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Optimal Placement of Hybrid STATCOM–SVC Controllers for Voltage Stability Enhancement using an Improved Strength Pareto Evolutionary Algorithm

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Abstract

Voltage instability in stressed transmission networks is exacerbated by reactive-power deficiency, heavy loading, and contingency events that drive bus voltages below acceptable statutory limits. This study presents an Improved Strength Pareto Evolutionary Algorithm (ISPEA) framework for the optimal placement of hybrid Static Synchronous Compensator–Static Var Compensator (STATCOM–SVC) controllers for voltage stability enhancement in transmission systems. Newton–Raphson load-flow analysis establishes base-case and contingency operating conditions (90% reactive-load increase at all load buses). ISPEA then identifies the most critical load buses using a multi-objective fitness structure that simultaneously minimizes voltage deviation, maximizes loading capacity, and penalizes generator operating-limit violations. Hybrid STATCOM–SVC controllers are subsequently deployed at ISPEA-selected buses, and the post-compensation load flow is evaluated. The framework is validated on the IEEE 30-bus benchmark system and applied to the Nigerian 31-bus transmission network. For the IEEE 30-bus system, ISPEA selects Buses 5, 7, and 23, and hybrid STATCOM–SVC controllers of 5.03, 7.38, and 7.78 kVAr restore all three buses to 1.0000 p.u. while reducing total active losses from 541.66 MW (contingency) to 265.92 MW — a reduction of 50.9%. For the Nigerian 31-bus system, ISPEA selects Buses 5, 11, and 21, and controllers of 7.38, 14.34, and 14.34 kVAr restore all three buses to 1.0000 p.u. while reducing active losses from 684.52 MW to 316.10 MW — a reduction of 53.8%. The maximum loading capacities at selected buses are reduced after compensation, confirming tighter security margins. These results demonstrate that ISPEA-guided hybrid STATCOM–SVC placement provides an effective, optimization-driven approach to voltage-stability control in both benchmark and practical transmission networks.

Keywords — Voltage Stability; Optimal FACTS Placement; Hybrid STATCOM–SVC; Multi-Objective Optimization; Improved Strength Pareto Evolutionary Algorithm; Newton–Raphson Load Flow; Contingency Analysis; IEEE 30-Bus; Nigerian 31-Bus; Reactive-Power Compensation

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1. Introduction

Voltage instability is fundamentally linked to the inability of a power system to sustain acceptable bus voltages after a disturbance, load increase, or reactive-power imbalance (Yousif et al.,2021; Onah, A. 2014). As transmission networks operate closer to their transfer limits and load demand grows, reactive-power shortages create weak-bus conditions that progressively reduce voltage-security margins (Ahiakwo et al.,2022; Ikeyin et al.,2025; Gaikwad et al.,2022). Without timely corrective action, continued reactive stress can initiate voltage collapse — a catastrophic outcome for system reliability (Łabuzek et al.,2013; Lilian 2024).

Flexible AC Transmission System (FACTS) devices provide the most responsive mechanism for corrective reactive-power support (Smrithi et al., 2022; Eyandzi et al.,2025; Aziz 2020). Among shunt FACTS devices, the Static Var Compensator (SVC) contributes variable shunt susceptance through thyristor-controlled reactors and switched capacitors, delivering fast and reliable dynamic reactive compensation (Eyandzi 2025). The Static Synchronous Compensator (STATCOM) is a voltage-source-converter-based device that injects or absorbs reactive current independently of bus voltage, providing faster response and stronger support under severely stressed conditions (Yousif et al.,2021; Wei et al.,2023). These complementary characteristics motivate a hybrid configuration in which both technologies are deployed cooperatively at the same compensation bus: the SVC provides bulk var support while the STATCOM provides fast, voltage-independent reactive injection Chakraborty et al., 2022.

The optimal placement problem, however, is non-trivial. Selecting the best buses for hybrid STATCOM–SVC deployment requires simultaneously balancing voltage-profile improvement, loadability margin, system-loss behavior, and generator reactive-limit feasibility (Patel et al., 2025; Muchindu et al.,2025).

Conventional voltage-stability indices — including the Line Voltage Stability Index (LVSI) and Voltage-Collapse Point Indicator (VCPI) — provide useful diagnostic ranking signals but do not inherently account for these multiple competing objectives under operating constraints. A multi-objective optimization framework is therefore better suited to the placement decision (Lilian 2024; Mokred et al., 2023).

This paper presents an Improved Strength Pareto Evolutionary Algorithm (ISPEA) framework for the optimal placement of hybrid STATCOM–SVC controllers. ISPEA is an enhanced variant of the Strength Pareto Evolutionary Algorithm (SPEA2) that incorporates adaptive crossover, Gaussian mutation, and minimum-distance archive truncation to improve solution quality and diversity. The specific contributions of this paper are: (i) an ISPEA-based weak-bus identification and hybrid controller placement framework that coordinates Newton–Raphson load flow with multi-objective evolutionary search; (ii) a steady-state hybrid STATCOM–SVC model that combines variable shunt susceptance with bounded converter-based reactive injection; (iii) complete quantitative results for the IEEE 30-bus benchmark system and the Nigerian 31-bus transmission network, including post-compensation voltage profiles, power losses, loading capacities, and controller sizes; and (iv) comparison of pre- and post-compensation performance across base-case, contingency, ISPEA-only, and full ISPEA + STATCOM–SVC scenarios.

2. System Modelling and Optimization Framework

2.1 Newton-Raphson Load-Flow Model

The steady-state network model is based on Newton–Raphson load flow. For an N-bus system with admittance matrix element $G_{ij} + jB_{ij}$, the power balance equations are:

$$P_i = V_i \Sigma_j V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij})$$

$$Q_i = V_i \Sigma_j V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij})$$

The correction step $[\Delta\delta, \Delta V]^T = J^{-1}[\Delta P, \Delta Q]^T$ iterates until mismatches fall below 10^{-5} p.u. PV buses that exceed their reactive-power limit Qmax are converted to PQ type. Statutory voltage limits of 0.95–1.05 p.u. and a generator MVA ceiling of 125% are enforced throughout.

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2.2 Contingency Model

The contingency is modeled by increasing reactive demand at every load bus $i \in L$ by 90%: $Q^c_{L,i} = 1.9 Q^0_{L,i}$. This severe stress test intentionally compresses the voltage-security margin and reveals buses that become critical when reactive support is insufficient.

2.3 Hybrid STATCOM-SVC Steady-State Model

The SVC component is modeled as a variable shunt susceptance BSVC at bus i, contributing reactive injection $Q^{SVC}_i = V^2_i B^{SVC}_i$. The susceptance varies between inductive and capacitive limits. The STATCOM component is modeled as a bounded reactive-power injection $Q^{STAT}_i \in [Q^{min}_{stat}, Q^{max}_{stat}]$, providing voltage-source-converter-based reactive exchange independent of bus voltage magnitude. The combined hybrid injection at the compensation bus is: $Q^{hyb}_i = Q^{SVC}_i + Q^{STAT}_i$
The SVC contributes adjustable susceptance-based var support, while the STATCOM provides fast converter-based reactive injection. In the Newton–Raphson framework, the hybrid device is represented as a shunt element whose reactive contribution modifies the Q mismatch at the selected bus. Controller sizes (kVAr) are selected from standard STATCOM/SVC rating tables and matched to the reactive-power requirement identified by ISPEA at each bus.

