Enhancing Bulk Power Transmission Efficiency in 330 kV Networks Using Thyristor Controlled Series Compensator (TCSC)

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Abstract
Power transmission efficiency is pivotal to the stability and reliability of any electrical grid. Nigeria's 330 kV transmission network is plagued by voltage violations and high technical losses exceeding acceptable thresholds. This study investigates the application of a Thyristor Controlled Series Compensator (TCSC) to mitigate these losses and improve operational efficiency. A 41-bus network representing Nigeria's transmission system was modeled using Power System Analysis Toolbox (PSAT) and MATLAB/Simulink. Load flow analysis was carried out using the Newton-Raphson method, and multiple sensitivity analysis was used to identify optimal placement of the TCSC. Results show a significant reduction in voltage violations—from 15 to 6 buses—and a 33% reduction in active power loss, validating the effectiveness of the TCSC integration. This study provides a cost-effective and scalable solution to power quality issues in the Nigerian grid.

Keywords: *TCSC, transmission line, technical losses, PSAT, 330 kV network, FACTS devices, load flow analysis*

1. Introduction

The demand for reliable and efficient electric power transmission is a global priority, particularly in emerging economies like Nigeria. Despite an installed capacity exceeding 10 GW, Nigeria's grid suffers from poor power quality, system collapses, and line losses exceeding 20%—far above the 5% industry benchmark. These losses translate into economic burdens, infrastructure degradation, and industrial decline.

Technical losses in transmission lines—caused by I^2R effects, electromagnetic induction, and low power factor—account for more than 50% of the observed inefficiencies. This research aims to mitigate these issues through the implementation of a Thyristor Controlled Series Compensator (TCSC), a type of Flexible AC Transmission System (FACTS) device, which dynamically adjusts line reactance to enhance voltage stability and reduce losses.

2. LITERATURE REVIEW

Numerous studies have explored different techniques and devices for minimizing technical losses and improving power quality in high-voltage transmission systems.
High Voltage Direct Current (HVDC) transmission has been widely adopted in developed countries for long-distance power delivery due to its lower line losses and improved controllability. Gupta (2013) emphasized that HVDC systems can mitigate power loss significantly by maintaining voltage and current in phase, thus minimizing reactive losses. However, the implementation of HVDC in countries like Nigeria remains impractical due to the high cost of

converters, lack of technical expertise, and regulatory barriers (Wang et al., 2011). Distributed Generation (DG) has been proposed as another solution for minimizing losses by generating power closer to the load centers. Salih (2015) argued that DG reduces the burden on transmission networks and allows for better voltage regulation. Nonetheless, in Nigeria, DG implementation is limited by laws restricting grid contributions above 10 MW and the inability of residential users to afford installation and maintenance costs (Pregelj, 2003; Maleh et al., 2013).

Flexible AC Transmission Systems (FACTS) have emerged as a viable approach for enhancing transmission efficiency. These include Static VAR Compensators (SVC), Static Synchronous Compensators (STATCOM), Unified Power Flow Controllers (UPFC), and Thyristor Controlled Series Compensators (TCSC). TCSC devices are particularly valuable for long-distance AC transmission due to their dynamic control of line impedance, improving both voltage stability and power transfer capability (Sain, 2013; Okakwu, 2018). Okakwu (2018) demonstrated the effectiveness of TCSC in maintaining voltage magnitude within the standard range of 0.95 to 1.05 p.u., though the study did not focus on loss reduction. Kumar (2016) presented a TCSC model that improved voltage stability, but did not quantify the efficiency gains. This study builds upon their work by evaluating not only voltage profiles but also the percentage reduction in line losses.

STATCOM-based approaches have also been employed in the Nigerian grid to enhance voltage profiles. For instance, Nwohu (2015) used a STATCOM to improve voltage stability in the North-East 330 kV network. More recently, Aneke, Eneh, and Iyidobi (2021) demonstrated the use of an Artificial Neural Network (ANN)-controlled STATCOM to mitigate voltage collapse during three-phase fault contingencies in a 44-bus Nigerian network. Further, Aneke, Okafor, and Iyidobi (2021) proposed an ANN-based adaptive STATCOM for voltage stability enhancement in the same network configuration, showcasing improved dynamic responsiveness. Aneke (2021) also explored STATCOM deployment for general efficacy improvement in Nigeria’s transmission network, reinforcing its potential in enhancing voltage stability under varying conditions. Nwohu (2015) used a STATCOM-based approach to enhance voltage profiles in the Nigerian North-East 330 kV network, while Mattew et al. (2014) applied an SVC configuration to stabilize voltage levels in a 28-bus system. Both approaches showed improvements in voltage stability but did not address technical losses explicitly.

Furthermore, multiple studies, such as those by Gruenbaum (2010) and Alizadeh et al. (2012), confirmed that capacitor-based compensation improves voltage regulation. However, these techniques offered limited dynamic adaptability and often led to suboptimal performance under varying load conditions. TCSC, with its thyristor-controlled reactance, provides a more flexible and responsive alternative.

In summary, the literature underscores the limitations of traditional compensation and distributed methods in the Nigerian context. This paper fills the gap by integrating TCSC into a realistic 41-bus transmission network and quantifying both voltage and loss improvements through simulation and sensitivity-based optimization.

- High Voltage Direct Current (HVDC): While effective, HVDC systems are costly and infeasible in Nigeria due to regulatory, financial, and technical constraints.
- Distributed Generation (DG): Though promising, Nigerian law limits DG contributions above 10 MW, making large-scale deployment impractical.
- FACTS Devices: These include SVCs, STATCOMs, and TCSCs. TCSCs are particularly well-suited for long-distance, high-voltage lines and offer rapid, dynamic control of reactive power.

Previous studies have highlighted the benefits of TCSC in improving voltage stability, but few have addressed its integration within the Nigerian grid. This study bridges that gap using real-world data and comprehensive simulation.

