



A comparative study of transmission expansion planning with consideration of voltage stability, loss reduction and congestion relief in a 30-bus 330 kV Nigerian Grid

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Abstract

This study presents a 30-bus, 330 kV Nigerian transmission network and applies five network improvement methods to assess transmission expansion planning with loss reduction and congestion relief as the objective functions. The base-case network indicated six topologically weak transmission lines, six overloaded lines and six buses having voltage magnitudes below the statutory $\pm 5\%$ limit with active and reactive power losses of 219.08 MW and 409.83 MVar respectively. To evaluate the reduction in network loss and the relief from congestion, five network compensator methods (two shunt and three series) were applied to the base-case network independently. The Shunt compensation involved static VAR compensators (SVCs) and shunt capacitors, each installed separately at the weak buses. The series compensator included a fixed series capacitor, thyristor-controlled series compensation (TCSC) and duplicate line reinforcement on the weak transmission lines. The weak bus voltage magnitudes were normalised using each of the five methods considered, but the results show varying power loss and varying congestion reductions relative to the base-case network. The congestion was completely eliminated by installing duplicate lines along both the weak and overloaded transmission lines. Active and reactive power loss reductions are: 185.46 MW, 96.61 MVar (SVC), 189.183 MW, 130.087 MVar (Shunt capacitor), 178.183 MW, -383.087 MVar for series capacitor, 174.06 MW, -395.932 MVar (TCSC) and 166.144 MW, -269.134 MVar (duplicate on weak lines) and 109.67 MW, -734.28 MVar (duplicate on both weak and overloaded lines). Although the SVC and shunt capacitor improved the voltage profile, overloaded lines still persist. These results show the limits of the shunt compensator (SVC and shunt capacitor) in removing congestion. However, series compensators installed on weak transmission lines provided significant relief from congestion, especially on the overloaded lines. The complete elimination of congestion by duplicate circuits on the overloaded lines was observed. The findings support evidence-based selection of upgrade options for transmission expansion planning.

Keywords: Congestion, compensation, loss reduction, stressed network, voltage profile

Introduction

Transmission networks in many developing nations face significant stress due to demand growth, power transfer over long transmission lines, and uneven distribution of generation and loads (Ogundare, *et al.*, 2022 a; Odigbo, *et al.*, 2026) [6, 7]. These conditions call for transmission expansion to accommodate higher power transfer, maintain acceptable voltage profile, reduce technical losses and prevent congestion on critical transmission lines. Poor transmission network performance is commonly due to buses with voltage magnitudes outside the statutory limit, overloaded transmission lines that constrain transfer capability, reduced operating security, and high active and reactive power losses (Odigbo, *et al.*, 2026; Davis, *et al.*, 2023; Adebisi, *et al.*, 2024) [3, 6, 11]. Addressing these inadequacies essentially requires a mix of network compensations and structural reinforcement. The structural reinforcement option includes duplicating transmission lines to directly increase power transfer capability and improve network robustness. Network compensation, on the other hand, includes shunt reactive support and series compensation, reshaping network power flows and the voltage profile by altering the effective impedance and the reactive power balance (Ifra, *et al.*, 2021) [5]. The selection of any of these approaches depends on the choice of objective functions.

Practical planning problems for transmission network expansion involve identifying weak elements and selecting

effective reinforcement options to address immediate implications for power system reliability and efficiency. In this study, a 30-bus, 330 kV Nigerian transmission network is used as a base-case network to evaluate and compare reinforcement and compensation strategies for loss reduction and congestion relief. The power flow results of the base-case network indicate a stressed network with six topologically weak transmission lines, six overloaded transmission lines and six buses with weak voltage magnitudes below the statutory limit of $\pm 5\%$. The base-case network indicates active and reactive power losses of 219.08 MW and 409.83 MVar, respectively. The poor performance of the base-case network highlights the combined effect of heavy loading, reactive power imbalance and inefficient power transfer.