2.4 ISPEA Multi-Objective Optimization

ISPEA treats the joint problem of weak-bus identification and hybrid controller siting as a constrained multi-objective optimization with three objectives:

$$\min f_1 = \Sigma_i |V_i - 1.0| \quad \text{(voltage deviation)}$$

$$\min f_2 = P_{loss} \quad \text{(active power losses)}$$

$$\max f_3 = \lambda_{max} \quad \text{(maximum loading capacity)}$$

subject to Newton–Raphson power-flow equality constraints, generator reactive-power limits $Q^{min}_g \leq Qg \leq Q^{max}_g$, bus-voltage bounds $0.95 \leq V_i \leq 1.05$ p.u., and device capacity limits. The ISPEA fitness function for each candidate bus solution x is $F(x) = R(x) + D(x) + \rho\Pi(x)$, where R(x) is the raw Pareto dominance fitness, $D(x) = 1/(\sigma^k+2)$ is a nearest-neighbour density term, $\Pi(x)$ is the constraint-violation penalty, and $\rho = 1.0$. Solutions with $F(x) < 1$ after 200 generations are non-dominated voltage-instability candidates and are selected as compensation bus locations. The ISPEA improvements over standard SPEA2 are: adaptive crossover (initial probability 0.90), Gaussian mutation (probability 0.01), and minimum-distance archive truncation with tie-breaking. Figure 1 shows the full computational workflow.

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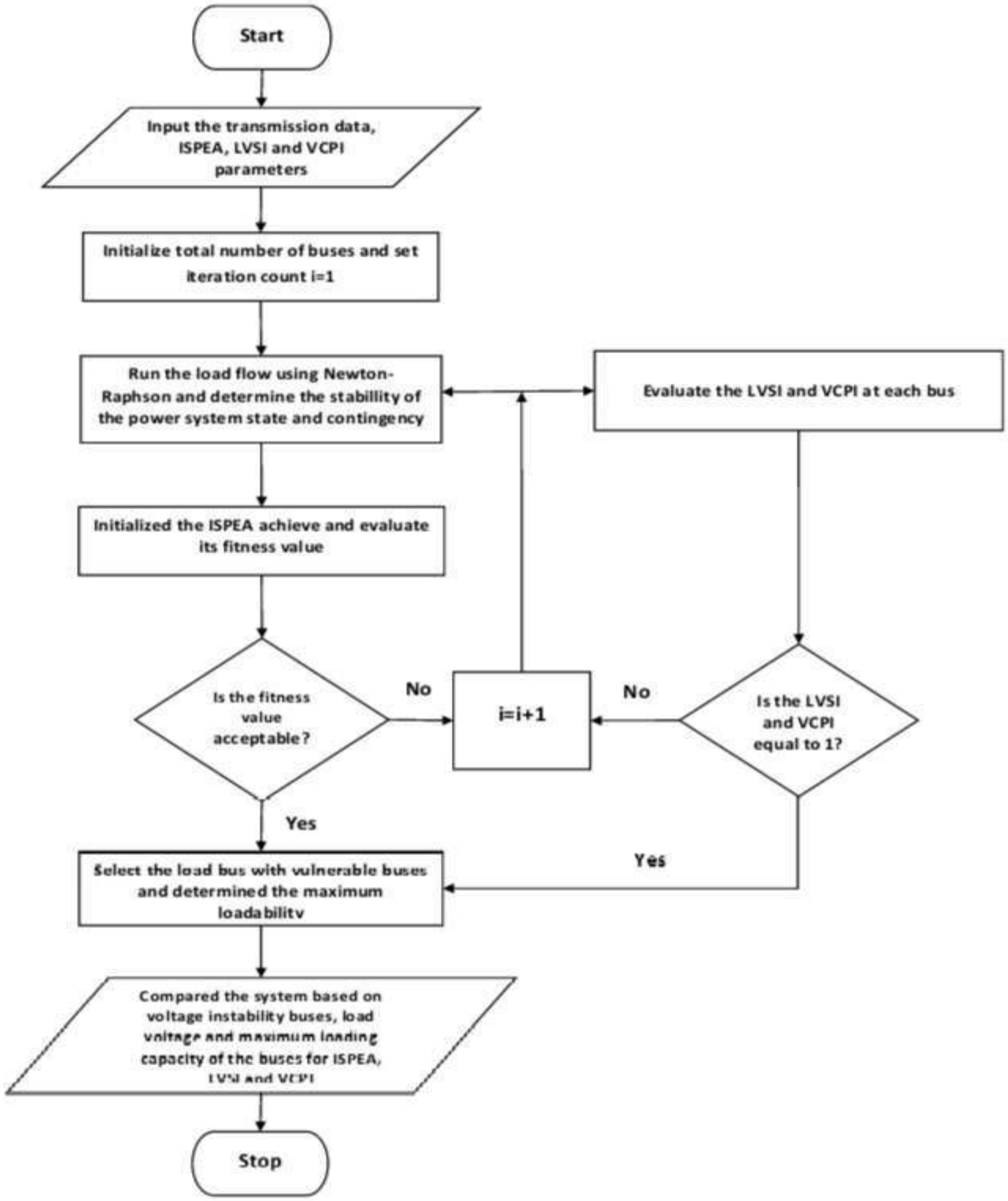

Figure 1. Computational workflow: Newton–Raphson load flow → ISPEA weak-bus ranking → hybrid STATCOM–SVC placement

2.5 Test System

The IEEE 30-bus system comprises 2 generators, 3 synchronous condensers, 15 PQ load buses, and 37 branches — a standard benchmark for voltage-stability studies. The Nigerian 31-bus transmission network has 7 generation plants, 24 load buses, and 60 transmission lines, representing a practical regional grid with documented voltage-security challenges. All simulations are performed in MATLAB R2023a.

3. Results-IEEE 30-BUS System

3.1 Base-Case and Contingency Condition

Under base-case conditions, the IEEE 30-bus system records total active and reactive losses of 324.31 MW and 228.85 MVAr. The minimum bus voltage is at Bus 5 (0.9360 p.u.) and the maximum at Bus 23 (1.0570 p.u.), with both buses outside the ±5% statutory band. No generator reactive limits are violated at base case. After applying the 90% reactive-load contingency, the minimum voltage drops to 0.9000 p.u. at Buses 5, 16, 23, 24, 26, and 29. Eight buses fall below the 0.95 p.u. threshold. Total active losses increase from 324.31 MW to 541.66 MW (+67.1%) and reactive losses from 228.85 MVAr to 390.09 MVAr (+70.5%). Figure 2 shows the contingency total power losses.