3. METHODOLOGY

3.1 Data Collection and Characterization: Line and bus data for a 41-bus 330 kV network were obtained from Nigeria's National Control Center. Load flow analysis was conducted using the Newton-Raphson method in PSAT, and the network was modeled in MATLAB/Simulink as shown below in figure 3.1.

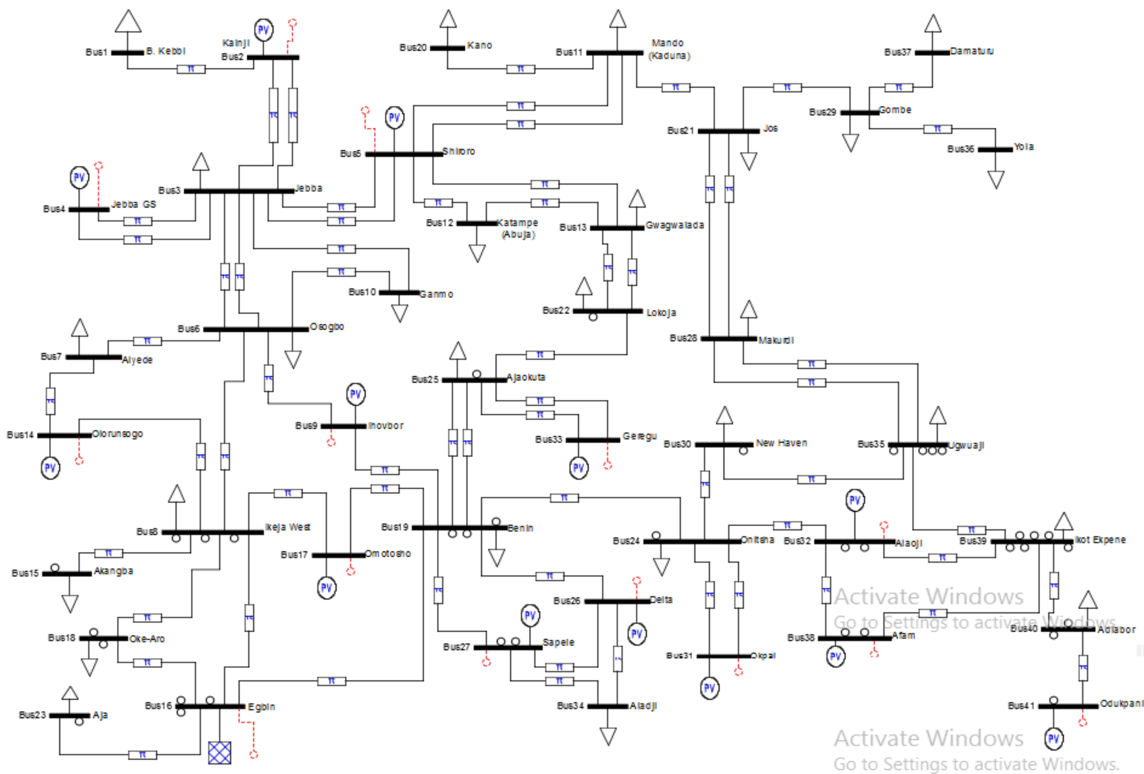

Figure 3.1: 330KV Transmission Network Model

3.2 TCSC Modeling: A TCSC is composed of a capacitor bank in parallel with a thyristor-controlled reactor. Its reactance can be adjusted by altering the thyristor firing angle (typically between 90° and 180°), enabling it to operate in inductive or capacitive mode.
By analyzing the behavior of a variable inductor connected in parallel with an FC. The equivalent impedance, Z_{eq}, of this LC combination is expressed as

- The impedance of the FC alone, however, is given by -j(l/ωC).
- If ωC - (l/ωL) > 0 or, in other words, ωL> (1/ωC), the reactance of the FC is less than that of the parallel-connected variable reactor and that this combination provides a variable-capacitive reactance are both implied.
- If ωC - (1/ωL) = 0, a resonance develops that results in an infinite-capacitive impedance-an obviously unacceptable condition.
- If, however, ωC – (1/ωL) < 0, the LC combination provides inductance above the value of the fixed inductor.

The mathematical equation of TCSC is given in equation 3.1.

$$TCSC = X_L \alpha \qquad (3.1)$$

where the $X_L$was the reactors

α was the firing angle of the thyristor

Power moving from sending end to receiving end was givenby

$$P = \frac{V_S V_R}{X_L} \cos\theta \qquad (3.2)$$

$V_S$was the sending voltage

$V_R$was the receiving end voltage

Cos θ was the power factor

$X_L$was the impedance of the line

When TCSC was connected in series with the line, equation. (3.2) became

$$P = \frac{V_S V_R}{X_{L\alpha}} \cos\theta \qquad (3.3)$$

The thyristors control the capacitor and the reactors. TCSC switches either to capacitive mode or to inductive mode using the firing angle. At firing angle of 180^0, TCSC switch to inductive mode, but it can be varied to get the desired compensation. Also, at firing angle 90^0, TCSC switch to capacitive mode but it can be varied to get the desired compensation.