To carry out evidence-based transmission network expansion planning for the base-case network, five upgrade scenarios were considered separately and their impacts on the network were compared. First, static var compensators (SVCs) were incorporated at the weak buses to give localised shunt reactive power support. This led to voltage normalization and a reduction in power losses from 219.08 MW, 409.83 MVar to 185.46 MW and 96.61 MVar. Nevertheless, the overloaded transmission lines still remained overloaded. Second, the shunt capacitors were installed on the weak buses to give localised reactive power support. This led to voltage normalization and a reduction in power losses from 219.08 MW, 409.83 MVar to 189.183

MW and 130.087 MVar. Nevertheless, the six overloaded transmission lines still remained overloaded. Third, series capacitors were installed on the topologically weak transmission lines. It improves voltage profile performance, reducing overloading and losses to 178.183 MW and -330.087 MVar from 219.08 MW and 409.83 MVar, respectively. This is followed by connecting TCSC along the topologically weak transmission lines. This results in a voltage profile performance with further reduction in active and reactive power losses to 174.061 MW and -395.923 MVar, from 219.08 MW and 409.83 MVar. However, five out of the six lines remain overloaded. The fifth scenario considers duplicate lines running in parallel with the weak transmission lines, as well as a parallel circuit with both weak and overloaded transmission lines. This led to an improvement in the voltage profile and the elimination of congestion.

This paper has the following structure: section one gives a detailed introduction of the article, section two presents materials and methods while section three presents results and discussion. Conclusion and the proposed direction of future research work are presented in section four. Many authors have contributed to power system transmission expansion planning TEP. TEP is described as a multi-objective problem that involves making decisions about how to improve power transfer capability, reduce technical losses, and maintain an acceptable voltage profile and thermal limits under growing demand and uncertainty (Odigbo, *et al.*, 2026; Ogundare, *et al.*, 2022^[6, 7] d). In a practical power system transmission network, weaknesses are essentially revealed by voltage violations, line overloading indicating congestion, high active and reactive losses, and insufficient reactive support (Ifra, *et al.*, 2021; Ogundare, *et al.*, 2022^[5, 10] b). In a developing system, these weaknesses are prone to coexist because constrained scenarios might force power through a few critical paths, thereby increasing current and voltage drops, which in turn increase active power losses and reactive absorption (Ghasemi Marzbali, *et al.*, 2017, Ogundare, *et al.*, 2022^[4, 10] c).

Two broad classes of consideration, reinforcement and compensation, are considered. Compensation solutions: SVC, shunt capacitors, series capacitors and TCSC. They can correct voltage problems and improve power-flow distribution without building new lines (a non-wire solution). In many studies, Compensation is classified as a transmission planning alternative to complement reinforcement (Davies, *et al.*, 2023; Ogundare, *et al.*, 2017) ^[3, 12]. Shunt compensation is best at voltage support while series compensation improves power transfer capability and reduces reactive power flow (Ogundare, *et al.*, 2024)^[11].

Adding duplicate lines (parallel circuits) is described as a reinforcement strategy. The benefits include lower effective impedance, improved power transfer capability and redundancy, significant congestion relief, and reduced active losses due to lower current per circuit (Tarafdar, *et al.*, 2024).

A common limitation in the literature is that many studies evaluate only one solution category (reinforcement or compensation). This scenario makes it difficult to compare practical alternatives under identical base case assumptions. The contribution of this paper is to address the gap by separately considering multiple reinforcement and compensation options on the same 30-bus, 330 kV Nigerian

grid as the base case and reporting comparable outcomes using consistent metrics. This method supports ready-made decisions on what works best for a particular objective and thereby provides a useful basis for multi-objective extensions.

Materials and Methods

1. Power Flow Analysis

Insightful information on the power system under steady-state operation is obtained from the power flow analysis (CITE). For this research, Nigeria's 30-bus, 330 kV transmission network was considered. It comprises 11 generations, 50 transmission lines and 19 load buses. The active and reactive power flow for the circuit shown in Figure 1 is given in equations (1) and (2) respectively.

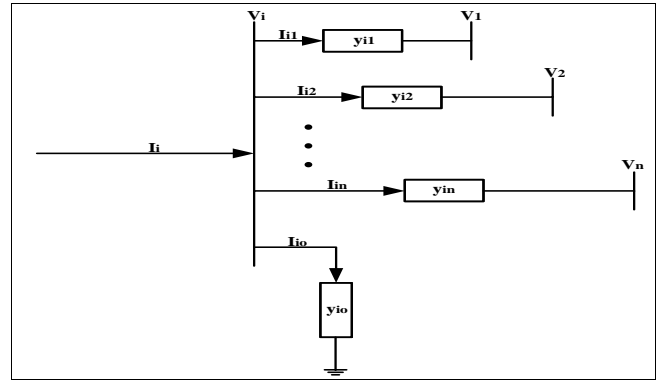


Fig 1: A typical power system n-bus arrangement (Gupta, 2011; Kothari and Nagrath, 2008; Hadi, 2008)

$$P_{ik} = -|V_i|^2 |Y_{ik}| \cos \theta_{ik} + |V_i| |V_k| |Y_{ik}| \cos(\theta_{ik} - S_i + S_k) \quad (1)$$

$$Q_{ik} = |V_i|^2 |Y_{ik}| \sin \theta_{ik} - |V_i| |V_k| |Y_{ik}| \sin(\theta_{ik} - S_i + S_k) - |V_i|^2 |y_{io}^0| \quad (2)$$

When the network was improved by SVC shown in figure 2, the power flow equations are given in (3) and (4).

