INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING, MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Voltage-Instability Bus Identification in Power Transmission Networks Using an Improved Strength Pareto Evolutionary Algorithm

[1] Ashiru S.K., [2]Amos Ibrahim S., [3]Akpan I.J., [4] Adebayo A.A.,[5] Olaoluwa I.A., [6] Ijaola M.O.,[7]Mafiana C.K., [8] Odia Akhere K.

[12356]National Space Research and Development Agency, Cooperative Information Network, Obafemi Awolowo University, Ile-Ife South-West Nigeria

[7,8] Centre for Transport and Propulsion, Epe, Lagos

DOI: https://doi.org/10.51583/IJLTEMAS.2026.150600269

Received: 13 July 2026; Accepted: 18 July 2026; Published: 03 August 2026

ABSTRACT

Voltage instability remains a major operational challenge in stressed transmission networks because reactive power deficiencies and contingency events can force bus voltages outside acceptable operating limits. This paper presents an Improved Strength Pareto Evolutionary Algorithm (ISPEA) for the identification of voltage-instability buses in transmission systems under steady-state and contingency loading. A Newton–Raphson load-flow model was first used to obtain the operating point of the network. Contingency severity is represented by a 90% increase in reactive demand at load buses, after which the ISPEA ranks buses using a multi-objective fitness structure based on voltage magnitude deviation, maximum loading capacity, and generator operating constraint penalties. ISPEA runs for 200 generations with a population of 100, an archive of 100, and a Newton–Raphson convergence tolerance of 10^{-5} p.u. The method was evaluated on the IEEE 30-bus and Nigerian 31-bus networks using MATLAB R2023a. Under base-case conditions, the IEEE 30-bus system reaches its minimum voltage at Bus 5 (0.9360 p.u.), whereas the Nigerian 31-bus system records its lowest voltage at Bus 21 (0.9430 p.u.). After contingency loading, the number of under-voltage buses increased from 2 to 8 in the IEEE system and from 2 to 9 in the Nigerian system. ISPEA identifies Buses 5, 7, and 23 as the most critical in the IEEE 30-bus system, and Buses 5, 11, and 21 in the Nigerian 31-bus system. Compared with LVSI and VCPI screening, ISPEA yields the lowest maximum loading capacity values across all evaluated buses, confirming the superior identification of genuinely vulnerable buses for reactive power compensation siting.

Keywords — Voltage instability; weak-bus identification; contingency analysis; transmission networks; multi-objective optimization; Improved Strength Pareto Evolutionary Algorithm; Newton–Raphson load flow; reactive-power planning

INTRODUCTION

Voltage stability is the ability of a power system to maintain acceptable voltage magnitudes under normal operating conditions and after any disturbances. When the system is heavily stressed, reactive power shortages, unfavorable power transfers, and topology changes can reduce the voltage stability margin and trigger progressive voltage decline or collapse (Zeitawyeh et al., 2025; Kobibi et al.,2022; Bharathi et al.,2023). Contemporary work continues to emphasize that contingency-aware voltage stability assessment remains essential because line outages and load increases can materially change the stability margin and ranking of vulnerable buses (Luo et al., 2024; Sobayo et al., 2024; Angadi et al., 2023).

The need for reliable weak-bus identification is especially critical in transmission systems that operate near security boundaries (Ismail et al., 2022; Puhan et al., 2024). In the Nigerian grid context, poor voltage profiles and network fragility remain operationally relevant concerns (Alayande et al., 2024; Adeyemi et al., 2025). A

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

recent Nigerian study also linked node-voltage improvement and reactive power support with improved grid security and resilience under contingencies (Okampo et al., 2022).

Classical approaches for locating voltage-vulnerable buses include the direct inspection of bus-voltage profiles, voltage stability indices, modal methods, continuation-power-flow-based critical-bus studies, and fuzzy or index-based ranking procedures (Valuva et al., 2023; Mamari et al., 2021; Putranto et al., 2024). Voltage stability indices are widely used to identify weak buses, estimate maximum loadability, and rank critical lines or areas (Ismail, 2022; Baleboina, 2024). Modal analysis is still used to identify the weakest buses using eigenvalues and participation factors (Ibrahim et al., 2021; Nappu et al., 2020). The continuation power flow remains a standard method for tracing P–V curves and determining the maximum loading points and weak buses, especially under contingencies (Wang, 2024). Fuzzy and index-based ranking procedures

They also continue to appear in decision support and compromise-solution selection for voltage-stability-constrained operation (Kyomugisha et al., 2022; Zhang et al., 2020; Kyomugisha et al.,2021).

These tools are valuable but are often used as deterministic screening instruments rather than explicit multi-objective decision frameworks (Alayande et al., 2024; Zhang et al., 2020). In practice, the weakest bus is rarely defined by voltage magnitude alone because operators also care about reactive power behavior, collapse proximity, maximum loading capacity, and compensation feasibility (Mokred et al., 2022; Adegoke et al.,2022; Adetokun et al.,2023). Recent studies have increasingly formulated voltage stability improvement and reactive power dispatch as constrained multi-objective optimization problems that balance voltage deviation, losses, cost, and security margins (A. A. Liu et al., 2024; Hu et al., 2026). Generator operating conditions and reactive power reserves are now also treated as part of the voltage stability assessment rather than peripheral details (B. B. Liu, 2023; Miyazaki et al.,2025).

This study addresses this gap by reformulating weak-bus identification as a constrained multi-objective search problem and solving it using an Improved Strength Pareto Evolutionary Algorithm (ISPEA). The central premise is that critical buses should be identified not only by their depressed voltage profile but also by their simultaneous association with a low voltage-security margin, lower maximum loading capacity, and tighter interaction with generator operating limits. The main contributions are as follows: (i) a Newton–Raphson–ISPEA voltage instability bus identification framework; (ii) a constraint-aware objective structure that explicitly incorporates generator operating limits; (iii) validation on both the IEEE 30-bus system and the Nigerian 31-bus network; and (iv) interpretation of selected buses as candidate locations for reactive power compensation.