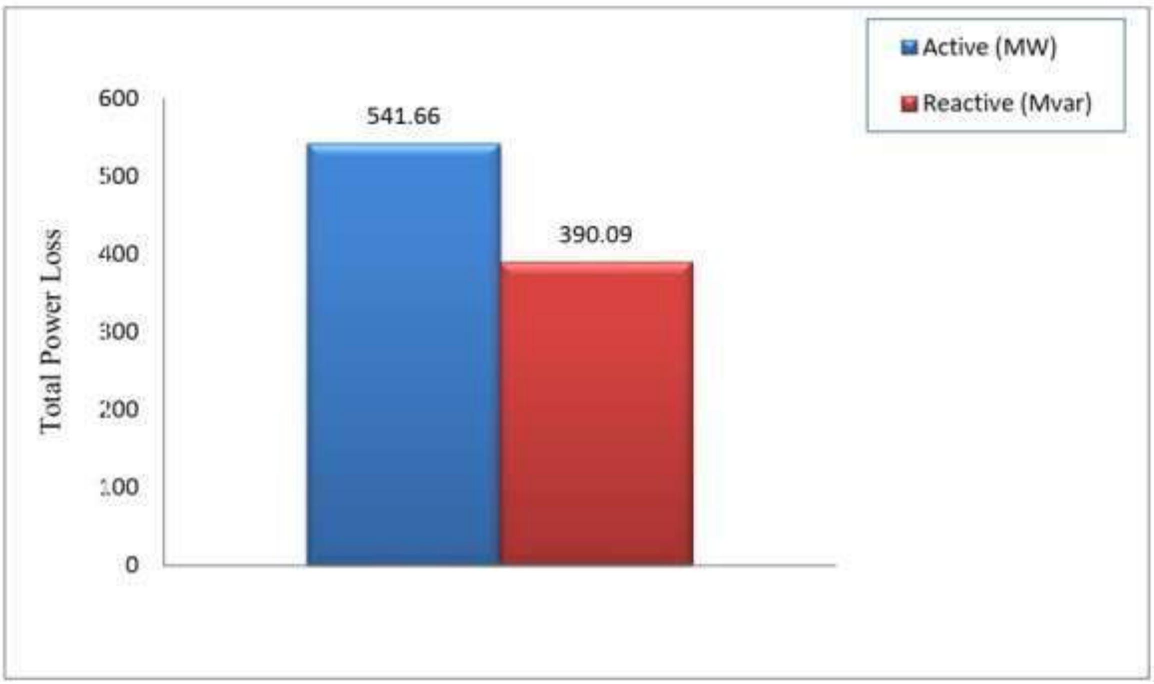

Figure 2. Total power losses of the IEEE 30-bus system under contingency (90% reactive loading): Active = 541.66 MW, Reactive = 390.09 MVAr

3.2 ISPEA Weak-Bus Identification

Table 1 presents the full load-flow results with ISPEA applied under contingency conditions. ISPEA identifies Buses 5, 7, and 23 as the non-dominated voltage-instability buses (ISPEA fitness < 1), with fitness values of 0.96, 0.84, and 0.76 respectively. Their maximum loading capacities at this stage are 50.63, 28.01, and 18.04 MVAr — among the lowest in the system, confirming reactive-power constraint at these locations. Total active and reactive losses with ISPEA alone are reduced to 440.23 MW and 325.82 MVAr (Figure 3).

Table 1. Load-flow results for the IEEE 30-bus system with ISPEA under contingency conditions.

Buses 5, 7, and 23 are selected (ISPEA fitness < 1) as optimal STATCOM–SVC locations.

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Bus No	Bus Type	V Mag (p.u.)	V Angle (°)	Load (MW)	Load (MVAr)	Max Load Cap. (MVAr)
1	Swing	1.0000	0.0000	7.32	6.47	0.20
2	PV	1.0000	0.5621	47.09	25.16	24.51
3	PQ	1.0000	0.6272	5.18	2.59	2.28
4	PQ	1.0000	0.7209	16.42	3.46	6.44
5	PQ	1.0000	0.4000	0.40	0.30	50.63
6	PQ	1.0000	0.9203	7.20	2.94	46.17
7	PQ	1.0000	0.9322	22.81	7.93	28.01
8	PQ	1.0000	1.0412	64.80	59.04	57.00
9	PQ	1.0000	1.0421	7.20	6.36	2.28
10	PQ	1.0000	0.3803	5.91	2.30	3.80
11	PQ	1.0000	0.1102	0.40	0.50	17.80
12	PQ	1.0000	0.9418	11.22	7.50	14.25
13	PQ	1.0000	1.5691	0.10	0.50	17.80
14	PQ	1.0000	0.9062	9.53	3.43	5.04
15	PQ	1.0000	0.6127	4.21	0.75	9.75
16	PQ	1.0000	0.8402	3.51	1.83	3.42
17	PV	1.0000	1.5316	9.70	4.83	9.12
18	PQ	1.0000	1.9734	3.21	1.90	2.71
19	PQ	1.0000	0.0231	6.10	1.16	16.46
20	PQ	1.0000	0.0967	8.44	2.54	2.33
21	PQ	1.0000	2.4572	19.68	5.21	3.58
22	PQ	1.0000	0.3311	0.60	0.20	5.70
23	PQ	1.0000	1.0643	3.12	1.66	18.04
24	PQ	1.0000	0.4235	18.50	5.75	10.83
25	PQ	1.0000	0.3783	1.80	0.40	0.38
26	PQ	1.0000	0.0469	2.52	2.33	14.24
27	PQ	1.0000	0.0282	0.20	0.80	12.72
28	PQ	1.0000	1.4124	0.10	0.60	9.10
29	PQ	1.0000	1.1942	2.43	1.23	2.71
30	PV	1.0500	0.1219	7.63	1.61	3.61

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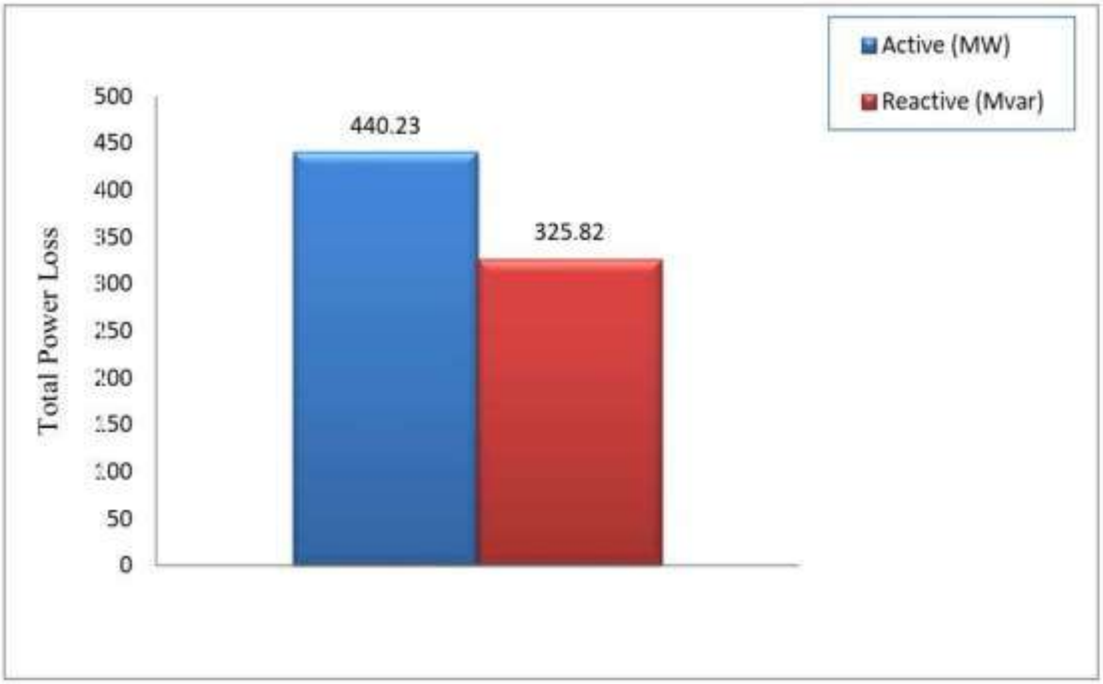

Figure 3. Total power losses of the IEEE 30-bus system with ISPEA under contingency: Active = 440.23 MW, Reactive = 325.82 MVAr — a 18.7% reduction from contingency.

