015	0.0839	0.3998
7	1.4223	2.6969	0.1127	0.3703
8	1.0326	1.9869	0.1127	0.3327
9	1.9369	2.8145	0.1089	0.3067
10	1.9815	2.6319	0.0860	0.3400
11	1.5003	2.4095	0.1064	0.3475
12	1.4986	2.4922	0.1007	0.2969
13	1.3380	2.1783	0.1189	0.3625
14	1.9341	2.3821	0.1060	0.3117
15	1.3714	2.8460	0.1120	0.3338
16	1.0979	2.4631	0.0982	0.3616
17	1.8071	2.4394	0.0973	0.3153
18	1.3931	2.1731	0.1130	0.3207
19	1.2362	2.4098	0.0833	0.3664
20	1.4081	2.5341	0.0853	0.3171
21	1.0822	2.5848	0.0869	0.3954
22	1.1199	2.3239	0.0956	0.4176
23	1.9786	2.2980	0.1133	0.3822
24	1.9935	2.8689	0.1121	0.3281
25	1.5897	1.9947	0.0824	0.3618
26	1.0434	2.7744	0.0960	0.2951
27	1.2289	2.8002	0.1011	0.4069
28	1.3543	2.6925	0.0967	0.4032
29	1.8505	2.0508	0.1063	0.3945
30	0.9963	2.2009	0.1051	0.3165
31	1.0256	2.2685	0.0917	0.3632
32	1.1591	2.5853	0.0973	0.2832

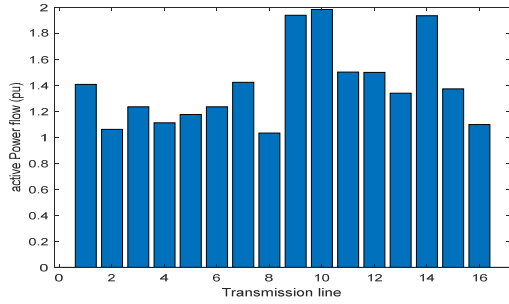


Figure 4.3 displays the active power flow of section 1.