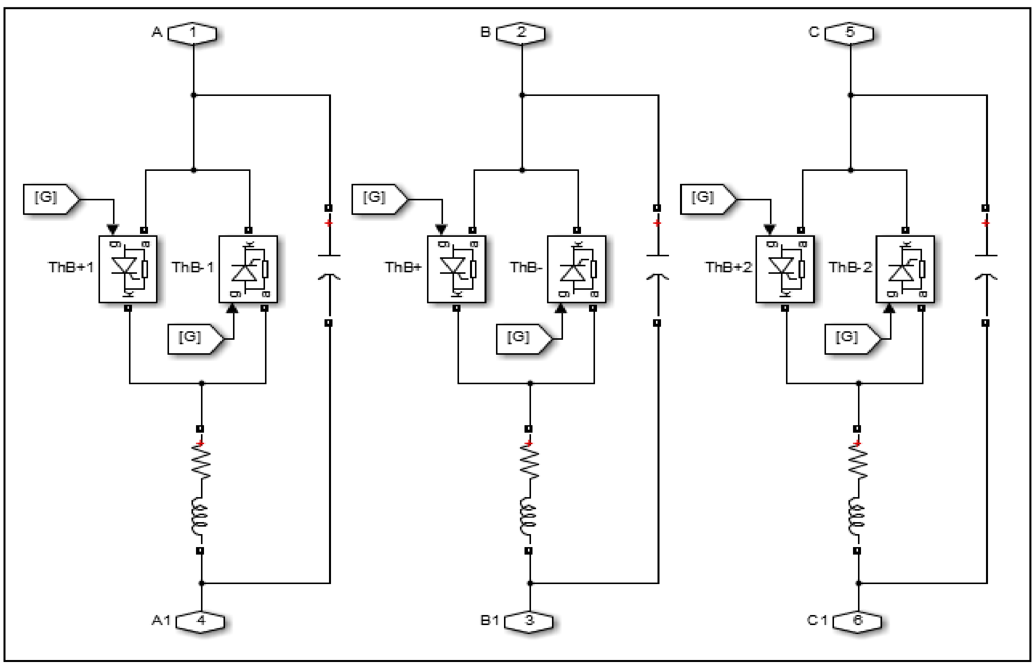

Fig 3.2: Simulink Model of TCSC

3.3 Simulation Scenarios

Three scenarios were considered as stated below.

- Base Case: Without TCSC
- Low Voltage Scenario: TCSC in capacitive mode
- High Voltage Scenario: TCSC in inductive mode

3.4 Optimal TCSC Placement: Multiple sensitivity analysis was used to determine the most effective locations for TCSC deployment. The analysis identified Bus 37 and lines 16 and 19 as optimal placement points.

4. Results and Discussion

Summary of Voltage Violations and Line Losses:

Table 4.1: Violated voltage in kilovolt

S/N	BUS NUMBER/ BUS NAME	VOLTAGE(KV)
1	Bus 1 (B. Kebbi)	305
2	Bus 12(Katampe)	305
3	Bus 13(Gwagwalada)	308
4	Bus 15(Akangba)	310
5	Bus 20(Kano)	303
6	Bus 21(Jos)	299
7	Bus 22(Lokoja)	311
8	Bus 28(Makurdi)	287
9	Bus 29(Gombe)	291
10	Bus 30(New Haven)	290
11	Bus 35(Ugwuaji)	289
12	Bus 36(Yola)	286
13	Bus 37(Damaturu)	285
14	Bus 8(Ikeja West)	313
15	Bus 7(Aiyede)	313

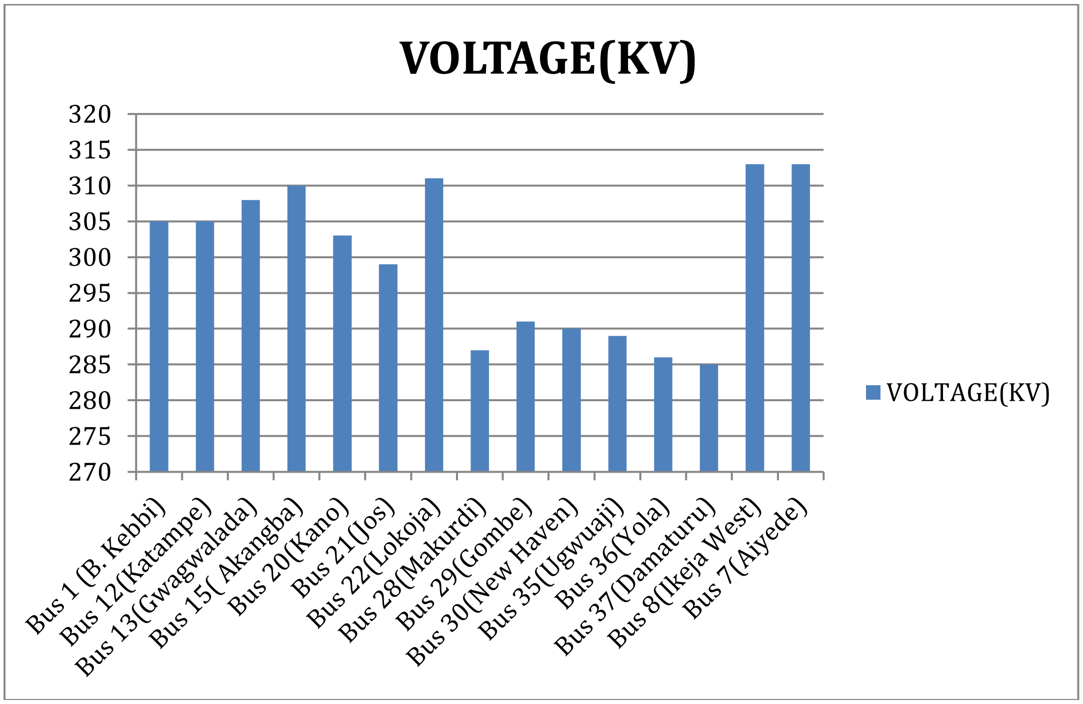

Fig 4.1: Violated voltage buses.

As evident in figure 4.1 above, the 15 violated buses are not up to 313.5KV, therefore, there is problem in the system and need for mitigation.
However, out of 63 transmission lines, 18 lines exceeded 5% losses as shown below.