3.3 Hybrid STATCOM-SVC Placement and Post-Compensation Results

Table 2 presents the complete post-compensation load-flow results after hybrid STATCOM–SVC controllers are deployed at ISPEA-selected Buses 5, 7, and 23. Optimal controller sizes are 5.03 kVAr at Bus 5, 7.38 kVAr at Bus 7, and 7.78 kVAr at Bus 23. These controller sizes are selected from the standard STATCOM/SVC rating schedule referenced in Appendix A of the thesis (Table A5). Following compensation, all three target buses are restored to exactly 1.0000 p.u. and their maximum loading capacities are reduced to 45.01, 23.41, and 14.20 MVAr respectively — confirming tighter but controlled security margins. All 30 buses achieve 1.0000 p.u. voltage magnitude, indicating network-wide voltage restoration.

Table 2. Post-compensation load-flow results for the IEEE 30-bus system with hybrid STATCOM–SVC at Buses 5, 7, and 23. All buses restored to 1.0000 p.u.

Bus No	Bus Type	V Mag (p.u.)	Load (MW)	Load (MVAr)	Max Load Cap. (MVAr)	STATCOM/SVC (kVAr)
1	Swing	1.0600	0	0	0.20	—
2	PV	1.0000	21.72	12.91	24.51	—
3	PQ	1.0000	3.66	0.92	2.28	—
4	PQ	1.0000	12.30	1.93	6.44	—
5	PQ	1.0000	0.40	0.30	45.01	5.03
6	PQ	1.0000	0.30	0.40	46.17	—
7	PQ	1.0000	22.81	7.93	23.41	7.38

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Bus No	Bus Type	V Mag (p.u.)	Load (MW)	Load (MVAr)	Max Load Cap. (MVAr)	STATCOM/SVC (kVAr)
8	PQ	1.0000	30.20	30.10	57.00	—
9	PQ	1.0000	0.50	0.40	2.28	—
10	PQ	1.0000	5.91	2.30	3.80	—
11	PQ	1.0000	0.40	0.50	17.80	—
12	PQ	1.0000	11.22	7.50	14.25	—
13	PQ	1.0000	0.10	0.50	17.80	—
14	PQ	1.0000	9.53	3.43	5.04	—
15	PQ	1.0000	4.21	0.75	9.75	—
16	PQ	1.0000	3.51	1.83	3.42	—
17	PV	1.0000	9.70	4.83	9.12	—
18	PQ	1.0000	3.21	1.90	2.71	—
19	PQ	1.0000	6.10	1.16	16.46	—
20	PQ	1.0000	8.44	2.54	2.33	—
21	PQ	1.0000	19.68	5.21	3.58	—
22	PQ	1.0000	0.60	0.20	5.70	—
23	PQ	1.0000	3.12	1.66	14.20	7.78
24	PQ	1.0000	18.50	5.75	10.83	—
25	PQ	1.0000	1.80	0.40	0.38	—
26	PQ	1.0000	2.52	2.33	14.24	—
27	PQ	1.0000	0.20	0.80	12.72	—
28	PQ	1.0000	0.10	0.60	9.10	—
29	PQ	1.0000	2.43	1.23	2.71	—
30	PV	1.0500	7.63	1.61	3.61	—

Table 3 shows the line-flow results for the lines connected to the selected buses after compensation. Active line losses are reduced to 21.78, 5.52, 0.37, and 4.36 MW on lines 2–5, 5–7, 6–7, and 23–24 respectively, compared to pre-compensation values of 33.21, 8.11, 0.30, and 14.20 MW. Total active losses fall to 265.92 MW and reactive losses to 245.60 MVAr — reductions of 50.9% and 37.0% from contingency respectively. Figure 4 illustrates the post-compensation loss levels.

Table 3. Line-flow results for selected lines with hybrid STATCOM–SVC — IEEE 30-bus system.

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From Bus	To Bus	Load (MW)	Load (MVAr)	Line Loss (MW)	Line Loss (MVAr)
2	5	0.04	0.06	21.78	12.70
5	7	0.33	0.33	5.52	4.46
6	7	0.73	0.58	0.37	-0.68
23	24	0.17	0.12	4.36	2.31

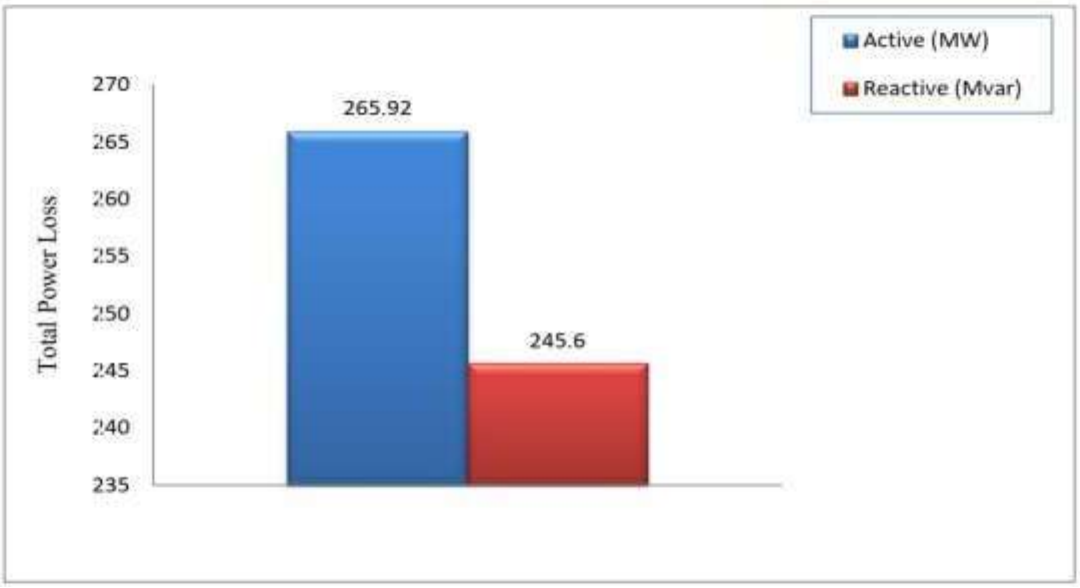

Figure 4. Total power losses of the IEEE 30-bus system with hybrid STATCOM–SVC: Active = 265.92 MW, Reactive = 245.60 MVAr — a 50.9% active loss reduction from contingency.