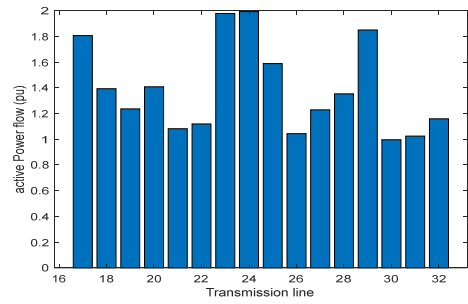


Figure 4.4: Active power flow for section 2

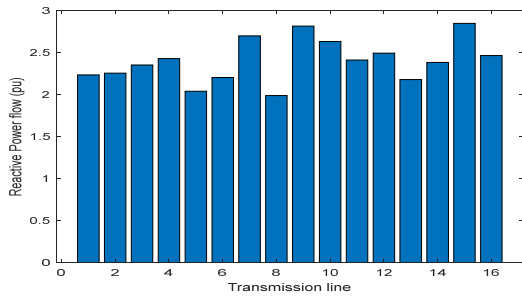


Figure 4.5: Reactive power flow for section 1

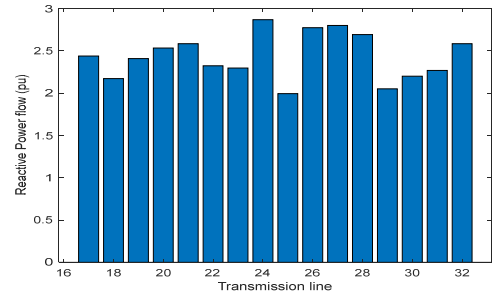


Figure 4.6: Reactive power flow for section 2

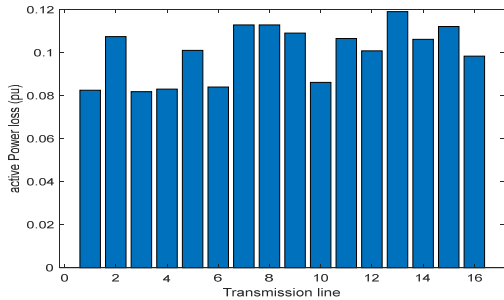


Figure 4.7: Active power loss for section 1

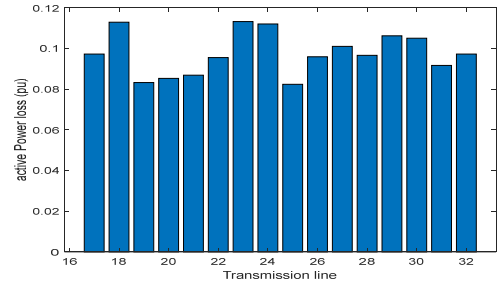


Figure 4.8: Active power loss for section 2

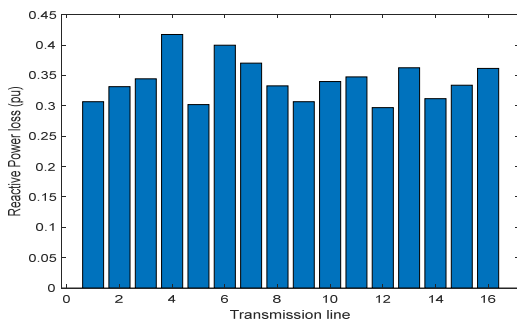


Figure 4.9: Loss of reactive power in Section 1

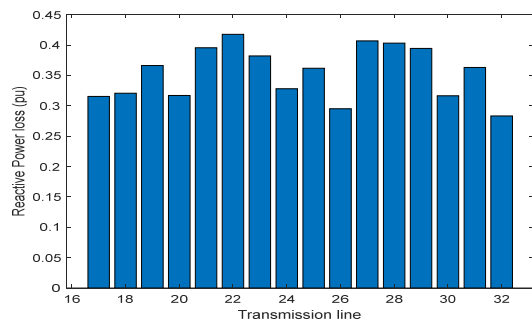


Figure 4.10: Active power loss for section 2

4.1.2 Results of the Power Flow analysis with TCSC FACTS
 Table 4.3 shows the result of voltage profile.

Table 4.3: Voltage profile of the power system network with TCSC

Bus location	Voltage profile (pu)
1	1.0000
2	0.9423
3	0.9449
4	0.9812
5	0.9747
6	0.9559
7	0.9875
8	0.9417
9	0.9619
10	0.9591
11	0.9783
12	0.9798
13	0.9493
14	0.9645
15	0.9623
16	0.9723
17	0.9755
18	0.9777
19	0.9538
20	0.9740
21	0.9728
22	0.9481
23	0.9459
24	0.9649
25	0.9880
26	0.9570
27	0.9693
28	0.9512

