

Optimisation of Reactive Power Control in Electrical Power Systems using Facts Devices

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Abstract: - The integration of D-STATCOM into the transmission system enables reactive power compensation in the SEP, with the aim of stabilizing voltage and reducing active power losses. Diverging from conventional models that depend on simplified linear assumptions, this work integrates full non-linear power-flow equations; these are subjected to rigorous operational and security boundaries and are resolved using a Sequential Quadratic Programming (SQP) algorithm. The system architecture is modelled via the Y-bus admittance matrix to capture the complex interactions between generators, load demands, and compensating elements. Within this topology, the D-STATCOM is conceptualized as a controllable shunt element capable of dynamic transitions between inductive and capacitive modes, responsive to immediate grid requirements. Optimal siting is determined through the application of the Voltage Sensitivity Load-Based Index (VSLBI), a metric specifically calibrated to pinpoint network nodes exhibiting high susceptibility to voltage fluctuations. Validation of the methodology's scalability and computational efficiency is conducted across four standard IEEE benchmark systems: the 30-, 57-, 118-, and 300-bus networks. The IEEE case studies validated the stability of the proposed optimization model; the values obtained after integrating the D-STATCOMs demonstrate that the voltage remains within the operating ranges, thereby reducing active power losses. In the sensitivity tests, when the load was increased by 10%, 20%, and 30%, the power system remained stable and did not experience voltage sags. These results validate the D-STATCOM's ability to compensate for reactive power and dynamically regulate voltage.

Key-Words: - D-STATCOM, SQP algorithm, reactive power control, electrical grid dynamics, renewable energy, and VSLBI index.

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1 Introduction

The growing reliance on renewable energy particularly sources with intermittent behavior together with the steady rise in nonlinear loads linked to modern power-electronic devices and the increasing presence of dispersed generation, has noticeably altered how transmission networks operate, [1]. Such factors render infrastructure management increasingly arduous. Operators must now contend with frequent voltage instabilities, congestion in transmission corridors, and harmonic distortion—phenomena that directly threaten supply quality and system reliability. Against this backdrop, the efficient governance of reactive power becomes a critical mechanism for maintaining voltage profiles and curtailing technical losses, [2].

While legacy devices such as capacitor banks and shunt reactors retain utility for steady-state voltage regulation and power factor correction, their efficacy is inherently limited during rapid transient events. Their slow response to disturbances, the lack

of flexibility to shift dynamically between inductive and capacitive behavior, and their diminished effectiveness when voltages fall below nominal values tend to limit their contribution under present-day operating conditions, [3]. The transition towards energy systems with higher renewable penetration has therefore increased the need for more versatile technologies that can adjust in real time to rapid variations in both generation and demand, [4].

To mitigate these operational constraints, Distribution Static Synchronous Compensators (D-STATCOM) provide a sophisticated alternative within the Flexible AC Transmission Systems (FACTS) domain. Unlike legacy equipment, these units utilize Pulse-Width Modulation (PWM) converters to inject or absorb reactive power continuously. These devices rely on power-electronic converters based on pulse-width modulation (PWM), allowing them to supply or absorb reactive power continuously and in either direction. Their ability to react in milliseconds, to operate independently of system voltage and to

perform symmetrically across the four quadrants of the P–Q plane makes them especially valuable for enhancing the responsiveness and resilience of modern transmission systems, [5].

A diverse array of solving strategies has been recorded in the literature. In the context of radial systems, for instance, the deployment of multi-objective genetic algorithms achieved loss reductions approaching 24% [6], whereas combining Particle Swarm Optimization (PSO) with voltage sensitivity metrics resulted in an 18% gain in stability margins. Current evidence further suggests that Sequential Quadratic Programming (SQP), when integrated into optimal power flow frameworks, yields superior solution precision and convergence reliability compared to heuristic baselines, [7].