Table 4.2: Violated line losses in megawatts

S/N	Transmission Line Number	Line Losses
1	Line 7	17.03
2	Line 10	10.77
3	Line 14	5.59
4	Line 16	93.44
5	Line 18	5.26
6	Line 19	34.85
7	Line 20	7.76
8	Line 23	22.39
9	Line 27	10.49
10	Line 30	6.29
11	Line 31	7.39
12	Line 34	25.61
13	Line 43	10.51
14	Line 51	6.97
15	Line 52	5.80
16	Line 54	6.97
17	Line 55	34.42
18	Line 58	16.50

From the table above, line 7, 10, 14,16,18,19,20,23,27,30,31,34,43,51,52,54,55 and 58, all exceeded the 5%, which is problematic to both the market operator and electricity consumers, and these losses runs in billions of naira. Therefore, there is need for mitigation. The bar chart below showed lines that its losses exceeded 5% for clarity and easy understanding.

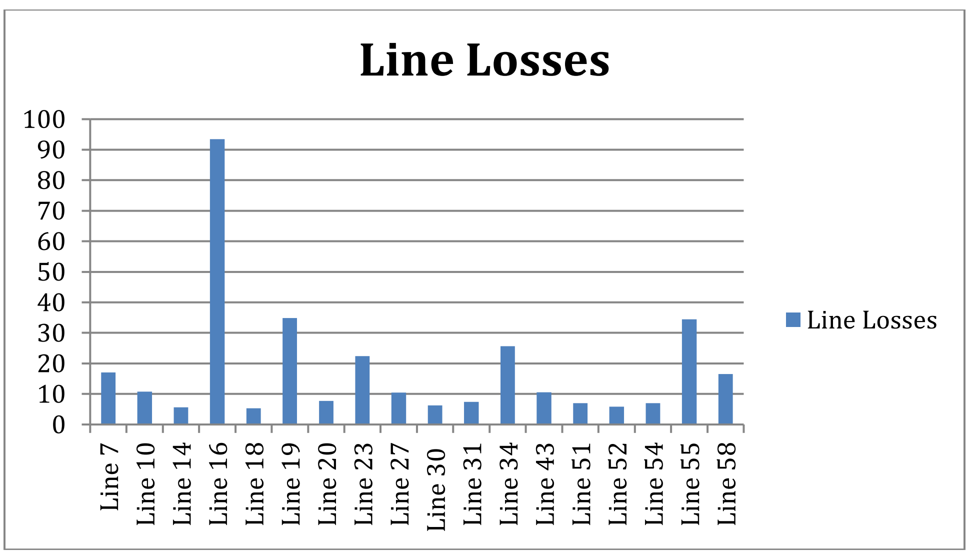

Fig 4.2: Violated line losses

Power system is dynamic in nature. Cases of dynamic nature of power system networks was introduced, the dynamics was evaluated with and without TCSC.
The simulation was run and the result got was presented. The simulation was repeated by varying the sending power because technical loses arising from high voltage and low voltage constitute over 50% of technical losses in transmission line (TCN log book 2018). The results obtained were shown below.

4.1.1: High Voltage condition result

The result of case one for dynamics of power system created to reflect the dynamic situation of power system. The first case of the dynamics was the high voltage condition and the second case was low voltage condition. The result of high voltage condition was presented below.

Table 4.3 Bus voltage for high voltage without TCSC

Bus number	Bus name	Bus peak voltage magnitude
1	B. Kebbi	310
2	Kainji	340
3	Jebba Ts	345
4	Jebba Gs	345
5	Shiroro	330
6	Osogbo	335
7	Aiyede	320
8	Ikeja West	315
9	Ihovbor	335
10	Ganmo	330
11	Mando	320
12	Katampe	310
13	Gwagwalada	310
14	Olorunsogo	320
15	Akangba	315
16	Egbin	347
17	Omotosho	335
18	Oke- Aro	320
19	Benin	330
20	Kano	305
21	Jos	305
22	Lokoja	315
23	Aja	340
24	Onitsha	325
25	Ajaokuta	320
26	Delta	335
27	Sapele	334
28	Makurdi	295
29	Gombe	295
30	New Haven	299
31	Okpai	340

32	Alaoji	335
33	Geregu	335
34	Aladja	335
35	Ugwuaji	290
36	Yola	285
37	Damaturu	285
38	Afam	340
39	Ikot Ekpene	320
40	Adiabor	325
41	Odukpani	340

From Table 4.3, the total voltage violation after increase in power is 12. Thereafter, TCSC was introduced into the networks to mitigate voltage violation in the network, and the result obtained is shown in Table 4.4

Table 4.4: Bus voltage for high voltage with TCSC

Bus number	Bus name	Bus peak voltage magnitude
1	B. Kebbi	320
2	Kainji	345
3	Jebba Ts	346
4	Jebba Gs	346
5	Shiroro	335
6	Osogbo	335
7	Aiyede	325
8	Ikeja West	320
9	Ihovbor	340
10	Ganmo	335
11	Mando	325
12	Katampe	315
13	Gwagwalada	315
14	Olorunsogo	325
15	Akangba	320
16	Egbin	345
17	Omotosho	340
18	Oke- Aro	325
19	Benin	335
20	Kano	315
21	Jos	315
22	Lokoja	320
23	Aja	345
24	Onitsha	330
25	Ajaokuta	325
26	Delta	340
27	Sapele	340
28	Makurdi	315

29	Gombe	315
30	New Haven	316
31	Okpai	345
32	Alaoji	340
33	Geregu	340
34	Aladja	340
35	Ugwuaji	310
36	Yola	305
37	Damaturu	305
38	Afam	345
39	Ikot Ekpene	325
40	Adiabor	330
41	Odukpani	345

From Table 4.4, the voltage violation was dropped from 12 to 3 which showed a significant improvement, while the loses before introduction of TCSC was shown in Table 4.5