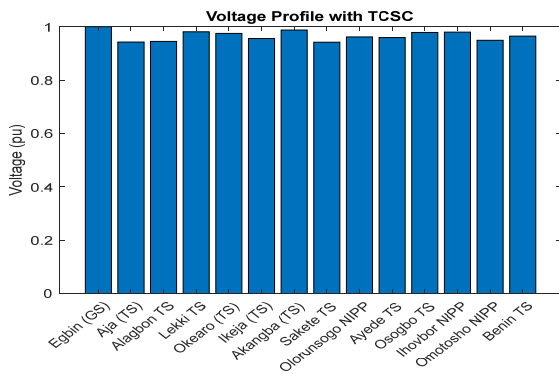


Figure 4.11: Voltage profile for section 1

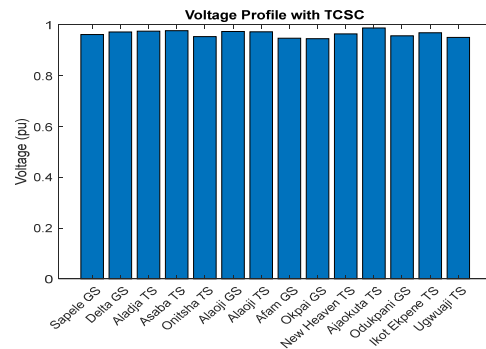


Figure 4.12: Voltage profile for section 2

Table 4.4: Power flow analysis of the system with TCSC

Transmissi on line number	Power flow (pu)		Power loss (pu)	
	Active flow	Reactive flow	Active loss	Reactiv e loss
1	3.6681	3.3587	0.0205	0.0970
2	3.7556	5.0660	0.0495	0.0925
3	3.6666	3.2717	0.0250	0.0865
4	3.4580	4.8690	0.0232	0.0872
5	3.5598	4.4030	0.0312	0.0969
6	3.2941	5.2348	0.0259	0.0838
7	3.7694	5.0479	0.0347	0.1039
8	3.1803	5.5989	0.0302	0.0988
9	3.7080	5.5615	0.0485	0.1078
10	3.1745	3.9358	0.0476	0.1080
11	3.3706	5.0003	0.0216	0.1055
12	3.6432	3.5376	0.0421	0.0813
13	3.8070	3.0492	0.0281	0.0828
14	3.0660	5.1327	0.0327	0.0928
15	3.9651	4.4201	0.0364	0.1012
16	3.8023	4.3614	0.0483	0.1062
17	3.4960	5.6018	0.0325	0.0963
18	3.4420	4.7408	0.0495	0.1128
19	3.4536	4.7636	0.0290	0.1087
20	3.3047	5.4696	0.0410	0.1187
21	3.5190	5.3120	0.0400	0.1013
22	3.5214	4.6440	0.0362	0.0930
23	3.8467	3.4941	0.0409	0.0842
24	3.8225	3.6606	0.0400	0.1044
25	3.6630	5.5486	0.0253	0.1112
26	3.3813	3.0437	0.0238	0.0969
27	3.8403	4.3905	0.0500	0.0836
28	3.5448	3.4503	0.0251	0.0907
29	3.3518	5.8177	0.0210	0.0861
30	3.9753	5.0411	0.0368	0.0912
31	3.9085	4.4214	0.0465	0.0976
32	3.5632	4.3356	0.0401	0.1011