Where: V_i , I_i , P_i , Q_i and S_i respectively denote voltage (V), current (A), active power (W), reactive power (VAr) and apparent power (VA)

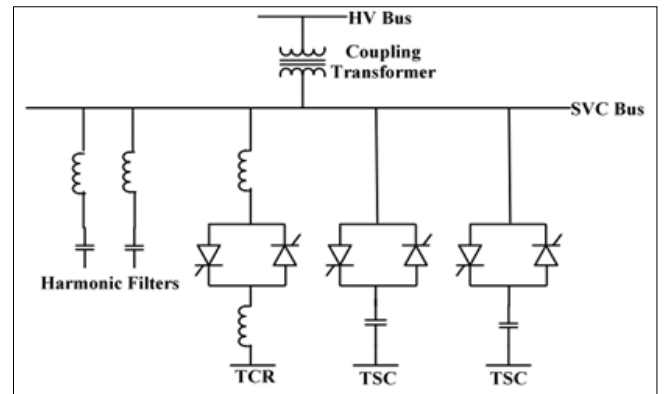


Fig 2: An SVC configuration (Adebisi *et al.*, 2024)^[2]

$$P_i = V_i^2 G_{ii} - V_i V_k [G_{ik} \cos(\theta_i - \theta_k) - B_{ik} \sin(\theta_i - \theta_k)] - V_i V_{cr} [G_{ik} \cos(\theta_i - \delta_{cr}) - B_{ik} \sin(\theta_i - \delta_{cr})] \quad (3)$$

$$Q_i = -V_i^2 B_{ii} - V_i V_k [G_{ik} \sin(\theta_i - \theta_k) - B_{ik} \cos(\theta_i - \theta_k)] - V_i V_{cr} [G_{ik} \sin(\theta_i - \delta_{cr}) - B_{ik} \cos(\theta_i - \delta_{cr})] \quad (4)$$

Network improvement with shunt capacitor has the same modification as the SVC.

Modification of the network with series capacitor shown in Figure 3

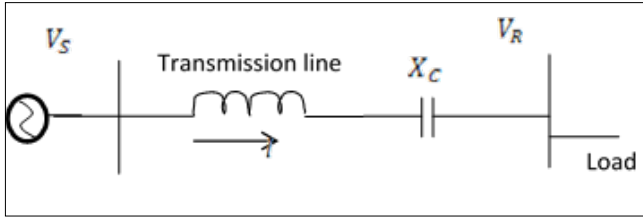


Fig 3: Series Capacitor

Voltage drop in the transmission line is given in (5) and (6) for the base case and series capacitor improvement respectively. This scenario change the power flow equations.

$$\Delta V \approx IR \cos \theta_R + IX_L \sin \theta_R \quad (5)$$

$$\Delta V \approx IR \cos \theta_R + I(X_L - X_C) \sin \theta_R \quad (6)$$

Where I is the current flowing through the line, R is the resistance, X_L is inductive reactance, X_C is capacitive reactance, is the load angle at the receiving end, V_R is the receiving end voltage and V_S is the source/sending end voltage.

Modification of the network with TCSC is shown in figure 4. The power flow operation in this network is similar to that of series capacitor. The pair of anti-parallel thyristor arrangement carries current in the opposite direction, thereby allowing current to flow in either direction through the load. Th_2 conducts when a gate signal is applied during the positive half cycle of the source, while Th_1 conducts when the gate signal is applied during the negative half cycle. This mode of operation provides a path for positive and negative load current. Hence, the losses is improved compare to that of series capacitor.

Results and Discussion

The results for the base-case network, indicate defect, are shown in Tables 1- 4 indicating a combined effect of heavy loading, reactive power balance and inefficient power transfer. Table 1 indicates six buses having voltage magnitudes below the statutory $\pm 5\%$ limit. Table 2 shows active and reactive power losses of 219.08 MW and 409.83 MVar, respectively, while Table 3 contains six topologically weak transmission lines and six overloaded lines displayed in Table 4. These defects indicate a need to improve impedance on topologically weak/overloaded transmission lines and to improve bus voltage magnitude by managing reactive power.