METHODOLOGY

Power-Flow Formulation

For each test network, the steady-state operating point was obtained using the Newton–Raphson method. The active and reactive power balance equations are $P_i = V_i \Sigma_j V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij})$ and $Q_i = V_i \Sigma_j V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij})$. The Newton–Raphson 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 reach Qmax are switched to the PQ type for the remainder of the iteration, consistent with the standard PV-to-PQ conversion practice.

Contingency Model

The contingency severity is represented by $Q^c_{L,i} = 1.9\, Q^0_{L,i}$, where $Q^0_{L,i}$ is the base-case reactive load. This 90% reactive increase intentionally compresses the voltage security margin. The generator loading was simultaneously monitored against a 125% megavolt-amperes (MVA) ceiling.

ISPEA-Based Weak-Bus Identification and Flowchart

The weak-bus identification problem is posed as a constrained multiobjective optimization with three coordinated objectives: (i) minimize voltage deviation $|V_i - 1.0|$; (ii) maximize loading capacity (equivalently, minimize its negative); and (iii) minimize generator-operating-limit penalty. The ISPEA begins with a

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

population P of 100 solutions and an empty archive A. Each member x is assigned a strength $S(x) = | \{y \in P \cup A \mid x \prec y\} |$, raw fitness $R(x) = \Sigma_{\{y \prec x\}} S(y)$, density $D(x) = 1/ (\sigma^k + 2)$, and overall fitness $F(x) = R(x) + D(x) + \rho\Pi(x)$ with $\rho = 1.0$. Buses with $F(x) < 1$ after 200 generations are candidates for voltage instability. The "improved" aspects relative to standard SPEA are: (i) adaptive crossover (initial probability 0.90); (ii) Gaussian mutation (probability 0.01); and (iii) minimum distance archive truncation with next-smallest-distance tie-breaking. Figure 1 shows the full comparison analysis flowchart used in this study.

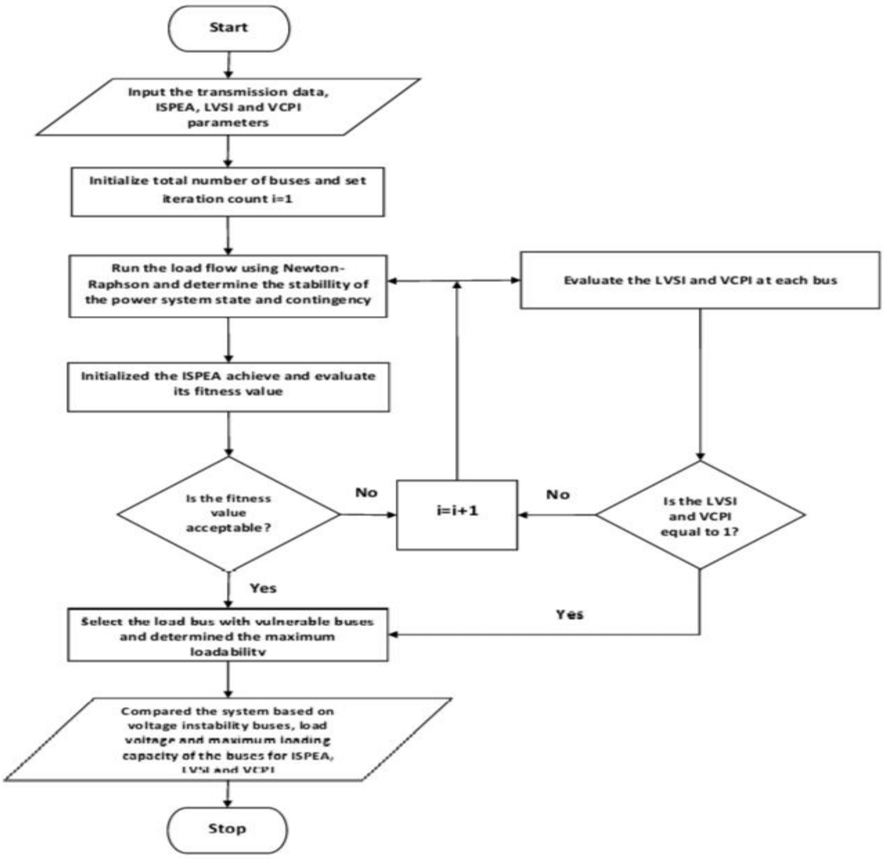

Figure 1. Flowchart of the Newton–Raphson–ISPEA comparison analysis framework

Bus-Ranking Rule

At convergence, the buses are ranked in ascending order of F(x). Buses with $F(x) < 1$ are non-dominated and classified as voltage instability candidates, and those with $F(x) \geq 1$ are excluded from the critical set.

Case Studies and Computational Setup

The IEEE 30-bus system has two generators, three synchronous condensers, 15 PQ load buses, and 37 branches. The Nigerian 31-bus system has seven generation plants, 24 load buses, and 60 transmission lines. Voltage limits of 0.95–1.05 p.u. and a 125% generator MVA ceiling were enforced. Table 1 shows the case study (CS) summaries for all ISPEA settings; stability was verified over 10 independent runs.

Table 1. Studies and Computational Setup CS. ISPEA computational parameters

Parameter	**Value**	**Notes**
Population size (|P|)	100	Fixed for both test systems
Archive size (|A|)	100	Maximum non-dominated solutions

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Max. generations	200	Stopping criterion
NR convergence tolerance	10^{-5} p.u.	Active/reactive mismatch threshold
Crossover probability	0.90	Adaptive single-point crossover
Mutation probability	0.01	Gaussian perturbation
Penalty coefficient ρ	1.0	Constraint-violation weighting
Voltage limits (p.u.)	0.95 – 1.05	±5% statutory band
Generator MVA ceiling	125% rated	Generator loading limit
Contingency loading	90% Q increase	Applied to all load buses
Independent runs	10	Solution stability verification
Software	MATLAB R2023a	Simulation environment

RESULTS AND DISCUSSION

Base-Case Load-Flow performance

Table 2 presents the base-case Newton–Raphson results for both networks. Under base-case conditions, the IEEE 30-bus network exhibits its lowest voltage at Bus 5 (V = 0.9360 p.u.), whereas Bus 23 registers V = 1.0570 p.u., both outside the ±5% statutory band. The total active and reactive losses were 324.31 MW and 228.85 MVAr, respectively. The Nigerian 31-bus network reaches its minimum at Bus 21 (V = 0.9430 p.u.), whereas Bus 5 exceeds the upper limit at V = 1.0700 p.u. No generator reactive limits were active in either system under the base conditions. The total losses for the Nigerian system were 341.93 MW and 257.69 MVAr. The maximum loading capacities at the two vulnerable IEEE buses are 45.13 MVAr (Bus 5) and 14.25 MVAr (Bus 23), confirming that the reactive headroom is already constrained before the contingency stress.