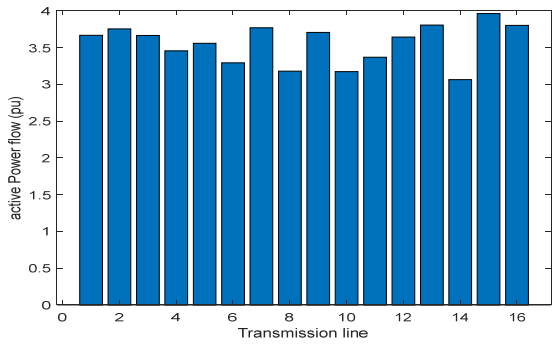


Figure 4.13: Active power flow for section 1

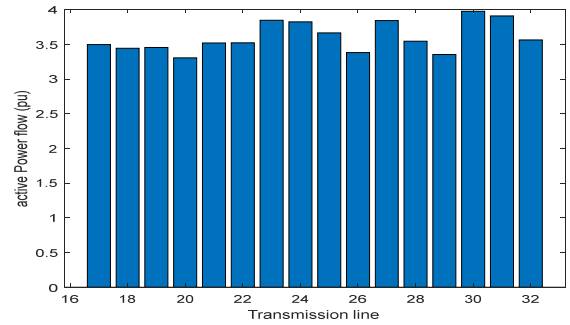


Figure 4.14: Active power flow for section 2

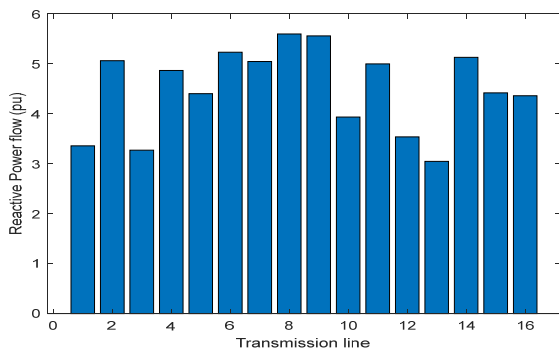


Figure 4.15: Reactive power flow for section 1

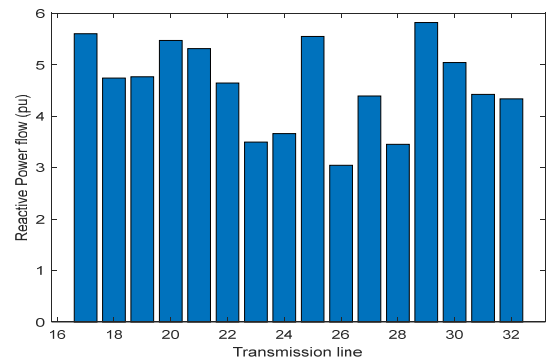


Figure 4.16: Reactive power flow for section 2

The active power loss for section 1 was shown in Figure 4.17.

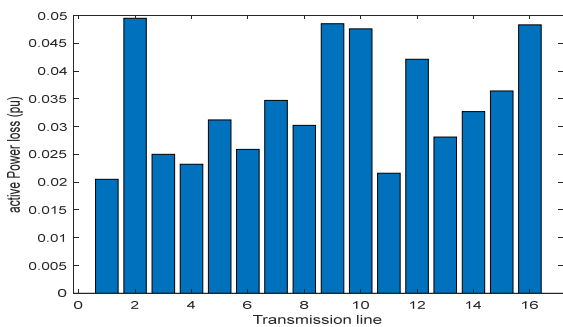


Figure 4.17: Active power loss for section 1

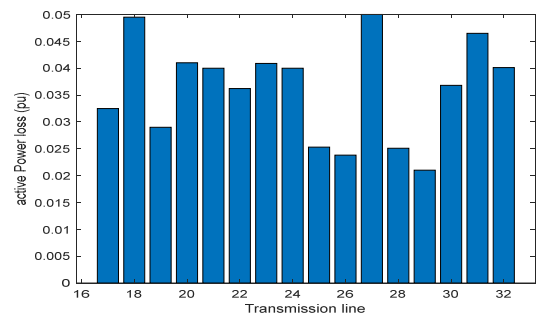


Figure 4.18: Active power loss for section 2

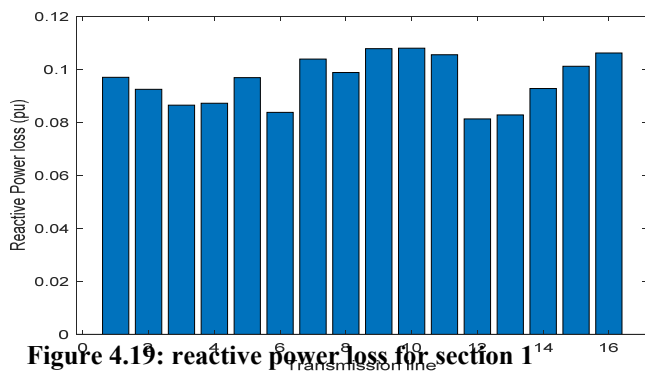


Figure 4.19: reactive power loss for section 1

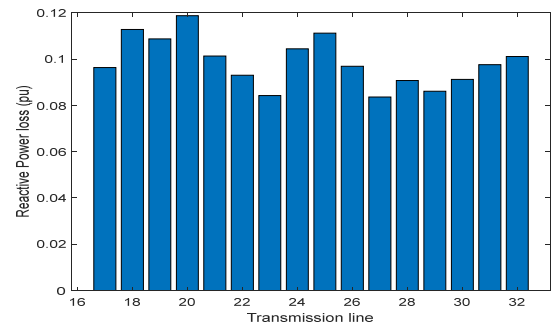


Figure 4.20: Reactive power loss for section 2

The active power flow for section 1 was shown in Figure 4.24.