1. Results of the Base-Case Network

Table 1: Bus Voltage Magnitude

Bus Name	Voltage P.U
Jos	0.8141
Kano	0.8138
Gombe	0.6608
New heaven	0.9002
Calabar	0.9319
Onitsha	0.94.66

Table 2: Summary of Load Flow Results

P Loss (MW)	Q Loss (MVar)	P Gen (MW)	Q Gen (MVar)	P Load (MW)	Q Load (MVar)
219.08	409.83	5,052.00	2,837.45	4,832.92	2,427.62

Table 3: The Topologically Weak Transmission Lines.

From Bus	To Bus	R (P.U)	X (P.U)	B (P.U)
Gombe	Jos	0.0104	0.0783	0.5205
Okpai	Calabar	0.0028	0.0213	0.1414
Kaduna	Kano	0.0090	0.0680	0.4518
Jos	Kaduna	0.0077	0.0582	0.3870
Benin	Onitsha	0.0054	0.0405	0.2691
New Haven	Onitsha	0.0038	0.0284	0.1886

Table 4: The Overloaded Transmission Lines

From Bus	To Bus	S(MVA)	R (P.U)	X (P.U)	B (P.U)
Ikeja West	Omotoso	491.47	0.0031	0.0236	0.0324
Alaoji	Onitsha	530.38	0.0054	0.0408	0.2711
Egbin	Ikeja West	471.54	0.0024	0.0183	0.1218
Alaoji	Calabar	654.44	0.0010	0.0074	0.0491
Okpai	Calabar	790.51	0.0028	0.0213	0.1414

Five improvement options were considered: shunt compensator (SVC) and shunt capacitor, which are incorporated at the weak buses; series compensator (Series capacitor); TCSC; and line duplication on stressed transmission lines. Each of these was carried out on the base-case network. The results for the SVC improvement of Table 5 show that all bus voltage magnitudes are within limits, and the active and reactive power losses shown in Table 6 are reduced to 185.46 MW and 96.61 MVar, respectively, down from 219.08 MW and 409.83 MVar. Notwithstanding this, the six overloaded transmission lines remain defective, with only an insignificant improvement as shown in Table 7.

The results for the network with shunt capacitor improvement, documented in Table 5, show that the voltage magnitudes are without defect, and the active and reactive power losses, shown in Table 6, are reduced to 189.183 MW and 130.087 MVar, respectively, from 219.08 MW and 409.83 MVar. Notwithstanding, the six overloaded transmission lines documented in Table 7 remain defective, with only an insignificant improvement.

The results for the network with series capacitor improvement show that all bus voltage magnitudes are without defect, and the active and reactive power losses are reduced to 178.183 MW and -330.087 MVar, respectively, from 219.08 MW and 409.83 MVar. Notwithstanding, the six overloaded transmission lines remain defective, though conditions have improved. The results for the network with TCSC improvement show that all bus voltage magnitudes are without defect, and the active and reactive power losses are reduced to 174.061 MW and -395.923 MVar, respectively, from 219.08 MW and 409.83 MVar. However, five out of the six lines remain overloaded. The results for the network with duplication-on-weak-lines improvement show that all bus voltage magnitudes are without defect, and the active and reactive power losses are reduced to 166.144 MW and -267.134 MVar, respectively, from 219.08 MW and 409.83 MVar. However, only two of the six base-case lines remain significantly overloaded. The results for the network with duplication on both weak and overloaded lines improvement show that all bus voltage magnitudes are without defect, and the active and reactive

power losses are reduced to 109.670 MW and -734.280 MVar, respectively, from 219.08 MW and 409.83 MVar.

However, no transmission line is overloaded. This demonstrates the ideal power flow results.

Table 5: Comparison of Voltage Magnitude of Weak Buses

Name of Bus	Base-case		Improvement				
	Base-case V (P.u)	SVC V p.u	Shunt Capacitor VP.u	Series Capacitor V P.u	TCSC V P.u	Duplicate Weak Lines	Duplicate Weak & Overloaded Lines V P.u
Jos	0.8141	1.002	0.955	0.955	0.980	1.000	0.994
Kano	0.8138	1.000	0.958	0.958	0.980	0.990	0.959
Gombe	0.6608	1.000	0.964	0.963	0.970	0.970	0.965
New heaven	0.9002	1.000	0.985	0.975	1.020	0.970	0.988
Calabar	0.9319	1.000	0.969	0.966	0.960	1.000	1.037
Onitsha	0.94.66	1.0001	0.974	0.970	1.030	0.990	1.008