Table 2. Base-case load-flow results. Buses marked * fall outside the 0.95–1.05 p.u. statutory band.

IEEE 30-Bus System — Base Case

Bus No	**Bus Type**	**V Mag (p.u.)**	**V Angle (°)**	**P Load (MW)**	**Q Load (MVAr)**	**Max Load Cap. (MVAr)**
1	Swing	1.0000	0.0000	0	0	0
2	PV	0.9630	1.5160	21.7	12.9	30.64
3	PQ	0.9780	1.6270	2.4	1.2	2.28
4	PQ	1.0240	0.6750	7.6	1.6	6.46
5	PQ	0.9360*	1.6700	0	0	45.13
6	PQ	1.0210	2.9380	0	0	46.08
7	PQ	0.9970	1.9510	22.8	7.9	24.13

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

8	PQ	1.0160	1.9530	30.0	30.0	71.25
9	PQ	0.9830	1.9520	0	0	2.28
10	PQ	0.9930	0.9360	5.9	2.0	4.75
11	PQ	1.0320	1.1170	0	0	17.81
12	PQ	1.0130	0.4970	11.2	7.5	24.51
13	PQ	1.0410	2.4740	0	0	17.81
14	PQ	1.0290	2.8950	6.2	1.6	9.12
15	PQ	1.0370	2.5940	8.4	2.5	10.83
16	PQ	1.0150	0.5880	3.5	1.8	3.61
17	PV	0.9820	2.5440	9.0	4.8	11.40
18	PQ	1.0220	2.9100	3.2	0.9	3.04
19	PQ	0.9950	0.6270	9.5	3.4	16.86
20	PQ	0.9910	0.5990	4.2	0.7	3.80
21	PQ	0.9890	3.4470	19.7	5.2	3.61
22	PQ	0.9880	2.4370	0	0	5.70
23	PQ	1.0570*	1.4210	3.2	1.6	14.25
24	PQ	0.9630	1.3450	18.0	5.7	15.91
25	PQ	0.9580	1.3660	1.0	0	0.38
26	PQ	1.0290	3.4320	2.5	2.3	14.25
27	PQ	1.0250	0.6320	0	0	12.73
28	PQ	1.0130	2.4520	0	0	9.12
29	PQ	0.9980	2.0770	3.7	0.9	3.61
30	PV	0.9940	1.0370	12.0	1.9	4.51

Nigerian 31-Bus System — Base Case

Bus No	Bus Type	V Mag (p.u.)	V Angle (°)	P Load (MW)	Q Load (MVAr)	Max Load Cap. (MVAr)
1	Swing	1.0500	0.000	68.9	51.7	108.4
2	PV	1.0000	3.3950	0	0	13.64
3	PQ	0.9550	-0.2860	274.4	205.8	431.5
4	PV	0.9730	0.5060	344.7	258.5	538.5

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

5	PQ	1.0700*	0.9160	633.2	494.9	988.7
6	PQ	0.9990	2.4750	13.8	10.3	21.7
7	PQ	0.9650	0.8260	96.5	72.4	150.7
8	PQ	0.9850	3.8390	383.3	287.5	600.5
9	PQ	0.9950	1.5840	275.8	216.8	431.4
10	PV	1.0100	2.0940	201.2	170.9	315.6
11	PQ	1.0130	0.7490	52.5	39.4	81.6
12	PQ	1.0150	0.1500	427.0	320.2	664.4
13	PQ	0.9850	0.0780	177.9	133.4	278.6
14	PQ	0.9600	2.7980	184.6	138.4	288.3
15	PQ	0.9850	3.9570	114.4	85.9	178.7
16	PV	1.0050	1.5900	130.6	99.5	203.1
17	PQ	1.0200	1.2290	130.6	97.9	203.4
18	PQ	1.0300	0.5300	0	0.001	13.04
19	PQ	1.0150	-2.1200	70.3	52.7	109.8
20	PQ	1.0180	4.8480	193.0	144.7	301.9
21	PQ	0.9430*	2.2840	7.0	0.25	8.8
22	PQ	0.9950	-4.4480	199.8	149.9	312.3
23	PQ	1.0150	-0.1480	320.1	256.1	513.3
24	PQ	0.9780	1.5920	20.6	15.4	32.0
25	PV	1.0150	3.9400	130.0	89.0	175.1
26	PQ	1.0190	2.7520	290.0	145.0	404.9
27	PV	1.0100	2.5520	0	0	12.73
28	PQ	1.0150	3.7960	0	0	9.12
29	PQ	1.0170	3.8550	0	0	128.8
30	PQ	1.0270	3.9740	0	0	4.51
31	PQ	1.0210	-1.3550	0	0	6.98

Contingency-Case Load-Flow Performance

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

Table 3 presents the contingency-voltage profiles. The minimum voltage in the IEEE 30-bus system dropped from 0.9360 p.u. to 0.9000 p.u. (Buses 5, 16, 23, 24, 26, and 29), while the Nigerian 31-bus minimum drops from 0.9430 p.u. to 0.9001 p.u. (Bus 5). The under-voltage bus count increases from 2 to 8 in the IEEE system and from 2 to 9 in the Nigerian system. IEEE 30-bus active losses rise from 324.31 to 541.66 MW (+67.1%), and Nigerian 31-bus active losses rise from 341.93 to 684.52 MW (+100.2%). These results confirm that the 90% reactive contingency constitutes a severe stress that materially degrades the voltage security margin of both networks.

Table 3. Contingency-case load-flow results (90% reactive-load increase). Buses marked * fall below 0.95 p.u.