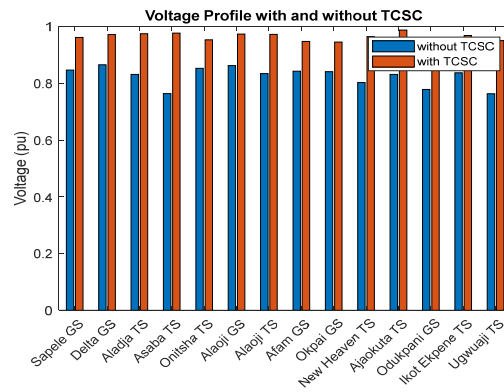


Figure 4.23: Voltage profile for section 2

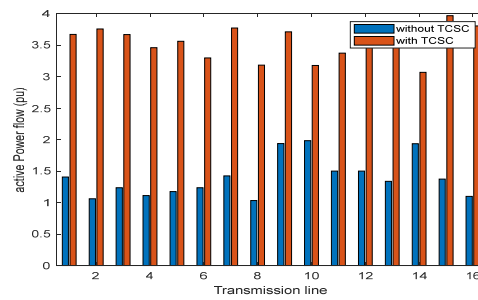


Figure 4.24: Active power flow for section 1

Figure 4.24 had a comparative analysis of the active power flow of the system with and without the TCSC FACTS for section 1. It was observed that the introduction of FACTS improved the active flow of the system due to power flow congestion reduction. The active power flow for section 2 was shown in Figure 4.25.

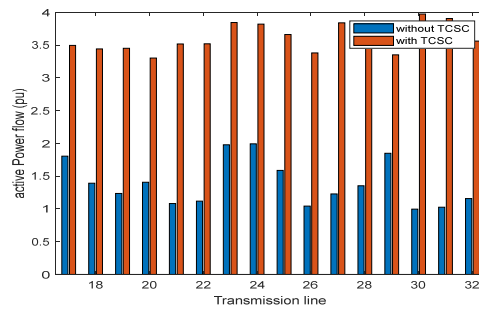


Figure 4.25: Active power flow for section 2

Figure 4.25 had a comparative analysis of the active power flow of the system with and without the TCSC FACTS for section 2. It was observed that the introduction of FACTS improved the active flow of the system due to power flow congestion reduction.

The reactive power flow for section 1 was shown in Figure 4.26.

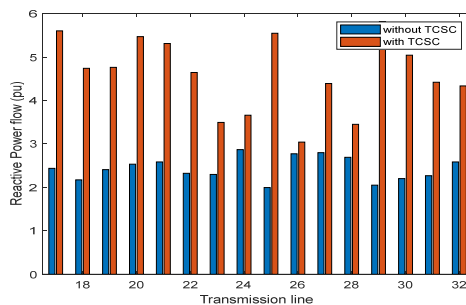


Figure 4.26: Reactive power flow for section 1

Figure 4.26 had a comparative analysis of the reactive power flow of the system with and without the TCSC FACTS for section 1. It was observed that the introduction of FACTS improved the reactive flow of the system due to power flow congestion reduction.

The reactive power flow for section 2 was shown in Figure 4.27.

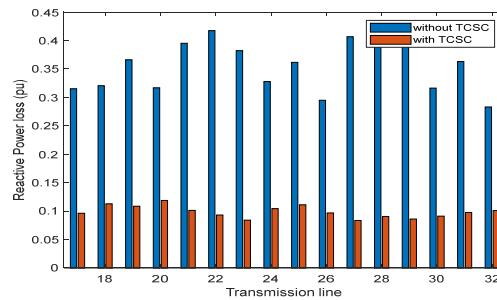


Figure 4.27: Reactive power flow for section 2

Figure 4.27 had a comparative analysis of the reactive power flow of the system with and without the TCSC FACTS for section 2. It was observed that the introduction of FACTS improved the reactive flow of the system due to power flow congestion reduction. The active power loss for section 1 was shown in Figure 4.28.

Figure 4.28 had a comparative analysis of the active power loss of the system with and without the TCSC FACTS for section 1. It was observed that the introduction of FACTS improved the active loss of the system due to power flow congestion reduction.