Beyond basic compensation, D-STATCOM deployment significantly enhances network utility. For instance, strategic siting can expand photovoltaic hosting capacity by up to 35%, effectively suppressing voltage fluctuations during periods of peak irradiance. Furthermore, proper siting is critical for supporting high-speed electric vehicle charging networks; it ensures power quality remains intact by keeping Total Harmonic Distortion (THD) strictly within the limits mandated by IEEE Std 519, [8].

Mathematically, the placement problem is often formulated as a multi-criteria optimization task that seeks to minimize active-power losses while improving voltage profiles. This formulation is subject to a range of constraints, including active and reactive power-balance equations, permissible voltage ranges, thermal limits of transmission lines and generation boundaries. Because of the non-convexity and inherent nonlinearities of the problem, more advanced optimization tools have been developed to achieve reliable solutions, [9]. Notably, introduced a mixed-integer optimization scheme aimed at easing congestion in transmission grids through selective line switching, combining DC power-flow representation with mixed-integer programming tailored to the Ecuadorian electrical system. The existing literature encompasses a diverse spectrum of formulations, ranging from LP, NLP, MILP, and MINLP to metaheuristic strategies like genetic algorithms and bee-swarm optimization, where each technique is tailored to specific operational environments. Furthermore, specific applications such as the CRITIC method applied to 69-kV sub-transmission grids underscore the capacity of structured optimization to bolster local voltage support mechanisms, [10].

The advent of machine learning has introduced novel dimensions to the siting and governance of FACTS assets. Researchers have, for instance, successfully employed deep neural networks to accelerate the search for optimal D-STATCOM nodes under diverse grid conditions, a strategy that drastically lowers computational costs. Simultaneously, methods based on adaptive differential evolution have emerged specifically to tackle the stochastic nature of renewable energy outputs, [11].

Notwithstanding such progress, the literature is still heavily populated by deterministic approaches that frequently overlook the random volatility typical of renewable generation and load demand. Consequently, this paper presents a hybrid framework that couples Sequential Quadratic Programming (SQP) with the Voltage Sensitivity Load-Based Index (VSLBI). The primary aim is to identify D-STATCOM configurations that simultaneously bolster voltage stability and curtail systemic losses. The method will be evaluated in four IEEE reference systems: 30-, 57-, 118-, and 300 bus systems. It also includes the sensitivity analysis under different load increase criteria. These results offer practical guidance for planners and operators of electrical networks, [12].

This paper is organized into four main parts. The Introduction outlines the motivation and scope of the research. The Methods section describes the modeling components and optimization procedure. The Results section presents the outcomes from the different IEEE test systems, comparing system performance before and after D-STATCOM installation. Finally, the Conclusions summarize the main findings and their implications for future application.

2 Problem Formulation

This study proposes a systematic approach for optimizing reactive power control through the implementation of D-STATCOM devices in electrical transmission systems. To achieve this, the methodology incorporates three complementary components: a mathematical representation of the transmission network and the FACTS device, an optimization process built around the VSLBI index, and a validation stage conducted using standard IEEE test cases. Through this approach, the work seeks to curtail active power losses and enhance voltage profiles, whilst strictly maintaining the system within secure operational limits.

2.1 Electrical System Representation

The transmission system considered in this work is composed of:

- **N:** Set of nodes or buses ($N = \{1, 2, \dots, n\}$)
- **L:** Set of transmission lines
- **G:** Set of connected generators
- **D:** Set of loads

Each bus can be connected to a power generation source, a load, and/or a D-STATCOM device; the system is represented by the admittance matrix Y_{BUS} which relates the injected currents to the nodal voltages:

$$I = Y_{bus} \cdot V \quad (1)$$

2.2 Nomenclature used in the Mathematical Model

Table 1 (Appendix) describes the notation used in the development of the mathematical model, as well as the variables and parameters used in the equations, ensuring an accurate and consistent interpretation of the theoretical framework and the formulations employed. It should be noted that the quantities are expressed in units (p.u.) where applicable, and their physical meaning is primarily associated with power flow, voltage control, and the performance of the D-STATCOM device within the power transmission system.