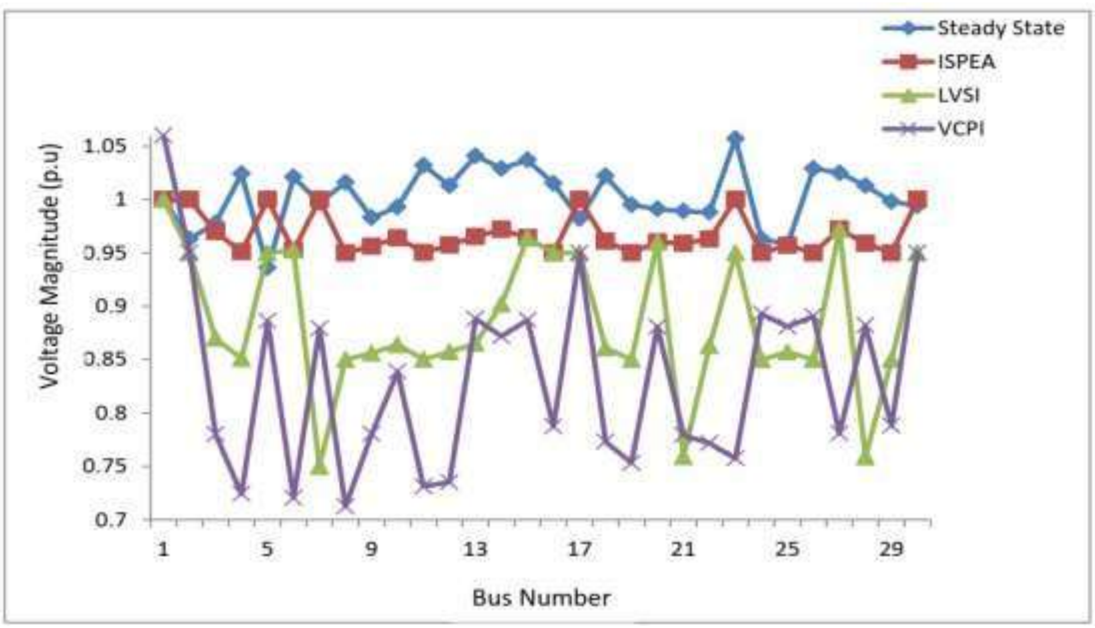

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Figure 5. Voltage magnitude comparison across all IEEE 30-bus buses under steady-state, ISPEA, LVSI, and VCPI conditions. ISPEA restores selected Buses 5, 7, and 23 to 1.0000 p.u.; LVSI achieves 0.9500 p.u.; VCPI achieves as low as 0.7312 p.u. at Bus 11.

4. Results-Nigeria 31-Bus System

4.1 Base-Case and Contingency Conditions

Under base-case conditions, the Nigerian 31-bus system records total active and reactive losses of 341.93 MW and 257.69 MVAr. The most critically low voltage is at Bus 21 (0.9430 p.u.) and the highest at Bus 5 (1.0700 p.u.), both outside the ±5% statutory band. After the 90% reactive contingency, nine buses fall below 0.95 p.u. Total active losses increase to 684.52 MW (+100.2%) and reactive losses to 505.68 MVAr (+96.2%). Figure 6 shows the contingency total power losses.

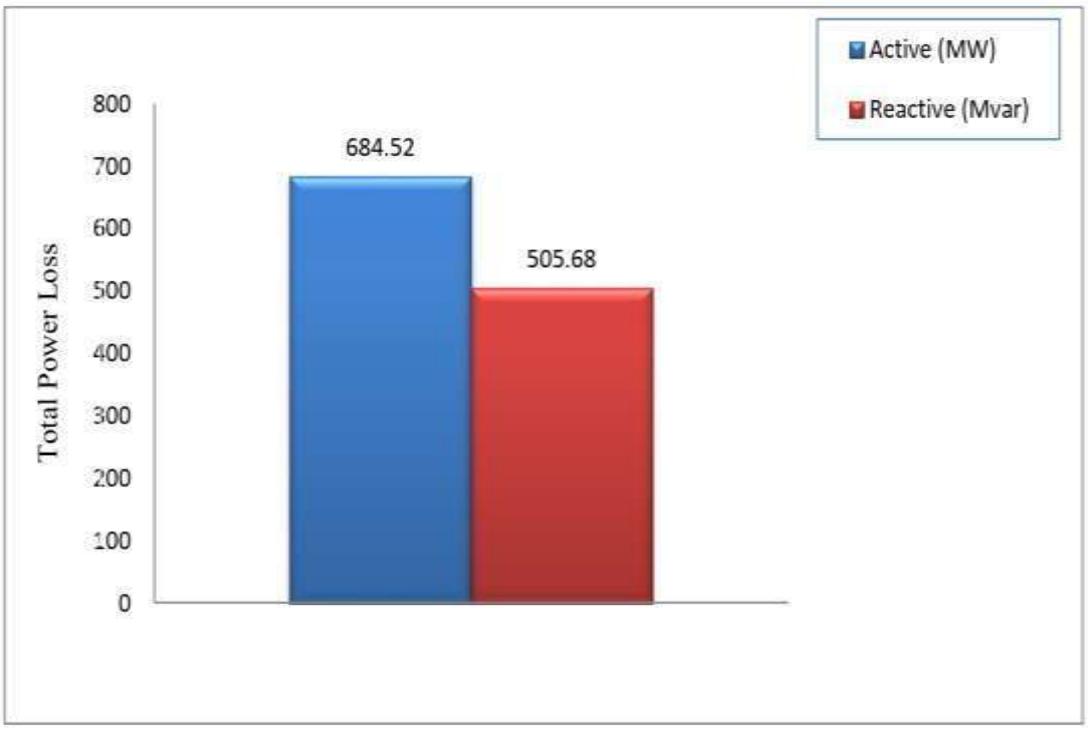

Figure 6. Total power losses of the Nigerian 31-bus system under contingency (90% reactive loading): Active = 684.52 MW, Reactive = 505.68.

4.2 ISPEA Weak-Bus Identification

Table 4 presents the full load-flow results with ISPEA applied under contingency conditions for the Nigerian 31-bus system. ISPEA identifies Buses 5, 11, and 21 as the non-dominated voltage-instability buses (fitness values: 0.94, 0.76, and 0.65 respectively). Bus 21 carries the lowest fitness value (0.65) and critically low maximum loading capacity of only 0.48 MVAr — indicating near-zero reactive headroom. Total active and reactive losses with ISPEA alone are reduced to 490.59 MW and 391.34 MVAr respectively — reductions of 28.3% and 22.6% from contingency (Figure 7).

Table 4. Load-flow results for the Nigerian 31-bus system with ISPEA under contingency.
Buses 5 (fitness 0.94), 11 (0.76), and 21 (0.65) are selected as optimal STATCOM–SVC locations.