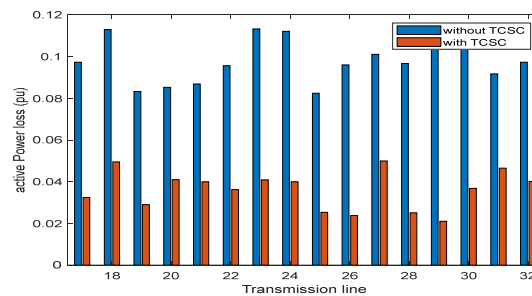


Figure 4.28: Active power loss for section 1

The active power loss for section 2 was shown in Figure 4.29.

Figure 4.29 shows a comparative analysis of the active power loss of the system with and without the TCSC FACTS for section 2. It was observed that the introduction of FACTS improved the active loss of the system due to power flow congestion reduction.

The reactive power loss for section 1 was shown in Figure 4.30.

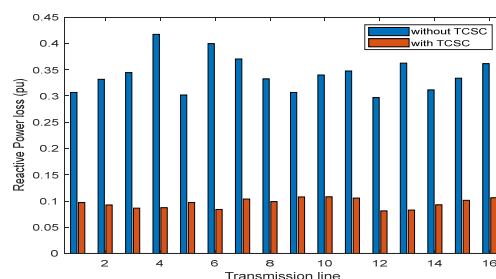
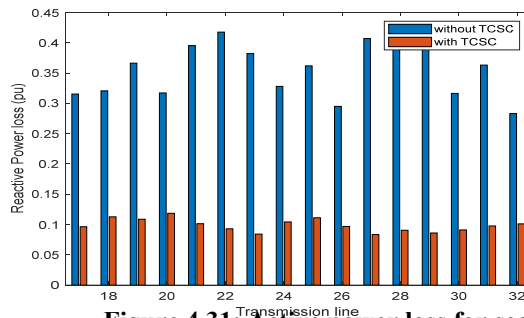


Figure 4.29: Active power loss for section 2

Figure 4.30: reactive power loss for section 1

Figure 4.30 had a comparative analysis of the reactive power loss of the system with and without the TCSC FACTS for section 1. It was observed that the introduction of FACTS improved the reactive loss of the system due to power flow congestion reduction.

**Figure 4.31: Active power loss for section 2**

The reactive power loss for section 2 was shown in Figure 4.31.

Figure 4.31 shows a comparative analysis of the reactive power loss of the system with and without the TCSC FACTS for section 2. It was observed that the introduction of FACTS improved the reactive loss of the system due to power flow congestion reduction.

4.2 Discussion of Results

To manage the complexity of the system, which consisted of 28 buses and 32 transmission lines, the data was divided into two sections for ease of analysis. Each section included 14 buses and 16 transmission lines. This segmentation allowed for clearer visualization and interpretation of the system's performance under different scenarios.

Table 4.1 presents the initial voltage data for the entire network, while Figures 4.1 and 4.2 display bar charts representing the voltage profile without TCSC, segmented into Section 1 and Section 2, respectively. In Figure 4.1, only the slack bus (Egbin TS) maintained a voltage within the acceptable tolerance range of 0.95 to 1.05 pu. All other buses recorded substandard voltage levels due to transmission line congestion. Figure 4.2 further illustrates the issue, as none of the buses exhibited voltage above 0.9 pu, indicating significant voltage instability in the system.

The results of the power flow analysis, including real and reactive power flows as well as active and reactive power losses, are presented in Table 4.2. Figures 4.3 and 4.4, show the real (active) power flow for Sections 1 and 2, respectively. No transmission line exceeded a flow of 2.0 pu, suggesting restricted power transfer due to high congestion. Figures 4.5 and 4.6 display the reactive power flow across the same sections. Again, no line exceeded 3.0 pu, reinforcing the presence of reactive power limitations.