Table 6: Comparison of Power Flow Results of the Base-case and Modified Networks

	P Loss (MW)	Q Loss (MVar)	P Gen (MW)	Q Gen (MVar)	P Load (MW)	Q Load (MVar)
Base-case	219.08	409.83	5,052.00	2,837.45	4,832.92	2,427.62
SVC	185.46	96.61	5,052.00	1,914.552	4,866.538	2,422.396
Shunt Capacitor	189.183	130.087	4561.284	2,819.799	4372.1	2689.711
Series Capacitor	178.183	-330.08	5052	2,819.799	4873.817	2689.711
TCSC	174.061	-395.923	5052	2017.933	4877.939	2413.857
Duplication of Weak Lines	166.144	-267.134	5052	2146.149	4885.856	2413.283
Duplication of Weak & Overloaded Lines	109.67	-734.28	5052	1639.49	4942.33	2373.769

Table 7: Comparison of Overloaded Lines for the Base-case and Modified Networks.

From Bus	To Bus	Base-case	SVC	Shunt Capacitor	Series Capacitor	TCSC	Duplication of Weak Lines	Duplication of Weak & Overloaded Lines
Ikeja West	Omotosho	491.47	489.23	489.23	489.23	505.11	452.20	312.39
Alaoji	Onitsha	530.38	523.38	525.28	523.38	540.461	460.99	276.35
Egbin	IkejaWest	471.54	569.53	469.53	469.53	494.36	450.63	345.51
Alaoji	Calabar	654.44	608.91	610.81	608.91	626.616	462.14	462.14
Okpai	Calabar	790.51	698.22	698.24	698.22	251.296	379.328	276.35

Table 8 indicates that the reduction in active power loss clearly differentiates the options. Duplicate on both topologically weak and overloaded lines produced the largest MW-loss reduction, indicating the largest improvement in voltage profile. TCSC and series capacitor improvements also resulted in a substantial reduction in active power loss, consistent with the impedance reduction. The SVC and Shunt capacitor improvements delivered a moderate reduction in power loss. This is consistent with their principal function of voltage support and impedance

tuning rather than adding physical transfer capacity. SVC and shunt capacitor provided the largest reductions in positive reactive loss, from 409.83 MVar in the base case to 96.61 MVar and 130.087 MVar, respectively. This indicates that the base case inefficiency was dominated by reactive circulation and insufficient reactive support. The series compensation indicated negative reactive power loss. A negative reactive power loss indicates that the net reactive power supplied back to the network or absorbed is reduced to the point that the total becomes negative.

Table 8: Quantitative Comparison Table

Case	Voltage at weak buses	P Loss (MW)	ΔP (MW)	ΔP (%)	Q Loss (MVar)	ΔQ (MVar)	ΔQ (%)	Overloading Outcome
Base case	Weak buses present	219.08	-	-	409.83	-	-	6 overloaded lines present
SVC on weak buses	normalised	185.46	33.62	15.34	96.61	313.22	76.43	Reduced, 6 overloaded present
Shunt Capacitor on weak buses	normalised	189.183	29.90	13.64	130.087	269.74	65.82	Reduced, 6 overloaded present
Series Capacitor on weak lines	normalised	178.183	40.90	18.67	-330.087	739.92	180.5	Reduced, 6 overloaded present
TCSC on weak lines	normalised	174.061	45.02	20.55	-395.92	805.75	196.6	Reduced, 5 overloaded line present
Duplicate on weak lines	normalised	166,144	52.94	24.16	-267.134	676.96	165.2	Reduced, 5 overloaded line present
Duplicate on both weak and overloaded lines	normalised	109.67	109.41	49.94	-734.28	1,144.1	279.1	No overloaded lines

Conclusion

The 30-bus, 330-kV Nigerian transmission network indicates a highly stressed power system. Five compensation options are applied to the base case (the Nigerian transmission network) to reduce active and reactive power loss, improve the voltage profile and remove congestion. All compensation options achieve voltage normalisation. The shunt compensator, consisting of an SVC and a shunt capacitor, reduces power loss and provides

positive reactive power compensation, but does not remove the congestion. SVC provides the highest reactive power compensation, followed by the shunt capacitor. The series compensator consists of a series capacitor, a TCSC, and duplicate lines on weak and overloaded lines, structurally modifying the network and providing combined voltage and loading improvements, increased transfer capacity, better reduction of active power loss, and net reactive injection (negative reactive loss).

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