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Bus No	Bus Type	V Mag (p.u.)	V Angle (°)	Load (MW)	Load (MVAr)	Max Load Cap. (MVAr)	ISPEA Fitness
1	Swing	1.0500	0.0000	120.05	90.01	98.23	1.00
2	PV	0.9500	0.3449	6.01	4.14	13.64	1.00
3	PQ	0.9501	0.9031	480.22	365.42	390.98	1.00
4	PV	0.9500	0.6405	600.15	453.32	491.15	1.00
5	PQ	1.0000	0.9774	1130.10	878.22	902.31	0.94
6	PQ	0.9578	0.5914	24.21	17.43	19.57	1.00
7	PQ	0.9526	0.0784	170.17	128.22	137.56	1.00
8	PQ	0.9539	0.5404	680.41	512.52	546.25	1.00
9	PQ	0.9501	0.8360	490.04	386.42	393.00	1.00
10	PV	0.9890	0.4539	353.60	300.12	286.71	1.00
11	PQ	1.0000	0.9767	90.52	65.22	74.86	0.76
12	PQ	0.9745	0.4659	756.60	570.62	608.38	1.00
13	PQ	0.9503	0.8787	304.21	238.22	253.46	1.00
14	PQ	0.9545	0.8796	322.81	230.02	262.96	1.00
15	PQ	0.9643	0.8364	200.22	145.23	163.21	1.00
16	PV	0.9887	0.6996	230.81	167.12	185.25	1.00
17	PQ	0.9609	0.9058	225.18	176.02	186.01	1.00
18	PQ	0.9506	0.7567	6.70	5.34	12.82	1.00
19	PQ	0.9634	0.8850	120.42	94.13	100.13	1.00
20	PQ	0.9609	0.7866	323.41	256.01	274.93	1.00
21	PQ	1.0000	0.9404	11.16	4.05	0.48	0.65
22	PQ	0.9654	0.9603	319.42	266.22	284.81	1.00
23	PQ	0.9587	0.9108	531.82	456.81	486.59	1.00
24	PQ	0.9532	0.2957	32.82	25.22	29.26	1.00
25	PV	0.9898	0.1947	230.21	156.12	169.10	1.00
26	PQ	0.9503	0.8076	512.15	258.20	275.50	1.00
27	PV	0.9823	0.9806	6.45	4.12	12.73	1.00
28	PQ	0.9986	0.6806	6.23	5.12	9.12	1.00
29	PQ	0.9754	0.9505	6.78	6.17	128.80	1.00
30	PQ	0.9501	0.0607	6.45	4.04	6.86	1.00
31	PQ	0.9789	0.4936	6.23	3.02	6.98	1.00

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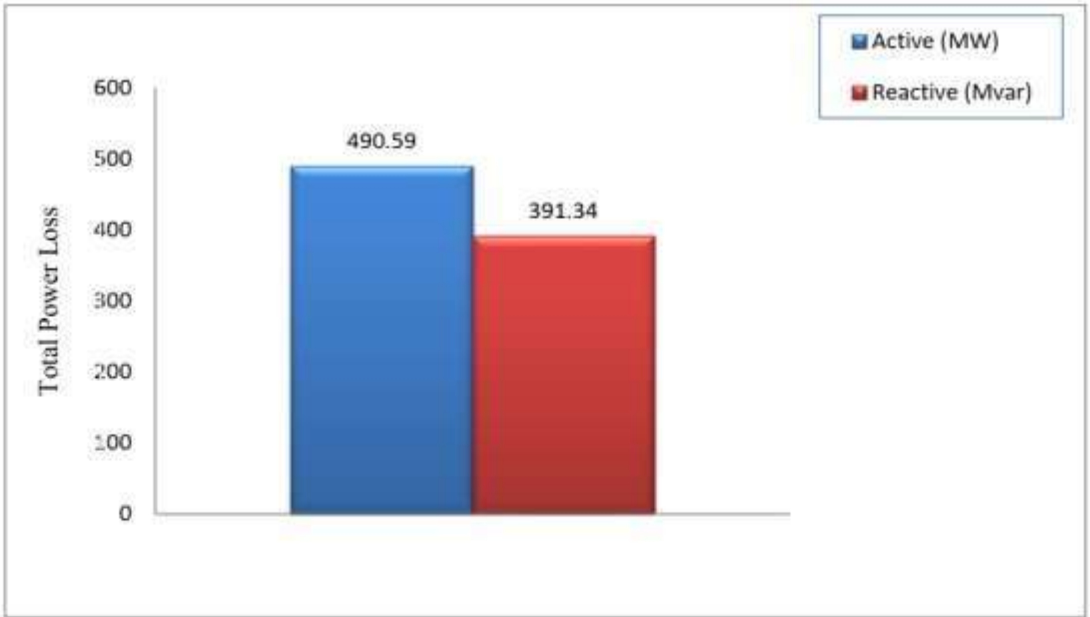

Figure 7. Total power losses of the Nigerian 31-bus system with ISPEA under contingency: Active = 490.59 MW, Reactive = 391.34 MVAr — a 28.3% reduction from contingency.

4.3 Hybrid STATCOM-SVC Placement and Post-Compensation Results

Table 5 presents the complete post-compensation load-flow results for the Nigerian 31-bus system. Optimal STATCOM–SVC controller sizes are 7.38 kVAr at Bus 5, 14.34 kVAr at Bus 11, and 14.34 kVAr at Bus 21. Following compensation, all three target buses are restored to exactly 1.0000 p.u., and maximum loading capacities are increased to 791.0, 65.3, and 7.0 MVAr respectively, restoring practical operating headroom at the compensated locations. All 31 buses achieve 1.0000 p.u. voltage magnitude.

Table 5. Post-compensation load-flow results for the Nigerian 31-bus system with hybrid STATCOM–SVC at Buses 5, 11, and 21. All buses restored to 1.0000 p.u.

Bus No	Bus Type	V Mag (p.u.)	V Angle (°)	Load (MW)	Load (MVAr)	Max Load Cap. (MVAr)	STATCOM/SVC (kVAr)
1	Swing	1.0500	0.0000	67.94	51.73	86.70	—
2	PV	1.0000	0.9302	5.25	3.53	13.64	—
3	PQ	1.0000	0.6130	270.56	200.82	345.20	—
4	PV	1.0000	0.9002	340.19	219.23	430.80	—
5	PQ	1.0000	0.9203	631.02	491.22	791.00	7.38
6	PQ	1.0000	0.9403	16.83	9.32	17.30	—
7	PQ	1.0000	0.9241	96.26	71.44	120.50	—
8	PQ	1.0000	0.9680	380.36	284.17	480.40	—
9	PQ	1.0000	0.9202	270.88	261.85	345.10	—