IEEE 30-Bus System — Contingency

Bus No	**Bus Type**	**V Mag (p.u.)**	**V Angle (°)**	**P Load (MW)**	**Q Load (MVAr)**	**Max Load Cap. (MVAr)**
1	Swing	1.0000	0.0000	8.76	7.68	0.38
2	PV	0.9500	0.5620	47.09	27.87	31.23
3	PQ	0.9600	0.6272	5.18	2.59	2.56
4	PQ	0.9500	0.7209	16.42	3.46	7.44
5	PQ	0.9000*	0.5919	7.2	4.08	68.60
6	PQ	0.9500	0.9203	7.2	2.94	50.04
7	PQ	0.9202*	0.9322	49.25	17.07	36.68
8	PQ	0.9501	1.0412	64.8	59.04	78.30
9	PQ	0.9501	1.0421	7.2	6.36	2.47
10	PQ	0.9600	0.3803	12.75	4.32	5.22
11	PQ	0.9500	0.1102	7.2	6.41	17.97
12	PQ	0.9573	0.9418	24.13	16.2	27.26
13	PQ	0.9600	1.5691	7.2	6.43	17.97
14	PQ	0.9500	0.9062	11.16	2.88	9.85
15	PQ	0.9601	0.6127	7.87	1.82	10.96
16	PQ	0.9000*	0.8402	25.92	4.11	6.65
17	PV	0.9500	1.5316	19.44	10.37	12.10
18	PQ	0.9601	1.9734	6.91	1.95	3.08
19	PQ	0.9200*	0.0231	20.52	7.35	17.05
20	PQ	0.9600	0.0967	9.07	1.51	3.98

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

21	PQ	0.9501	2.4572	28.37	7.90	5.49
22	PQ	0.9600	0.3311	7.2	6.42	5.96
23	PQ	0.9000*	1.0643	6.91	1.355	21.66
24	PQ	0.9000*	0.4235	38.88	12.31	24.18
25	PQ	0.9500	0.3783	2.16	6.72	0.90
26	PQ	0.9000*	0.0469	5.4	5.26	21.66
27	PQ	0.9500	0.0282	7.2	6.28	13.35
28	PQ	0.9500	1.4124	7.22	6.54	9.86
29	PQ	0.9000*	1.1942	18.15	5.20	5.49
30	PV	0.9500	0.1219	7.56	3.89	4.86

Nigerian 31-Bus System — Contingency

Bus No	**Bus Type**	**V Mag (p.u.)**	**V Angle (°)**	**P Load (MW)**	**Q Load (MVAr)**	**Max Load Cap. (MVAr)**
1	Swing	1.0500	0.0000	148.74	111.67	108.4
2	PV	0.9500	0.3463	7.92	5.45	13.64
3	PQ	0.9055*	0.9323	592.71	444.53	489.08
4	PV	0.9522	0.0053	744.06	558.36	538.5
5	PQ	0.9001*	0.9742	1266.80	1068.98	1127.56
6	PQ	0.9500	0.7012	29.81	22.25	21.7
7	PQ	0.9500	0.3043	208.44	156.38	150.7
8	PQ	0.9531	0.5443	827.93	621.0	600.5
9	PQ	0.9041*	0.8362	595.73	468.29	490.17
10	PV	0.9500	0.6392	434.59	369.14	315.6
11	PQ	0.9060*	0.9061	113.4	85.11	81.6
12	PQ	0.9500	0.0365	922.32	691.63	664.4
13	PQ	0.9003*	0.0772	384.24	288.15	316.48
14	PQ	0.9501	0.0763	398.74	298.94	288.3
15	PQ	0.9541	0.8343	247.10	185.55	178.7

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

16	PV	0.9500	0.6964	282.10	214.92	203.1
17	PQ	0.9534	0.9558	282.10	211.86	203.4
18	PQ	0.9201*	0.0773	8.06	6.73	19.82
19	PQ	0.9501	0.8023	151.85	113.83	109.8
20	PQ	0.9500	0.8662	416.88	312.11	301.9
21	PQ	0.9101*	0.9540	15.12	5.4	0.59
22	PQ	0.9541	0.0832	431.57	323.78	312.3
23	PQ	0.9561	0.9780	691.42	553.18	513.3
24	PQ	0.9504	0.0690	44.50	33.26	32.0
25	PV	0.9500	0.0427	280.8	192.24	175.1
26	PQ	0.9400*	0.2026	626.4	313.20	343.44
27	PV	0.9500	0.8046	8.06	5.45	12.73
28	PQ	0.9601	0.8301	7.92	6.61	9.12
29	PQ	0.9500	0.8025	8.29	7.63	128.8
30	PQ	0.9350*	0.1640	8.17	5.17	6.86
31	PQ	0.9500	0.0536	7.92	4.66	6.98

ISPEA Weak-Bus Ranking

Tables 4 and 5 present the core ISPEA weak-bus rankings, respectively. Figure 2 (IEEE) and 3 (Nigerian) show the corresponding total power losses after the ISPEA application. In the IEEE 30-bus network, ISPEA identifies Buses 5, 7, and 23 as the most critical under contingency loading (ISPEA fitness: 0.96, 0.84, 0.76; max loading caps: 50.63, 28.01, 18.04 MVAr). Bus 7 migrated into the critical set only under contingency, revealing contingency-sensitive vulnerability. In the Nigerian 31-bus network, buses 5, 11, and 21 are the most vulnerable (fitness: 0.94, 0.76, 0.65; max loading caps: 902.31, 74.86, 0.48 MVAr). Bus 21 had the lowest fitness value (0.65) with near-zero reactive headroom (0.48 MVAr), indicating extreme sensitivity to reactive stress.

Table 4. ISPEA weak-bus ranking — IEEE 30-bus system.