2.3 System Optimization and Objective Function

The optimization problem is established with the objective of minimizing active power losses in the transmission system of the established IEEE bus models, as shown in equation (2). This expression represents the difference between the total power generated and the total power consumed, including loads and the D-STATCOM. Under ideal conditions, the D-STATCOM does not exchange active power with the grid, which allows for simplifying the model according to equation (6).

$$FO: \text{Min}P_{\text{loss}} = \sum_{i \in G} P_{gi} - \sum_{j \in D} (P_{dj} + P_{dstj}) \quad (2)$$

where:

$i \in G$: index representing the generator set

$j \in D$: index representing the load set

The equilibrium of active and reactive power is inherently tied to the nodal characteristics of each bus. Within this framework, Equations (3) and (4) function as governing constraints that maintain the power flow balance across transmission lines, strictly respecting their individual thermal and stability limits. Furthermore, the integration of D-

STATCOM units serves as a dynamic mechanism for system compensation; by utilizing its reactive banks, the device actively mitigates voltage excursions and enhances the overall power quality of the transmission network.

The active power balance at each node i is governed by the following non-linear relationship, considering the network's conductance and susceptance:

$$P_{gen i} - P_{dem i} = \sum_{j \in N} |V_i| |V_j| (G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)) \forall i \in N \quad (3)$$

Simultaneously, the reactive power equilibrium must account for the dynamic support provided by the D-STATCOM unit $Q_{dst i}$ which adjusts based on the nodal voltage deviation:

$$Q_{gen i} - (Q_{den i} - Q_{dst i}) = \sum_{j \in N} |V_i| |V_j| (G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j)) \forall i \in N \quad (4)$$

The following equations are established for this mathematical model.

$$P_{gen i} = 0 \text{ si } i \notin G \quad (5)$$

$$P_{dem i} = 0 \text{ si } i \notin D \quad (6)$$

$$Q_{gen i} = 0 \text{ si } i \notin G \quad (7)$$

$$Q_{dem i} = 0 \text{ si } i \notin D \quad (8)$$

2.4 Power Flow Modeling and D-STATCOM

Equations (9) and (10) describe the active and reactive power flows between nodes, based on system electrical parameters and nodal voltage magnitudes and angles.

These expressions characterize the power flow exchange between buses, which are integrated into the admittance matrix along with the active power transmission losses. To evaluate the actual loading of the network links, the active power circulating between any pair of nodes i and j is rigorously determined by the following non-linear relationship

$$P_{ij} = |V_i|^2 G_{ij} - |V_i| |V_j| [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] \quad \forall (i, j) \in L \quad (9)$$

Conversely, the behavior of reactive power within the same network segments is governed by the interaction between voltage magnitudes and line susceptance, formulated as follows:

$$Q_{ij} = -|V_i|^2 B_{ij} - |V_i| |V_j| [G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j)] \quad \forall (i, j) \in L \quad (10)$$

where:

$(i, j) \in L$: pair of nodes connected by a transmission line

i : sending-end bus
 j : receiving-end bus

Equations (11) and (12) define the operational dynamics of the D-STATCOM. Given that active power exchange remains at zero, the reactive power injection is modeled as a function of the bus voltage, the internal voltage of the device, and the coupling reactance. This physical interdependence facilitates reactive power regulation through a binary decision variable, which effectively governs the optimal placement of the unit within the transmission network.

$$P_{dst,j} = 0 \forall j \in D_{DST} \quad (11)$$

where:

- $j \in D_{DST}$: candidate node for D-STATCOM installation

The D-STATCOM functions as a dynamic voltage regulator to counteract load fluctuations. During peak demand, the device operates in capacitive ($Q_{dst,j} > 0$), mode to support and elevate bus voltages. Conversely, during off-peak hours (valley periods) when low demand causes voltage levels to rise, the D-STATCOM absorbs reactive ($Q_{dst,j} < 0$), power to maintain stability. This dual-mode operation ensures that the nodal voltage remains within standardized operational limits regardless of the load profile.