Table 4.5: High Voltage power flow losses without TCSC

From Bus	To Bus	Line	P Loss [MW]
Bus 2	Bus 3	1	0.831621
Bus 1	Bus 2	2	2.674906
Bus 5	Bus 12	3	1.351684
Bus 6	Bus 10	4	0.37867
Bus 3	Bus 6	5	1.347945
Bus 3	Bus 6	6	1.347945
Bus 8	Bus 6	7	14.188117
Bus 6	Bus 7	8	3.858877
Bus 10	Bus 3	9	1.108196
Bus 8	Bus 14	10	8.970408
Bus 7	Bus 14	11	0.735233
Bus 21	Bus 11	12	1.884923
Bus 8	Bus 15	13	0.42596
Bus 16	Bus 8	14	4.660076
Bus 23	Bus 16	15	0.088084
Bus 16	Bus 19	16	77.864842
Bus 8	Bus 18	17	1.116764
Bus 18	Bus 16	18	4.384692
Bus 8	Bus 17	19	29.039858
Bus 17	Bus 19	20	6.463523
Bus 4	Bus 3	21	0.291979
Bus 25	Bus 19	22	1.515923
Bus 19	Bus 24	23	18.661433

Bus 25	Bus 19	24	1.581892
Bus 33	Bus 25	25	1.626396
Bus 33	Bus 25	26	1.626396
Bus 19	Bus 27	27	8.749583
Bus 27	Bus 26	28	0.371698
Bus 2	Bus 3	29	0.831621
Bus 19	Bus 26	30	5.242002
Bus 24	Bus 30	31	6.158407
Bus 31	Bus 24	32	1.511734
Bus 24	Bus 31	33	1.511734
Bus 24	Bus 32	34	21.3412
Bus 32	Bus 38	35	1.267019
Bus 30	Bus 35	36	0.038453
Bus 25	Bus 22	37	4.175339
Bus 4	Bus 3	38	0.291979
Bus 9	Bus 19	39	0.488676
Bus 34	Bus 27	40	0.082661
Bus 34	Bus 26	41	0.563844
Bus 36	Bus 29	42	0.22532
Bus 11	Bus 20	43	8.754575
Bus 29	Bus 21	44	3.255894
Bus 29	Bus 37	45	0.359588
Bus 13	Bus 22	46	2.365274
Bus 3	Bus 5	47	0.107351
Bus 13	Bus 22	48	2.365274
Bus 5	Bus 13	49	1.276023
Bus 12	Bus 13	50	0.616003
Bus 35	Bus 28	51	5.804215
Bus 21	Bus 28	52	4.836655
Bus 21	Bus 28	53	4.836655
Bus 35	Bus 28	54	5.804215
Bus 39	Bus 35	55	28.686875
Bus 3	Bus 5	56	0.107351
Bus 39	Bus 40	57	4.174202
Bus 6	Bus 9	58	13.750325
Bus 39	Bus 32	59	1.060988
Bus 39	Bus 38	60	1.997412
Bus 11	Bus 5	61	1.954072
Bus 40	Bus 41	62	1.601574
Bus 11	Bus 5	63	1.954072

From table 4.5, the total active power losses before TCSC was introduced into the network are 336.5462MW. Thereafter, TCSC was introduced into the network and the result obtained was shown in table 4.6

Table 4.6: High Voltage power flow losses with TCSC

From Bus	To Bus	Line	P Loss [MW]
Bus 2	Bus 3	1	0.554414
Bus 1	Bus 2	2	1.783271
Bus 5	Bus 12	3	0.901123
Bus 6	Bus 10	4	0.252447
Bus 3	Bus 6	5	0.89863
Bus 3	Bus 6	6	0.89863
Bus 8	Bus 6	7	9.458745
Bus 6	Bus 7	8	2.572585
Bus 10	Bus 3	9	0.738797
Bus 8	Bus 14	10	5.980272
Bus 7	Bus 14	11	0.490155
Bus 21	Bus 11	12	1.256615
Bus 8	Bus 15	13	0.283973
Bus 16	Bus 8	14	3.106717
Bus 23	Bus 16	15	0.058722
Bus 16	Bus 19	16	51.909895
Bus 8	Bus 18	17	0.744509
Bus 18	Bus 16	18	2.923128
Bus 8	Bus 17	19	19.359905
Bus 17	Bus 19	20	4.309015
Bus 4	Bus 3	21	0.194653
Bus 25	Bus 19	22	1.010615
Bus 19	Bus 24	23	12.440956
Bus 25	Bus 19	24	1.054595
Bus 33	Bus 25	25	1.084264
Bus 33	Bus 25	26	1.084264
Bus 19	Bus 27	27	5.833055
Bus 27	Bus 26	28	0.247799
Bus 2	Bus 3	29	0.554414
Bus 19	Bus 26	30	3.494668
Bus 24	Bus 30	31	4.105605
Bus 31	Bus 24	32	1.007823
Bus 24	Bus 31	33	1.007823
Bus 24	Bus 32	34	14.227467
Bus 32	Bus 38	35	0.844679

Bus 30	Bus 35	36	0.025635
Bus 25	Bus 22	37	2.783559
Bus 4	Bus 3	38	0.194653
Bus 9	Bus 19	39	0.325784
Bus 34	Bus 27	40	0.055107
Bus 34	Bus 26	41	0.375896
Bus 36	Bus 29	42	0.150213
Bus 11	Bus 20	43	5.836383
Bus 29	Bus 21	44	2.170596
Bus 29	Bus 37	45	0.239725
Bus 13	Bus 22	46	1.576849
Bus 3	Bus 5	47	0.071567
Bus 13	Bus 22	48	1.576849
Bus 5	Bus 13	49	0.850682
Bus 12	Bus 13	50	0.410669
Bus 35	Bus 28	51	3.869477
Bus 21	Bus 28	52	3.224437
Bus 21	Bus 28	53	3.224437
Bus 35	Bus 28	54	3.869477
Bus 39	Bus 35	55	19.124583
Bus 3	Bus 5	56	0.071567
Bus 39	Bus 40	57	2.782801
Bus 6	Bus 9	58	9.166883
Bus 39	Bus 32	59	0.707325
Bus 39	Bus 38	60	1.331608
Bus 11	Bus 5	61	1.302715
Bus 40	Bus 41	62	1.067716
Bus 11	Bus 5	63	1.302715