Bus	V Mag (p.u.)	Max Load Cap. (MVAr)	ISPEA Fitness	Base-Case Rank	Contingency Rank	Rank Shift
5	1.0000	50.63	0.96	1	1	0 (persistent)
7	1.0000	28.01	0.84	3	2	+1 (contingency-sensitive)
23	1.0000	18.04	0.76	2	3	-1 (less critical under stress)

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

24	0.9500	10.83	1.00	4	4	0
26	0.9500	14.24	1.00	5	5	0
29	0.9500	2.71	1.00	6	6	0

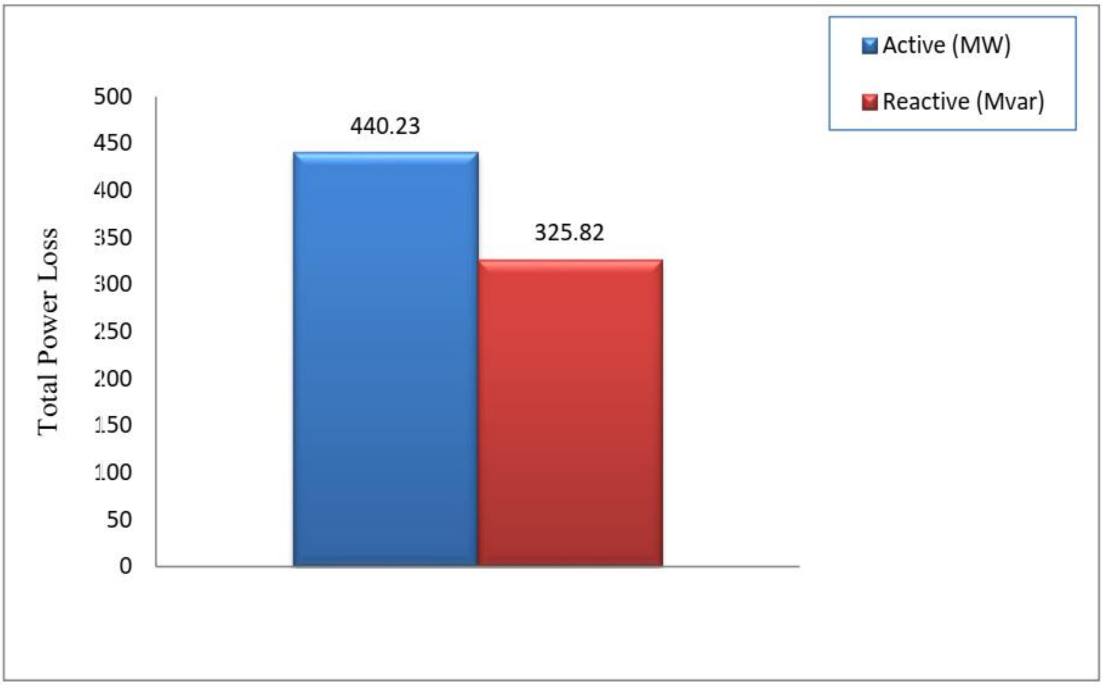

Figure 2. Total active and reactive power losses of the IEEE 30-bus system after ISPEA application: Active = 440.23 MW, Reactive = 325.82 MVAr

Table 5. ISPEA weak-bus ranking — Nigerian 31-bus system.

Bus	**V Mag (p.u.)**	**Max Load Cap. (MVAr)**	**ISPEA Fitness**	**Base-Case Rank**	**Contingency Rank**	**Rank Shift**
5	1.0000	902.31	0.94	1	1	0 (persistent)
11	1.0000	74.86	0.76	3	2	+1 (contingency-sensitive)
21	1.0000	0.48	0.65	2	3	-1 (severe, near-zero headroom)
26	0.9503	275.50	1.00	4	4	0
30	0.9501	6.86	1.00	5	5	0
3	0.9501	390.98	1.00	6	6	0

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

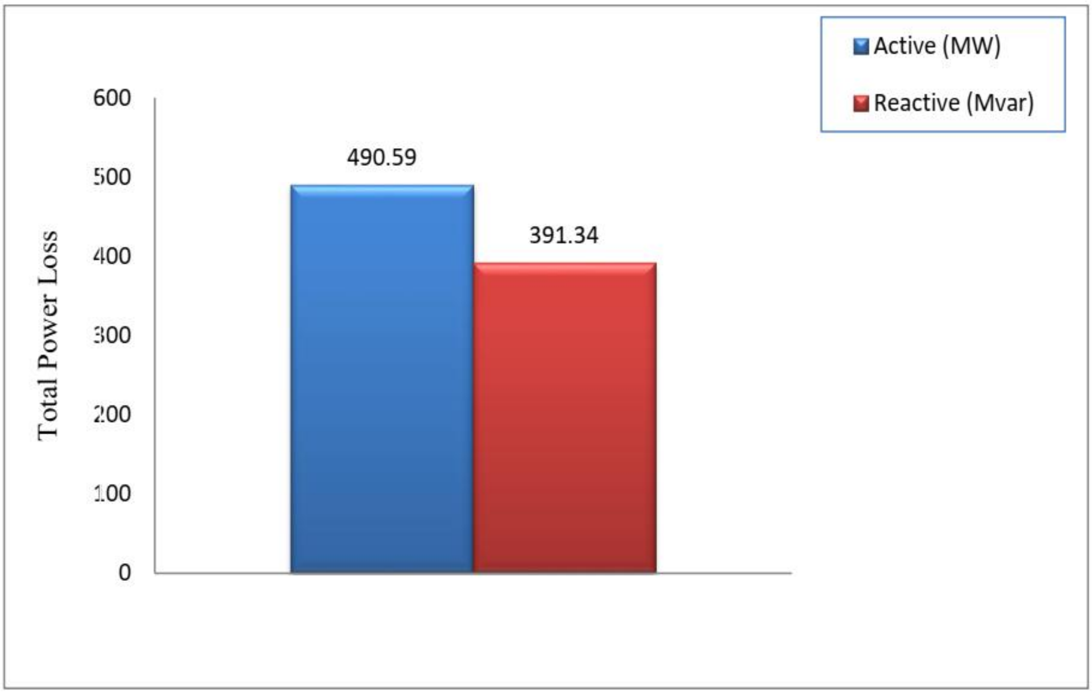

Figure 3. Total active and reactive power losses of the Nigerian 31-bus system after ISPEA application: Active = 490.59 MW, Reactive = 391.34 MVAr

Voltage-Profile Comparison (Figure 2 and 3)

Figure 2 compares the voltage magnitudes across all buses for the IEEE 30-bus system under steady-state, ISPEA, LVSI, and VCPI conditions. With ISPEA, buses 5, 7, and 23 each achieved 1.0000 p.u. In contrast, LVSI produces 0.9500 p.u. at buses 5, 16, and 23, whereas VCPI yields magnitudes of 0.8862, 0.7312, and 0.7793 p.u. at buses 5, 11, and 21, respectively. Figure 3 shows the corresponding comparison for the Nigerian 31-bus system. The ISPEA maintains 1.0000 p.u. at buses 5, 11, and 21; the LVSI produces 0.9503 p.u. at buses 5 and 21; and the VCPI achieves 0.9824, 0.9510, and 0.9822 p.u. at buses 5, 11, and 29, respectively. ISPEA consistently provided the strongest voltage recovery at the identified critical buses.