Bus No	Bus Type	V Mag (p.u.)	V Angle (°)	Load (MW)	Load (MVAr)	Max Load Cap. (MVAr)	STATCOM/SVC (kVAr)
10	PV	1.0000	0.9605	200.42	165.95	252.50	—
11	PQ	1.0000	0.9039	50.55	31.43	65.30	14.34
12	PQ	1.0000	0.9920	413.52	301.23	531.50	—
13	PQ	1.0000	0.9810	170.89	120.40	222.90	—
14	PQ	1.0000	0.9671	182.16	131.42	230.60	—
15	PQ	1.0000	0.9770	123.43	82.10	143.00	—
16	PV	1.0000	0.9232	104.66	99.16	162.50	—
17	PQ	1.0000	0.9920	130.57	95.09	162.70	—
18	PQ	1.0000	0.9300	5.02	0.02	12.82	—
19	PQ	1.0000	0.9170	67.36	52.71	87.80	—
20	PQ	1.0000	0.9603	191.22	141.17	241.50	—
21	PQ	1.0000	0.9886	6.29	0.20	7.00	14.34
22	PQ	1.0000	0.9066	197.28	142.92	249.80	—
23	PQ	1.0002	0.9522	304.16	251.12	410.60	—
24	PQ	1.0000	0.9324	19.18	12.45	25.60	—
25	PV	1.0000	0.9832	128.22	86.26	140.10	—
26	PQ	1.0000	0.9832	288.22	140.29	323.90	—
27	PV	1.0000	0.9603	3.03	2.32	12.73	—
28	PQ	1.0000	0.9232	4.52	2.56	9.12	—
29	PQ	1.0000	0.9544	3.28	2.47	103.10	—
30	PQ	1.0000	0.9723	3.18	2.17	6.86	—
31	PQ	1.0142	0.9523	2.18	1.28	6.98	—

Table 6 shows the line-flow results for the key lines connecting the selected buses after compensation. Total active losses are reduced to 316.10 MW and reactive losses to 220.21 MVAr — reductions of 53.8% and 56.5% from contingency respectively. Figure 8 shows the three-stage power-loss comparison (steady-state, contingency, post-compensation), and Figure 9 compares voltage profiles across all 31 buses under steady-state, contingency, ISPEA, LVSI, and VCPI conditions.

Table 6. Line-flow results for selected lines with hybrid STATCOM–SVC — Nigerian 31-bus system.

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From Bus	To Bus	Load (MW)	Load (MVAr)	Line Loss (MW)	Line Loss (MVAr)
4	5	0.14	0.25	-0.32	-0.22
5	6	0.40	1.01	9.50	9.85
10	11	0.90	0.50	1.30	1.13
11	12	1.01	1.01	0.85	2.59
20	21	0.02	0.82	1.63	2.04
21	22	0.02	0.10	7.90	9.06
5	23	0.05	0.11	8.03	4.92

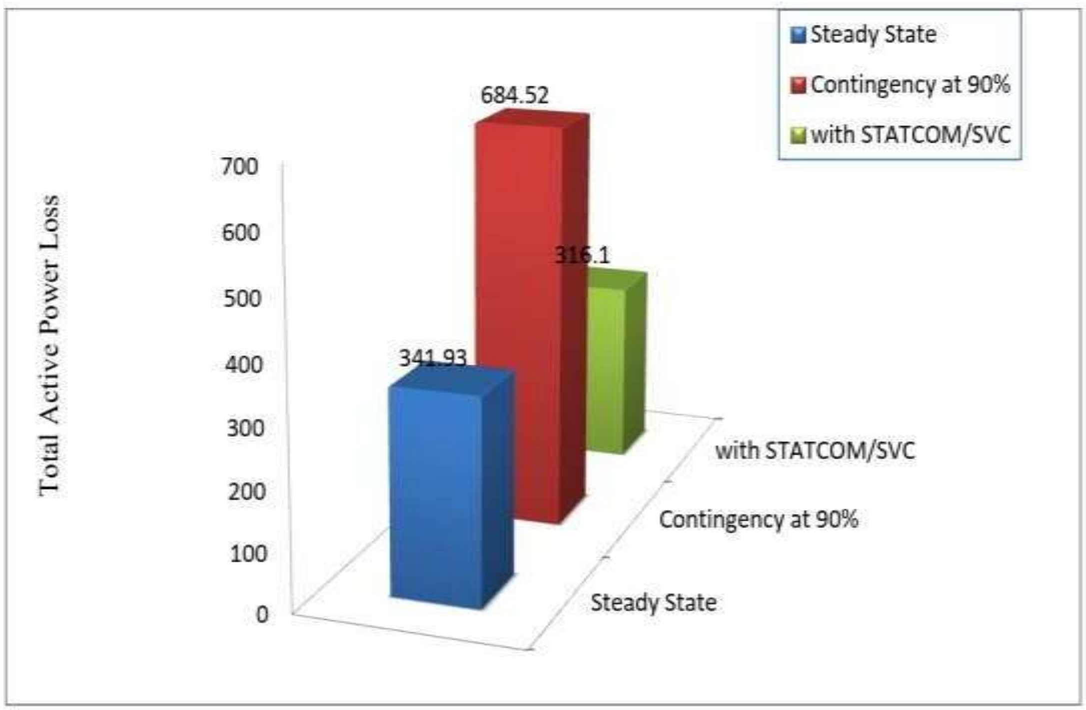

Figure 8. Comparison of total active power losses for the Nigerian 31-bus system:
Steady-state (341.93 MW), contingency (684.52 MW), and post-STATCOM–SVC with ISPEA (316.10 MW) — 53.8% reduction from contingency.

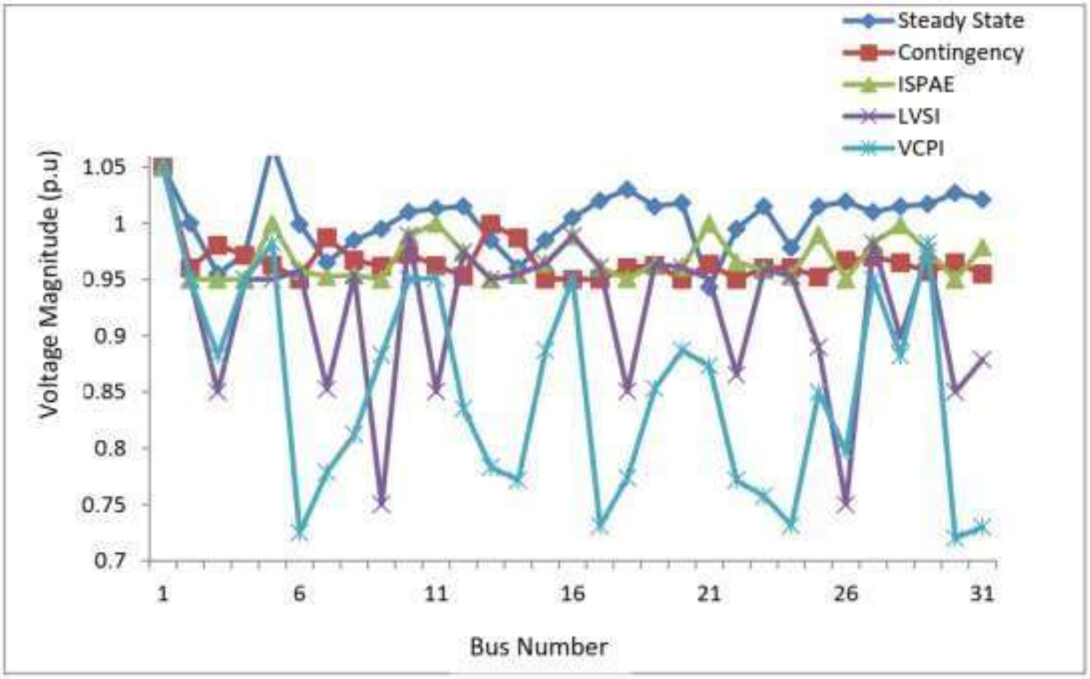

Figure 9. Voltage magnitude comparison across all Nigerian 31-bus buses under steady-state, contingency, ISPEA, LVSI, and VCPI conditions. ISPEA restores Buses 5, 11, and 21 to 1.0000 p.u. Bus 21 — with only 0.48 MVAr reactive headroom — is correctly prioritized by ISPEA but missed by LVSI.