From Table 4.6, it showed the result of total active loses when TCSC was introduced into the network, which was minimized from 336.5462MW to 224.3641MW, which is a significant improvement in loss reduction

4.1.2: Low Voltage condition result

The second case of the dynamic scenario in power system, which was the low voltage, was presented below because according to TCN log, technical losses experienced in transmission line, high and low voltage condition constitute 50% of technical problem experienced in transmission line (TCN log book, 2018)

Table 4.6: Bus voltage for low voltage condition without TCSC

Bus number	Bus name	Bus peak voltage magnitude
1	B. Kebbi	300
2	Kainji	325
3	Jebba Ts	335
4	Jebba Gs	335
5	Shiroro	325
6	Osogbo	325
7	Aiyede	310
8	Ikeja West	310
9	Ihovbor	320
10	Ganmo	320
11	Mando	315
12	Katampe	300
13	Gwagwalada	305
14	Olorunsogo	312
15	Akangba	310
16	Egbin	340
17	Omotosho	329
18	Oke- Aro	315
19	Benin	320
20	Kano	299
21	Jos	285
22	Lokoja	311
23	Aja	335
24	Onitsha	315
25	Ajaokuta	314
26	Delta	330
27	Sapele	330
28	Makurdi	285
29	Gombe	290
30	New Haven	288
31	Okpai	325
32	Alaoji	330
33	Geregu	330
34	Aladja	327
35	Ugwuaji	285
36	Yola	285
37	Damaturu	284
38	Afam	330
39	Ikot Ekpene	315

40	Adiabor	320
41	Odukpani	325

From Table 4.6, showed the result after generator rating was reduced to trigger low voltage, the result obtained showed that 16-buses had violation of voltages, thereafter, TCSC was introduced

Table 4.7: Bus voltage for Low voltage condition with TCSC

Bus number	Bus name	Bus peak voltage magnitude
1	B. Kebbi	320
2	Kainji	330
3	Jebba Ts	340
4	Jebba Gs	340
5	Shiroro	330
6	Osogbo	330
7	Aiyede	330
8	Ikeja West	330
9	Ihovbor	325
10	Ganmo	325
11	Mando	320
12	Katampe	320
13	Gwagwalada	320
14	Olorunsogo	320
15	Akangba	315
16	Egbin	345
17	Omotosho	335
18	Oke- Aro	320
19	Benin	325
20	Kano	314
21	Jos	305
22	Lokoja	316
23	Aja	340
24	Onitsha	320
25	Ajaokuta	320
26	Delta	335
27	Sapele	335
28	Makurdi	305
29	Gombe	310
30	New Haven	310
31	Okpai	330
32	Alaoji	335
33	Geregu	335
34	Aladja	340
35	Ugwuaji	305
36	Yola	305
37	Damaturu	305

38	Afam	335
39	Ikot Ekpene	320
40	Adiabor	325
41	Odukpani	330

From Table 4.7, results showed after TCSC was introduce in the Low voltage network, voltage violation dropped from 14 to 7 which was a significant improvement. The result of line loses before TCSC was introduced into the network was shown in Table 4.8

Table 4.8: Low Voltage power flow losses without TCSC

From Bus	To Bus	Line	P Loss [MW]
Bus 2	Bus 3	1	1.097945
Bus 1	Bus 2	2	3.309888
Bus 5	Bus 12	3	1.722021
Bus 6	Bus 10	4	0.554404
Bus 3	Bus 6	5	1.717534
Bus 3	Bus 6	6	1.717534
Bus 8	Bus 6	7	20.22574
Bus 6	Bus 7	8	4.730652
Bus 10	Bus 3	9	1.429835
Bus 8	Bus 14	10	11.96449
Bus 7	Bus 14	11	0.982328
Bus 21	Bus 11	12	2.361907
Bus 8	Bus 15	13	0.611152
Bus 16	Bus 8	14	6.792091
Bus 23	Bus 16	15	0.205701
Bus 16	Bus 19	16	103.23781
Bus 8	Bus 18	17	1.440117
Bus 18	Bus 16	18	6.46163
Bus 8	Bus 17	19	38.44783
Bus 17	Bus 19	20	8.956228
Bus 4	Bus 3	21	0.450375
Bus 25	Bus 19	22	1.919107
Bus 19	Bus 24	23	24.79372
Bus 25	Bus 19	24	1.998271
Bus 33	Bus 25	25	2.051675
Bus 33	Bus 25	26	2.051675
Bus 19	Bus 27	27	11.6995
Bus 27	Bus 26	28	0.546038
Bus 2	Bus 3	29	1.097945
Bus 19	Bus 26	30	7.490402
Bus 24	Bus 30	31	8.590088
Bus 31	Bus 24	32	1.914081
Bus 24	Bus 31	33	1.914081
Bus 24	Bus 32	34	30.80944
Bus 32	Bus 38	35	1.620423