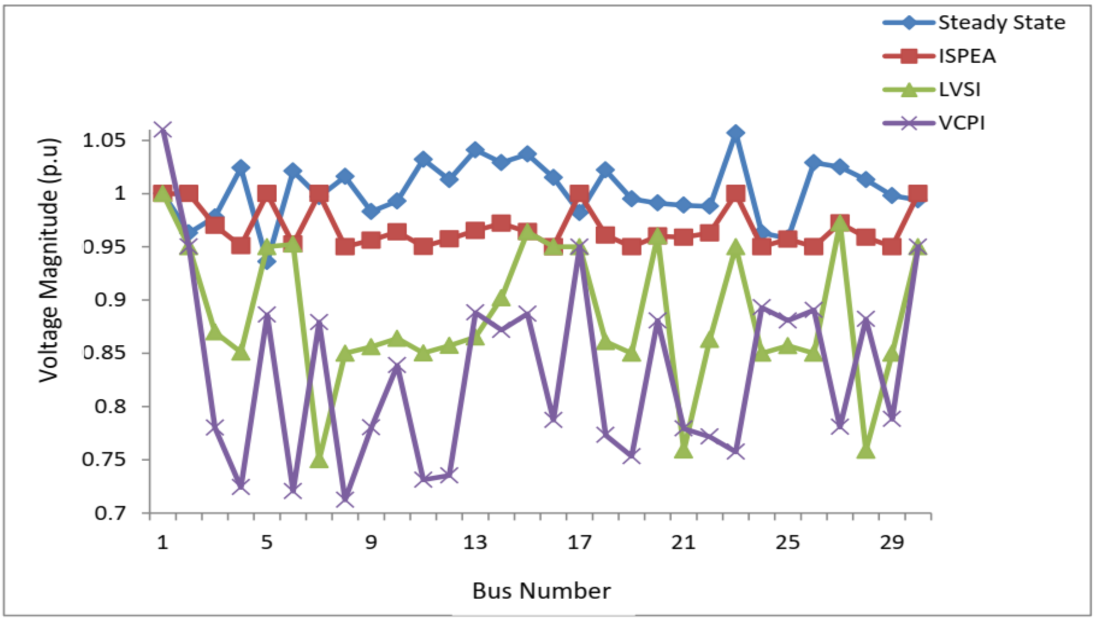

Figure 4. Comparison of voltage magnitude across all buses — IEEE 30-bus system under steady-state, ISPEA, LVSI, and VCPI conditions

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

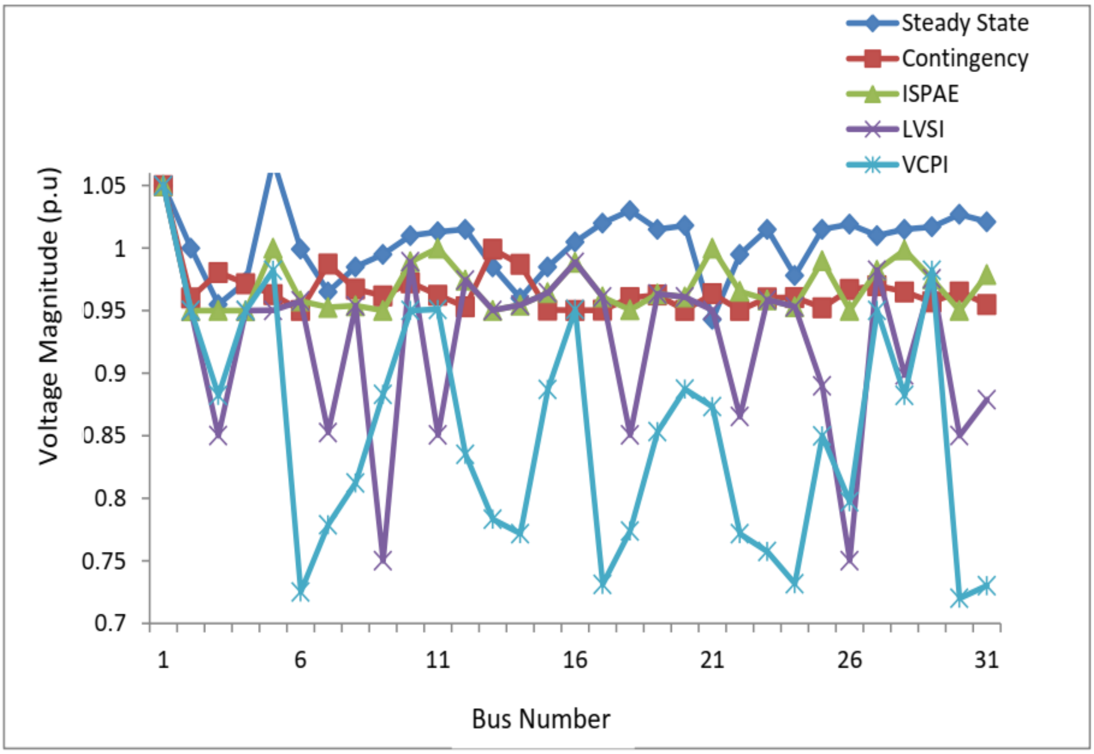

Figure 5. Comparison of voltage magnitude across all buses — Nigerian 31-bus system under steady-state, contingency, ISPEA, LVSI, and VCPI conditions.