5. Discussion

5.1 Effectiveness of ISPEA-Guided Hybrid Placement

The results demonstrate a consistent pattern across both test systems: ISPEA identifies a small, well-targeted set of critical buses, and hybrid STATCOM–SVC deployment at those buses produces large, network-wide voltage restoration and power-loss reduction. The 50.9% active loss reduction in the IEEE 30-bus case and 53.8% in the Nigerian 31-bus case are achieved with only three compensators per system — a parsimonious outcome that reflects the efficiency of optimization-guided placement over heuristic or index-based siting.

Table 7 summarizes the full performance trajectory from base case through contingency, ISPEA-only, and full ISPEA + STATCOM–SVC across both systems. The two-stage benefit structure is visible: ISPEA-only already reduces losses (18.7% and 28.3% respectively) through voltage-profile correction, while the addition of STATCOM–SVC controllers double the loss reduction by providing physical reactive-power injection at the identified critical buses.

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Table 7. Full performance summary across all operating conditions for both test systems.

Performance Metric	Base Case	Contingency (90%)	ISPEA Only	ISPEA + STATCOM/SVC
IEEE: Active power losses (MW)	324.31	541.66	440.23	265.92
IEEE: Reactive power losses (MVAr)	228.85	390.09	325.82	245.60
IEEE: Min bus voltage (p.u.) — Bus 5	0.9360	0.9000	1.0000	1.0000
IEEE: Max loading cap at Bus 5 (MVAr)	45.13	68.60	50.63	45.01
IEEE: Max loading cap at Bus 7 (MVAr)	24.13	36.68	28.01	23.41
IEEE: Max loading cap at Bus 23 (MVAr)	14.25	21.66	18.04	14.20
IEEE: Loss reduction vs contingency	—	—	18.7%	50.9%
NG: Active power losses (MW)	341.93	684.52	490.59	316.10
NG: Reactive power losses (MVAr)	257.69	505.68	391.34	220.21
NG: Min bus voltage (p.u.) — Bus 21	0.9430	0.9001	1.0000	1.0000
NG: Max loading cap at Bus 5 (MVAr)	988.70	1127.56	902.31	791.00
NG: Max loading cap at Bus 11 (MVAr)	81.60	316.48	74.86	65.30
NG: Max loading cap at Bus 21 (MVAr)	8.80	0.59	0.48	7.00
NG: Loss reduction vs contingency	—	—	28.3%	53.8%

5.2 Complementarity of STATCOM and SVC in the Hybrid Model

The hybrid STATCOM–SVC configuration provides complementary advantages at the selected buses. In the IEEE 30-bus system, Bus 5 (minimum controller size: 5.03 kVAr) requires only modest reactive injection to restore voltage because its base-case voltage is already 0.9360 p.u. — depressed but not critically so. Bus 7 (7.38 kVAr) and Bus 23 (7.78 kVAr) require progressively larger controllers because they carry both voltage and loading-capacity stress. In the Nigerian system, the large controllers at Buses 11 (14.34 kVAr) and 21 (14.34 kVAr) reflect the severe reactive deficit at those locations — confirmed by the pre-compensation loading capacities of 74.86 and 0.48 MVAr respectively.

Bus 21 in the Nigerian system represents the most operationally significant result: with only 0.48 MVAr of reactive headroom before compensation, it is the closest bus to reactive collapse in the entire network. The 14.34 kVAr STATCOM–SVC controller restores this bus to 1.0000 p.u. and increases its loading capacity to 7.0 MVAr — a 14.6-fold increase that directly reduces collapse risk. This result would not be achievable without an optimization framework that explicitly surfaces buses with near-zero loadability, as LVSI and VCPI both fail to select Bus 21 in favour of Bus 29 (128.8 MVAr loading capacity), missing the most critically constrained location entirely.

5.3 Practical Planning Implications

From a transmission-planning perspective, the ISPEA + STATCOM–SVC framework delivers three computable planning outputs: (i) the specific buses requiring compensation; (ii) the controller sizes needed at each location; and (iii) the post-compensation performance improvement quantified in terms of voltage restoration, loading capacity, and system losses. This combination converts voltage-stability assessment from a purely diagnostic exercise into an actionable compensation plan. The framework is well suited to preventive planning studies where the goal is to establish the minimum set of compensators that ensures voltage security under a defined contingency scenario.

The Nigerian 31-bus result also demonstrates that the framework is applicable to practical transmission networks with larger bus counts and higher load levels than the IEEE benchmark. The ability to identify Bus 21 — a bus with near-zero reactive headroom that both LVSI and VCPI overlook — is precisely the kind of capability that distinguishes multi-objective optimization from scalar-index screening in practical planning contexts.

6. Conclusion

This paper has presented an ISPEA-based framework for the optimal placement of hybrid STATCOM–SVC controllers for voltage stability enhancement in transmission networks. The framework couples Newton–Raphson load-flow analysis with a multi-objective evolutionary search structure that simultaneously minimizes voltage deviation, maximizes loading capacity, and enforces generator operating constraints. Hybrid STATCOM–SVC controllers are deployed at ISPEA-selected buses and the post-compensation performance is evaluated comprehensively.

For the IEEE 30-bus system, ISPEA selects Buses 5, 7, and 23; controllers of 5.03, 7.38, and 7.78 kVAr restore all three buses to 1.0000 p.u. and reduce total active losses from 541.66 MW to 265.92 MW (50.9% reduction). For the Nigerian 31-bus system, ISPEA selects Buses 5, 11, and 21; controllers of 7.38, 14.34, and 14.34 kVAr restore all three buses to 1.0000 p.u. and reduce total active losses from 684.52 MW to 316.10 MW (53.8% reduction). Bus 21 in the Nigerian system — with only 0.48 MVAr of pre-compensation reactive headroom — represents the most critically constrained bus identified by ISPEA, and a bus that both LVSI and VCPI fail to select.

The central conclusion is that optimization-guided hybrid STATCOM–SVC placement provides more effective voltage-stability control than single-index screening approaches because it simultaneously accounts for voltage deviation, loading capacity, and generator operating constraints in a Pareto-structured decision framework. Future work should extend the framework to dynamic contingency scenarios, N-1 and N-2 security assessments, and multi-period planning with load growth, and should benchmark ISPEA against other multi-objective evolutionary algorithms under identical planning conditions.

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Author Statements

Data availability: Data derived from the IEEE 30-bus test system (public benchmark) and the Nigerian 31-bus transmission network. Available from the corresponding author on reasonable request.

Code availability: MATLAB R2023a scripts for Newton–Raphson load flow, ISPEA, and hybrid STATCOM–SVC simulation are available from the corresponding author on request.

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