The active and reactive power losses in the network without TCSC were found to be significantly high: Figures 4.7 and 4.8 illustrate the active power losses for Section 1 and Section 2, respectively. Losses in several lines exceeded 0.11 pu, highlighting inefficiencies. Figures 4.9 and 4.10 show reactive power losses, with some values surpassing 0.4 pu, indicating a risk of system instability and potential power outages if not mitigated.

After introducing TCSC into the network at the optimal location, the voltage profiles improved markedly: Figure 4.11 shows the voltage profile for Section 1, and Figure 4.12 for Section 2. In both cases, all buses fell within the normal range of 0.95 to 1.00 pu, demonstrating the effectiveness of TCSC in stabilising voltage levels.

The inclusion of the TCSC led to a significant improvement in both active and reactive power flow: Figures 4.13 and

4.14 Show that real power flow increased to 3.92 pu and 3.987 pu in Sections 1 and 2, respectively.

Figures 4.15 and 4.16 indicate reactive power flow rose to 5.33 pu and 5.71 pu, respectively, an enhancement over the initial low-flow conditions.

Power losses were notably reduced following TCSC integration. Figures 4.17 and 4.18 show that the active power losses decreased to 0.0478 pu and 0.05 pu in Sections 1 and 2, Figures 4.19 and 4.20 show that the reactive power losses were significantly reduced to 0.011 pu and 0.0119 pu, respectively, confirming the improved efficiency of the transmission system.

4.3 Optimisation Results and Comparative Analysis

The optimal polynomial order used as the objective function in the Genetic Algorithm (GA) was a fifth-order polynomial, yielding an R-square value of 93.3%, as shown in Table 4.5. This high accuracy confirmed the model's suitability for optimisation.

The GA identified the transmission line between Benin TS and Onitsha TS as the optimal placement for the TCSC device. A comprehensive comparative analysis (see Table 4.8) demonstrated that the strategic location and integration of TCSC significantly improved the voltage profiles, active and reactive power flow and reduction in power losses.

These improvements affirm the efficacy of TCSC in enhancing power quality and system stability within the Nigerian 330 kV transmission network.

Table 4.6: Power flow improvement achieved with TCSC

Power flow diagram	Values (%)
Voltage	39
Active power flow	43.27
Reactive power flow	49.12
Active losses	38.44
Reactive losses	48.31

Based on the comparative analysis conducted and the data presented in Table 4.8, the integration of the Thyristor Controlled Series Capacitor (TCSC) demonstrated a clear enhancement in power system performance. The results indicated a significant improvement in voltage profiles, as illustrated in Figures 4.22 and 4.23 for Sections 1 and 2, respectively. In addition, the implementation of TCSC led to better power flow and a notable reduction in power losses across the transmission network.

In continuation, a comparative assessment was also performed between the power active loss reduction achieved in this study and those reported in existing literature. The outcomes of this evaluation are compiled and presented in Table 4.9.

Table 4.7: Comparative analysis between the research and the literature reviewed.

Author (year)	% active power loss reduced
The research (2025)	38.44
Minale Birlie Bizumen (2022)	18
Fabrice Nyanyu Shimwa (2021)	12
Getnet Baye Demeke (2019)	22.5

The level of improvement achieved in this research can be attributed to the procedure followed in the determination of the optimal location for the TCSC allocation, which was a contribution to the knowledge of the research.

5. Conclusion

One of the key factors contributing to recurring blackouts in Nigeria's power system is the issue of power flow congestion within the 330 kV transmission network. To address this challenge, real-world operational data was collected from the National Control Centre in Osogbo. This included a detailed line diagram and associated bus data, which was then modelled in PSAT.

Through this modelling, power flow analysis was conducted to identify areas of instability. Using MATLAB's CFtool, a fifth-order polynomial ($R^2 = 93\%$) was developed to serve as the objective function for GA-based optimisation. The Benin TS–Onitsha TS line was identified as the optimal location for the TCSC installation.

The implementation of TCSC resulted in measurable improvements of voltage profile, improved by 39%, active power flow increased by 43.27%, reactive power flow increased by 38.44%, active power losses reduced by 38.44%, and reactive power losses reduced by 48.31%.