Practical Implication for Compensation Placement

The ISPEA-selected buses constitute priority candidate locations for corrective reactive power support because they are not merely low-voltage buses; they are buses whose voltage weakness persists after loadability and generator operating constraints are incorporated. For the IEEE 30-bus system, a hybrid STATCOM/SVC at Buses 5, 7, and 23 with sizes 5.03, 7.38, and 7.78 kVAr restores all voltages to 1.0000 p.u. and reduces active losses to 265.92 MW (−50.9% from the contingency). For the Nigerian 31-bus system, STATCOM/SVC sizes of 7.38, 14.34, and 14.34 kVAr at Buses 5, 11, and 21 similarly restored voltages to 1.0000 p.u. and reduced active losses to 316.10 MW (−53.8% from contingency). ISPEA consistently yielded the lowest loading capacity values across all evaluated buses, which is an operationally meaningful outcome when the goal is to prioritize buses that are most susceptible to reactive power collapse.

CONCLUSION

This paper presents an Improved Strength Pareto Evolutionary Algorithm for voltage instability bus identification in transmission networks under steady-state and contingency loading. By combining the Newton–Raphson load-flow analysis with a constraint-aware multiobjective ranking structure, the ISPEA identifies weak buses using three coordinated criteria: voltage magnitude behavior, maximum loading capacity, and generator operating constraints. Application to the IEEE 30-bus and Nigerian 31-bus systems demonstrates that ISPEA is an effective decision-support tool for locating critical buses that should be prioritized for voltage-support interventions.

This method reframes weak-bus identification as an optimization problem rather than a single-index screening exercise. Under reactive power stress, the most problematic bus is the one that combines poor voltage with a low security margin and high exposure to operating constraints. A comparison with LVSI and VCPI confirmed that ISPEA yielded the lowest loading-capacity values across all evaluated buses, demonstrating superior prioritization of genuinely vulnerable locations. Future studies should validate the rankings against alternative contingencies, multiple loading patterns, and additional multi-objective optimizers.

Author Statements

Data availability: Derived from the IEEE 30-bus test system and Nigerian 31-bus transmission network dataset. Available from the corresponding author on reasonable request.

Code availability: MATLAB R2023a scripts are available. Available from the corresponding author on reasonable request.

Conflict of interest: The authors declare no conflicts of interest.

Funding: This research did not receive any external funding.

REFERENCES

1. Adegoke, S. A., & Sun, Y. (2022). Power system optimization approach to mitigate voltage instability issues: A review. Cogent Engineering. https://doi.org/10.1080/23311916.2022.2153416
2. Adetokun, B. B., Muriithi, C., Ojo, J., & Oghorada, O. (2023). Impact assessment of increasing renewable energy penetration on voltage instability tendencies of power system buses using a QV-based index. Scientific Reports, 13. https://doi.org/10.1038/s41598-023-36843-5
3. Adeyemi, N. A., & Adebayo, I. (2025). Power System Stability Development and Application of Mathematical Model of Reactive Power Loss Index as a Measurement of Voltage Stability in Nigerian Transmission System. LAUTECH Journal of Engineering and Technology. https://doi.org/10.36108/laujet/5202.91.0302
4. Alayande, A. S., Hassan, A., Olobaniyi, F., Osokoya, S. O., Adebeshin, A. I., & Ogundare, A. B. (2024). L-Index-Based Technique for Voltage Collapse Prediction and Voltage Stability Enhancement in Electrical Power Systems. ABUAD Journal of Engineering Research and Development (AJERD). https://doi.org/10.53982/ajerd.2024.0701.27-j
5. Angadi, R. V., Mangai, J. A., Manohar, V., Daram, S. B., & Rao, P. (2023). Ensemble-based data mining model for contingency analysis of power system under STLO. International Journal of Applied Power Engineering (IJAPE). https://doi.org/10.11591/ijape.v12.i4.pp349-358
6. Babu, R., Raj, S., Dey, B., & Bhattacharyya, B. (2021). Optimal reactive power planning using oppositional grey wolf optimization by considering bus vulnerability analysis. Energy Conversion and Economics. https://doi.org/10.1049/enc2.12048
7. Baleboina, G. M., & Rudramoorthy, M. (2024). Stability analysis of power system under n-1 contingency condition. Bulletin of Electrical Engineering and Informatics. https://doi.org/10.11591/eei.v13i4.6133
8. Bharathi, Atla, C. S. R., & M. R. S. (2023). Power System Voltage Collapse Mitigation Employing Optimization-Based Dynamic Voltage Stability Analysis. U.Porto Journal of Engineering. https://doi.org/10.24840/2183-6493_009-003_001645
9. Chi, Y.-Q., Tao, A., Xu, X., Wang, Q., & Zhou, N. (2023). Adaptive Many-objective Robust Optimization Model of Dynamic Reactive Power Sources for Voltage Stability Enhancement. Journal of Modern Power Systems and Clean Energy. https://doi.org/10.35833/mpce.2022.000431
10. Hu, Y., Hu, W., Li, X., Shi, Y., Jin, J., Ren, X., Fan, X., & Yang, T. (2026). Optimal reactive power dispatch based on a multitask-assisted constrained multimodal multi-objective evolutionary algorithm. iScience, 29. https://doi.org/10.1016/j.isci.2026.115434
11. Hu, Y., Hu, W., Li, X., Shi, Y., Jin, J., Ren, X., Fan, X., & Yang, T. (2026). Optimal reactive power dispatch based on a multitask-assisted constrained multimodal multi-objective evolutionary algorithm. iScience, 29. https://doi.org/10.1016/j.isci.2026.115434
12. Ibrahim, M., & Jasim, A. (2021). Voltage Collapse Prediction of IEEE 30-Bus System. Tikrit Journal of Engineering Sciences. https://doi.org/10.25130/tjes.28.1.10
13. Ismail, B., Wahab, N. A. A., Othman, M., Radzi, M., Vijyakumar, K. N., & Naain, M. N. M. (2020). A Comprehensive Review on Optimal Location and Sizing of Reactive Power Compensation Using Hybrid-Based Approaches for Power Loss Reduction, Voltage Stability Improvement, Voltage Profile Enhancement, and Loadability Enhancement. IEEE Access, 8, 222733-222765. https://doi.org/10.1109/access.2020.3043297