Bus 30	Bus 35	36	0.146144
Bus 25	Bus 22	37	6.210407
Bus 4	Bus 3	38	1.350375
Bus 9	Bus 19	39	0.786411
Bus 34	Bus 27	40	0.199193
Bus 34	Bus 26	41	0.876613
Bus 36	Bus 29	42	0.370384
Bus 11	Bus 20	43	12.90549
Bus 29	Bus 21	44	4.107073
Bus 29	Bus 37	45	0.531505
Bus 13	Bus 22	46	3.238329
Bus 3	Bus 5	47	0.228821
Bus 13	Bus 22	48	3.238329
Bus 5	Bus 13	49	1.9312274
Bus 12	Bus 13	50	1.139204
Bus 35	Bus 28	51	8.165058
Bus 21	Bus 28	52	7.003986
Bus 21	Bus 28	53	7.003986
Bus 35	Bus 28	54	8.165058
Bus 39	Bus 35	55	41.22425
Bus 3	Bus 5	56	0.228821
Bus 39	Bus 40	57	6.209042
Bus 6	Bus 9	58	19.70039
Bus 39	Bus 32	59	1.373186
Bus 39	Bus 38	60	2.596894
Bus 11	Bus 5	61	2.544886
Bus 40	Bus 41	62	2.321889
Bus 11	Bus 5	63	2.544886

From Table 4.8, showed the total line losses before TCSC was introduce into the network. The total active line losses were 463.2555MW. Thereafter, TCSC was introduced into the network to mitigate the losses. The result obtained after the mitigation was shown in Table 4.9

Table 4.9: Low Voltage power flow losses with TCSC

From Bus	To Bus	Line	P Loss [MW]
Bus 2	Bus 3	1	0.731963
Bus 1	Bus 2	2	2.206592
Bus 5	Bus 12	3	1.148014
Bus 6	Bus 10	4	0.369603
Bus 3	Bus 6	5	1.145023
Bus 3	Bus 6	6	1.145023
Bus 8	Bus 6	7	13.483827
Bus 6	Bus 7	8	3.153768
Bus 10	Bus 3	9	0.953223
Bus 8	Bus 14	10	7.976327

Bus 7	Bus 14	11	0.654889
Bus 21	Bus 11	12	1.574605
Bus 8	Bus 15	13	0.407435
Bus 16	Bus 8	14	4.528061
Bus 23	Bus 16	15	0.137134
Bus 16	Bus 19	16	68.825207
Bus 8	Bus 18	17	0.960078
Bus 18	Bus 16	18	4.307753
Bus 8	Bus 17	19	25.631887
Bus 17	Bus 19	20	5.970819
Bus 4	Bus 3	21	0.30025
Bus 25	Bus 19	22	1.279405
Bus 19	Bus 24	23	16.529147
Bus 25	Bus 19	24	1.3321807
Bus 33	Bus 25	25	1.367783
Bus 33	Bus 25	26	1.367783
Bus 19	Bus 27	27	7.799667
Bus 27	Bus 26	28	0.3640253
Bus 2	Bus 3	29	0.731963
Bus 19	Bus 26	30	4.993601
Bus 24	Bus 30	31	5.726725
Bus 31	Bus 24	32	1.276054
Bus 24	Bus 31	33	1.276054
Bus 24	Bus 32	34	20.539627
Bus 32	Bus 38	35	1.080282
Bus 30	Bus 35	36	0.097429
Bus 25	Bus 22	37	4.140271
Bus 4	Bus 3	38	0.90025
Bus 9	Bus 19	39	0.524274
Bus 34	Bus 27	40	0.132795
Bus 34	Bus 26	41	0.584409
Bus 36	Bus 29	42	0.246923
Bus 11	Bus 20	43	8.60366
Bus 29	Bus 21	44	2.738049
Bus 29	Bus 37	45	0.354337
Bus 13	Bus 22	46	2.158886
Bus 3	Bus 5	47	0.152547
Bus 13	Bus 22	48	2.158886
Bus 5	Bus 13	49	1.287485
Bus 12	Bus 13	50	0.759469
Bus 35	Bus 28	51	5.443372
Bus 21	Bus 28	52	4.669324
Bus 21	Bus 28	53	4.669324
Bus 35	Bus 28	54	5.443372

Bus 39	Bus 35	55	27.482833
Bus 3	Bus 5	56	0.1495
Bus 39	Bus 40	57	4.139361
Bus 6	Bus 9	58	13.133593
Bus 39	Bus 32	59	0.915457
Bus 39	Bus 38	60	1.731263
Bus 11	Bus 5	61	1.696591
Bus 40	Bus 41	62	1.547926
Bus 11	Bus 5	63	1.896591

From Table 4.9, showed the results after TCSC was introduced into the network. The result showed that the total active loses was minimized from 463.2555MW to 309.034MW, which was a significant improvement in line loss reduction, thereby
Improving the efficiency of the line invariably, because, as the active line loses was reduced; efficiency of the line was improved.

4.2 Efficiency Improvement:
Load Flow Analysis (Without TCSC)
- 15 buses violated the standard voltage range (0.95–1.05 p.u.).
- Total active power loss: 403.86 MW
- Reactive power loss: 377.22 Mvar

Load Flow Analysis (With TCSC)
- Voltage violations reduced from 15 to 6 buses.
- Active power loss decreased to 269.46 MW.
- Reactive power loss significantly dropped.

Table 5.0: Efficiency Improvement Comparison

Parameter	Without TCSC	With TCSC
Violated Buses	15	6
Active Power Loss (MW)	403.86	269.46
Reactive Power Loss (Mvar)	377.22	Reduced
Efficiency Improvement	-	+2%
Loss Reduction Compared to Previous Work	-	14.65%

The simulation results highlight the substantial benefits of integrating a Thyristor Controlled Series Compensator (TCSC) into the Nigerian 330 kV transmission network. As can be seen from table 5.0, figures 4.2 and 4.3 respectively, before the introduction of the TCSC, 15 buses experienced voltage violations outside the acceptable range of 0.95–1.05 per unit. These violations are indicative of potential system instability, increased equipment stress, and reduced power quality for consumers. Upon integrating the TCSC at strategically identified points using the multiple sensitivity method, voltage violations were significantly reduced to just 6 buses. This indicates an improvement in overall voltage regulation and stability. Furthermore, active power loss across the network decreased from 403.86 MW to 269.46 MW—a reduction of approximately 33%. Reactive power losses also saw a significant decline, contributing to improved voltage stability and reduced stress on transmission components. The efficiency of the transmission line was improved by approximately 2%, signifying better utilization of generated power and lower operational costs. Compared to earlier work by Ademola (2016), the TCSC approach presented in this study achieved a 14.65% greater reduction in losses. These findings confirm that FACTS devices like TCSC, when optimally placed and properly controlled, are highly effective in addressing technical losses and voltage instability in transmission systems. They also suggest the potential for wider implementation in similar high-voltage transmission networks, particularly in developing countries where grid inefficiencies are common.