The analysis of this paper shows that adding TCSC FACTS devices in the best positions will greatly improve the performance of the power system.

REFERENCES

- Adedokun, R. F. (2024). *A roadmap for energy transition strategic planning and governance: a case study of Nigeria's grid-based renewable electricity sector* (Doctoral dissertation).
- Babatunde, O., Buraimoh, E., Tinuoye, O., Ayegbusi, C., Davidson, I., & Ighravwe, D. E. (2023). Electricity sector assessment in Nigeria: the post-liberation era. *Cogent Engineering*, *10*(1), 2157536.
- Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A.S., Aghahosseini, A., Gulagi, A., Solomon, A.A., Keiner, D., Lopez, G. and Østergaard, P.A., (2022). On the history and future of 100% renewable energy systems research. *IEEE Access*, *10*, pp.78176 78218.
- Chanchangi, Y. N., Adu, F., Ghosh, A., Sundaram, S., & Mallick, T. K. (2023). Nigeria's energy review: Focusing on solar energy potential and penetration. *Environment, Development and Sustainability*, *25*(7), 5755-5796.
- Olubode, A. T., & Oluwabamise, A. A. (2022). Electricity demand pattern and supply availability on Nigeria grid system. *Journal of Applied Science & Process Engineering*, *9*(1).
- Olusanya, O., Onokwai, A. O., & Oyebisi, R. O. (2024). Medium Term Load Forecasting of 33 Kv Line Loading: A Case Study Of Ota 132/33 Kv Sub-Station Ogun State, Nigeria. *Nigerian Journal of Technology*, *43*(4).

8. Olusanya, S.O., Babalola, O.P., Nwanya, S.C., Kilanko, O., Leramo, R.O., Aworinde, A.K., Adekeye, T., Oyebanji, J.A., Abidakun, A.O. and Agberegha, O.L.(2018). Towards a sustainable electricity supply in nigeria: the role of decentralized renewable energy system. *European Journal of Sustainable development research*, 2(4), p.40.
9. Remy, T., &Chattopadhyay, D. (2021). Enhancing dispatch efficiency of the Nigerian power system: Assessment of benefits. *Energy for Sustainable Development*, 62, 29-43.
10. Shari, B. E., & Moumouni, Y. (2020).A system dynamics modelling for energy planning and carbon dioxide estimation of the Nigerian power sector. *International Journal of Energy Technology and Policy*, 16(5-6), 470-492.
11. Tambari, I. T., Dioha, M. O., &Failler, P. (2020). Renewable energy scenarios for sustainable electricity supply in Nigeria. *Energy and Climate Change*, 1, 100017.
12. Ugwuanyi, N. S., Ozioko, I. O., Uma, U. U., Nwogu, O. A., Ugwuoke, N. C., Ekwue, A. O., &Nwokocha, N. (2024). Enhancing Renewable Energy-Grid Integration by Optimally Placed FACTS Devices: The Nigeria Case Study. *Science Journal of Energy Engineering*, 10(6), 16-25.
13. Yetano Roche, M., Verolme, H., Agbaegbu, C., Binnington, T., Fishedick, M., &Oladipo, E.O. (2020).Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways. *Climate Policy*, 20(7), 846-865.
14. Yohan and Han, R. V., Elavarasan, R. M., Pugazhendhi, R., Premkumar, M., Mihet-Popa, L., &Terzija, V. (2022). A holistic review on Cyber-Physical Power System (CPPS) testbeds for secure and sustainable electric power grid–Part–I: Background on CPPS
15. Yuguda, T. K., Imanche, S. A., Ze, T., Akintunde, T. Y., & Luka, B. S. (2023). Hydropower development, policy and partnership in the 21st century: A China-Nigeria outlook. *Energy & Environment*, 34(4), 1170-1204.
16. Zhang, Y., Shi, X., Zhang, H., Cao, Y., &Terzija, V. (2022). Review on deep learning applications in frequency analysis and control of modern power system. *International Journal of Electrical Power & Energy Systems*, 136, 107744.