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

14. Ismail, B., Wahab, N., Othman, M. L., Radzi, M., Vijayakumar, K. N., Rahmat, M., & Naain, M. M. (2022). New Line Voltage Stability Index (BVSI) for Voltage Stability Assessment in Power System: Comparative Studies. IEEE Access, 10, 103906-103931. https://doi.org/10.1109/access.2022.3204792
15. Izzati, T. N., Soeprijanto, A., Syifa, B. N., Aryani, N. K., & Rahayu, P. (2025). Voltage Stability Enhancement Using NCPI-Based Optimal Reactive Power Compensation during Critical Line Outages. 2025 International Seminar on Intelligent Technology and Its Applications (ISITIA), 755-760. https://doi.org/10.1109/isitia66279.2025.11137457
16. Kobibi, Y. D., Djehaf, M. A., Khatir, M., & Ouadafraksou, M. (2022). Continuation Power Flow Analysis of Power System Voltage Stability with a Unified Power Flow Controller. Journal of Intelligent Systems and Control. https://doi.org/10.56578/jisc010106
17. Kyomugisha, R., Muriithi, C., & Nyakoe, G. (2022). Performance of Various Voltage Stability Indices in Stochastic Multiobjective Optimal Power Flow Using Mayfly Algorithm. J. Electr. Comput. Eng., 2022, 7456333:1-7456333:22. https://doi.org/10.1155/2022/7456333
18. Luo, Y., & Liu, C. (2024). Power Systems Static Voltage Stability Assessment Considering N-1 Contingencies Based on Holo-morphic Embedding Method. 2024 IEEE Power & Energy Society General Meeting (PESGM), 01-05. https://doi.org/10.1109/pesgm51994.2024.10761098
19. Luo, Y., & Liu, C. (2024). Power Systems Static Voltage Stability Assessment Considering N-1 Contingencies Based on Holo-morphic Embedding Method. 2024 IEEE Power & Energy Society General Meeting (PESGM), 01-05. https://doi.org/10.1109/pesgm51994.2024.10761098
20. Mamari, A. S. A., Toha, S., Ahmad, S., & Mamari, A. (2021). Modal analysis based on reactive power compensation on 6-bus Oman electrical grid. International Journal of Power Electronics and Drive Systems (IJPEDS). https://doi.org/10.11591/ijpeds.v12.i2.pp757-764
21. Miyazaki, M., Aoki, M., & Nakamura Y. (2025). Voltage Stability Estimation Considering Variability in Reactive Power Reserves Using Regression Trees. Energies. https://doi.org/10.3390/en18051260
22. Mokred, S., Wang, Y., & Chen, T.-L. (2023). A novel collapse prediction index for voltage stability analysis and contingency ranking in power systems. Protection and Control of Modern Power Systems, 8, 1-27. https://doi.org/10.1186/s41601-023-00279-w
23. Mossie, M. A., Yetayew, T., Bitew, G. T., Yenealem, M. G., & Beza, T. M. (2025). Machine learning algorithms for voltage stability assessment in electrical distribution systems. Scientific Reports, 15. https://doi.org/10.1038/s41598-025-15791-2
24. Nappu, M. B., Arief, A., Alam, N., & Zulfachri, M. (2020). Voltage stability assessment of the Southern Sulawesi power system in Indonesia for 2020 using modal analysis. IOP Conference Series: Earth and Environmental Science, 473. https://doi.org/10.1088/1755-1315/473/1/012097
25. Nascimento, S., & Gouvêa, M. (2021). Multi-objective Adaptive Evolutionary Algorithm to Enhance Voltage Stability in Power Systems. International Journal of Control, Automation and Systems, 19, 2596 - 2610. https://doi.org/10.1007/s12555-020-0095-4
26. Nascimento, S., & Gouvêa, M. (2021). Multi-objective Adaptive Evolutionary Algorithm to Enhance Voltage Stability in Power Systems. International Journal of Control, Automation and Systems, 19, 2596 - 2610. https://doi.org/10.1007/s12555-020-0095-4
27. Okampo, E., Nwulu, N., & Bokoro, P. (2022). Optimization of Voltage Security with Placement of FACTS Device Using Modified Newton–Raphson Approach: A Case Study of Nigerian Transmission Network. Energies. https://doi.org/10.3390/en15124211
28. Olasunkanmi, O. G., Barron, A. R., White, A. O., & Todeschini, G. (2024). Evaluation of HVDC Interconnection to Improve Voltage Stability of Nigerian Transmission Network. Journal of Electronics and Electrical Engineering. https://doi.org/10.37256/jeee.3120243799
29. Puhan, S. S., Sharma, R., & Mallick, M. (2024). Ensuring grid resilience: Voltage stability analysis and contingency ranking in electric power systems. e-Prime - Advances in Electrical Engineering, Electronics and Energy. https://doi.org/10.1016/j.prime.2024.100696
30. Puppala, V., & Chandrarao, D. T. P. (2018). Voltage stability assessment considering power system contingencies using continuation power flow method with regression.
31. Putranto, L. M., & Azhar, I. F. (2024). A proposed PMU-based voltage stability and critical bus detection method using an artificial neural network. Energy Informatics, 7. https://doi.org/10.1186/s42162-024-00302-w

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XV, Issue VI, June 2026

32. Sobayo, A. S., Adejumobi, O. I., Adebisi, I. A., & Adams, D. O. (2024). Contingency Approach for Static Security Assessment on the Nigerian 330 Kv Electric Power Transmission Grid. Advances in Science and Technology, 154, 203 - 212. https://doi.org/10.4028/p-stvce4
33. Valuva, C., Chinnamuthu, S., Khurshaid, T., & Kim, K.-C. (2023). A Comprehensive Review on the Modelling and Significance of Stability Indices in Power System Instability Problems. Energies. https://doi.org/10.3390/en16186718
34. Zeitawyeh, R. A., & Faza, A. (2025). Optimal Reactive Power Planning Using FACTS Devices for Voltage Stability Enhancement in Power Transmission Systems. Energy Sci. Eng., 13. https://doi.org/10.1002/ese3.70064.
35. Zhang, M., & Li, Y. (2020). Multi-objective optimal reactive power dispatch of power systems by combining classification-based multi-objective evolutionary algorithm and integrated decision-making. IEEE Access, 8, 38198-38209. https://doi.org/10.1109/access. 2020.2974961, 1(5): 186–200.