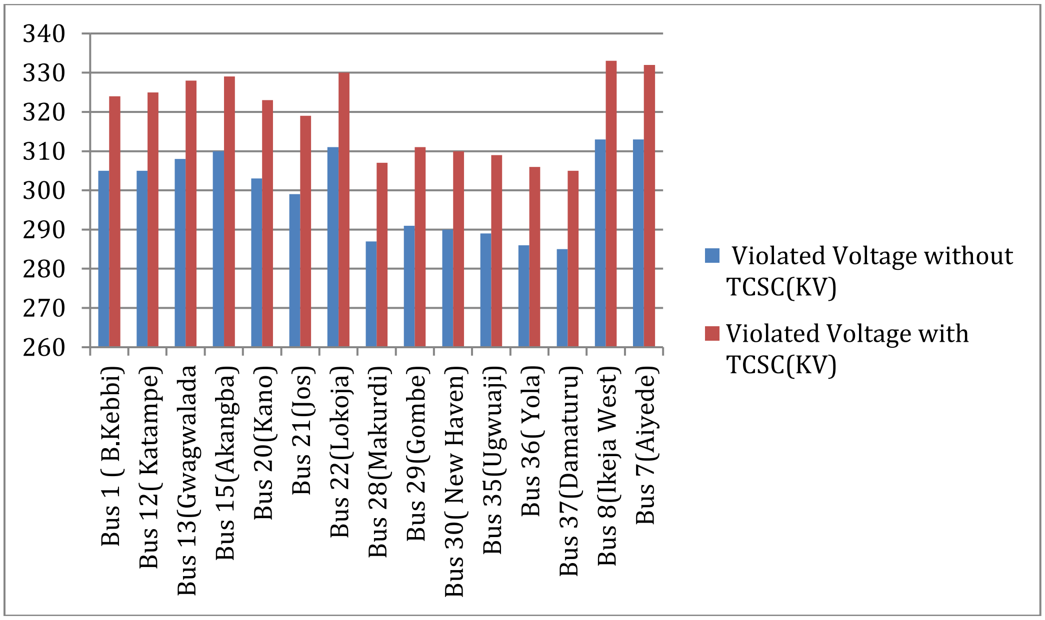

Figure 4.2: Voltage Profile Across Buses Before and After TCSC Integration

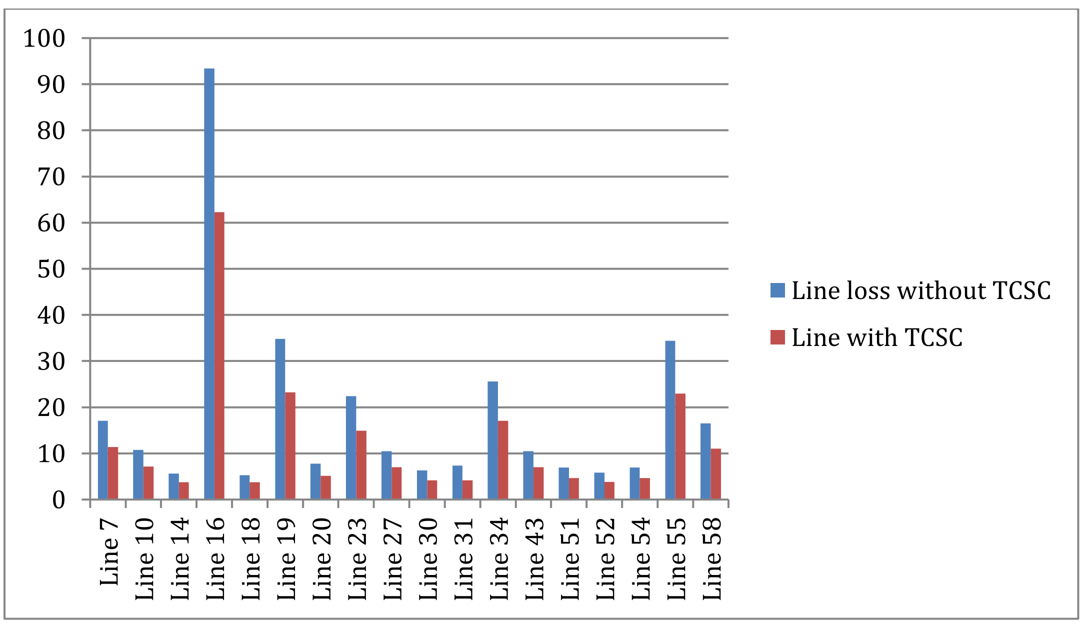

Figure 4.3: Active Power Loss Comparison Between Base Case and TCSC Case

5. Conclusion

The integration of a Thyristor Controlled Series Compensator (TCSC) in the Nigerian 330 kV transmission network significantly improves voltage stability and reduces technical losses. With a 33% loss reduction and improved operational efficiency, TCSC proves to be a viable solution to Nigeria's power transmission challenges. The application of multiple sensitivity analysis further optimizes its placement, enhancing the overall system performance.

6. Recommendations

- Further research should focus on real-time hardware-in-loop testing of TCSC systems.
- Policy revisions are needed to support full-scale adoption of FACTS devices in Nigeria.
- Grid modernization plans should prioritize TCSC deployment on high-loss corridors.

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