2.5 Operational and Security Constraints of the System

To maintain system integrity, inequality constraints enforce a voltage regulation range between 0.95 and 1.05 p.u., targeting a nominal value of 1.0 p.u. for optimal steady-state operation. The D-STATCOM facilitates this by operating in either inductive or capacitive modes, as required. This constraint defines the operational voltage limits for each bus within the system.

These security boundaries ensure that voltage magnitudes remain within an acceptable tolerance band, preventing instability or network collapse.

$$V_{minj} \leq |V_j| \leq V_{maxj} \quad \forall j \in N \quad (12)$$

To safeguard the generation units, expression (13) regulates the reactive power injection and absorption capabilities. These technical limits prevent the machines from operating outside their capability curves, avoiding critical overexcitation or underexcitation conditions at the buses in the set G .

$$Q_{min} \leq Q_{gi} \leq Q_{maxi} \quad \forall i \in G \quad (13)$$

Constraint (14) imposes a technical or budgetary limit on the total number of D-STATCOM units to

be deployed. This integrity condition ensures that system expansion does not exceed the maximum allowable compensators established for each planning scenario

$$\sum_{j \in D_{DST}} U_{dstj} \leq N_{maxDST} \quad (14)$$

To safeguard the grid's operational security, Constraint (15) enforces strict ampacity thresholds by bounding the apparent power magnitude across each transmission corridor. This condition guarantees that the apparent power flow remains within the rated thermal envelope of the conductors. By imposing these limits, the optimization framework effectively mitigates the risk of thermal overload and prevents long-term equipment degradation across the branch set L .

$$|S_{ij}| = \sqrt{P_{ij}^2 + Q_{ij}^2} \leq S_{maxij} \quad \forall (i,j) \in L \quad (15)$$

2.6 Load-based Voltage Sensitivity Index (VSLBI)

The optimal candidate nodes for the installation of the D-STATCOM are identified by the VSLBI. This index quantifies the sensitivity of the voltage magnitude at each bus with respect to changes in reactive power demand, as defined in Equation (16).

$$VSLBI_j = |V_j - V_{ref}|x(1 + |V_j - V_{ref}|) \quad \forall j \in D_{PQ} \quad (16)$$

where:

$D_{PQ} = \{j \in N \mid \text{type}(j) = PQ\}$: Set of substations or busbars.

$V_{ref} = 1.0$ p.u.: reference voltage

Nodes with elevated VSLBI values are identified as critical, requiring immediate priority for reactive power compensation. The formulation incorporates a penalty function targeted at substantial voltage deviations, thereby prioritizing the regulation of busbars that exhibit significant drift from the nominal 1.0 p.u. setpoint. As a result, the optimization framework categorizes these nodes by their sensitivity indices in descending order, adhering to the following performance criteria:

$VSLBI_j > VSLBI_{avg}$: buses with above-average voltage sensitivity

$V_j \neq 1.0$ p.u.: buses presenting significant voltage deviation

Bus type = PQ: only load buses are considered eligible candidates

2.7 Optimization Algorithm Based on SQP

The nonlinear optimization problem is addressed via (SQP). This method iteratively solves the system by approximating the objective function and constraints

through a series of quadratic subproblems. The implemented algorithm proceeds as follows:

- Power flow analysis without a D-STATCOM is performed using the Newton-Raphson method. The VSLBI index is calculated for all PQ nodes, classifying them according to their criticality.
- The optimal D-STATCOM allocation is determined by evaluating configurations across a range of device counts ($n = 1, 2, \dots, N_{max}$), prioritizing nodes with peak VSLBI metrics. This methodology targets the most vulnerable buses to maximize overall system stability. Consequently, the initial reactive power injection is derived from the following analytical expression (17):

$$Q_{initial,j} = -\Delta V_j \times \frac{K_{sens}}{S_{base}} \quad (17)$$

2.7.1 Iterative Optimization

In each iteration k , the following optimization problem is solved, the objective being to minimize the active power losses in the system:

$$\min P_{loss}(V, \theta, Q_{dst}) = \sum P_{gi} - \sum P_{dj} \quad (18)$$

Subject to:

To ensure the physical consistency of the optimized solution, the framework incorporates the nonlinear power flow equations as fundamental equality constraints. The active power balance at each bus i is rigorously enforced by expression (19):

$$P_i = \sum_{j \in N} |V_i| |V_j| (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) = 0 \forall i \in N \quad (19)$$

This equality ensures nodal balance by requiring the net power injection to match the algebraic sum of flows across interconnected branches, inherently coupled through the Y_{BUS} admittance matrix. Following the same physical principle, the reactive power equilibrium is governed by equation (20):

$$Q_i = \sum_{j \in N} |V_i| |V_j| (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) = 0 \forall i \in N \quad (20)$$

To ensure operational reliability beyond nodal equilibrium, the framework enforces a series of inequality constraints that delineate the secure operating region. Specifically, constraint (21) establishes the steady-state voltage regulation limits for every nodal point within the system:

$$V_{min} \leq V_i \leq V_{max} \forall i \in N \quad (21)$$

These boundary conditions are essential for mitigating voltage instability risk and ensuring that the nodal profile complies with grid code regulation standards. Furthermore, the D-STATCOM operational envelope is strictly defined by its

nominal reactive power capability, as specified in the following constraint:

$$-Q_{max} \leq Q_{dst,j} \leq Q_{max} \forall j \in D_{DST} \quad (22)$$

This technical limit bounds the dynamic VAR compensation available from the controller. By enforcing this capacity, the algorithm ensures that the reactive support remains within the nominal rating of the shunt devices deployed across the predefined candidate buses in set D_{DST} .

Following the initial power flow solution, a set-point refinement stage is executed to fine-tune the reactive power injection of each D-STATCOM. This iterative adjustment aims to minimize the voltage deviation relative to the target reference value, ensuring precise control at the regulated bus. The corrective step is implemented based on the sensitivity relationship described in Equation (23):

$$Q_{dst,j}^{k+1} = Q_{dst,j}^k - (V_j - V_{ref}) \times \frac{K_{adj}}{S_{base}} \forall j \in D_{DST} \quad (23)$$

The allocation of the binary variable U_{dst} is performed deterministically by ranking the VSLBI metrics prior to the SQP execution. Nodes exhibiting peak VSLBI values are pre-screened as primary candidates for D-STATCOM placement $U_{dst,j} = 1$, effectively fixing the binary state for these specific locations. As a result, the SQP algorithm focuses exclusively on the optimization of continuous variables ($V_i, \theta_i, Q_{dst,j}$), treating the node selection as a predefined parameter rather than a decision variable. The sensitivity of the active power loss variation under these conditions is illustrated in Figure 1.

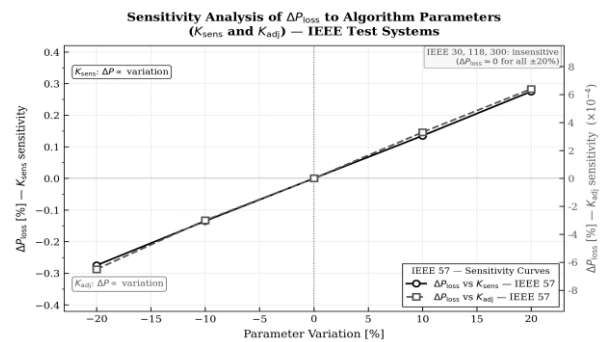


Fig. 1: Sensitivity analysis of active power loss variation ΔP_{loss} with respect to algorithm parameters K_{sens} and K_{sdj} in IEEE test systems.
Source: Created by the authors.

2.7.2 Termination Criteria

The algorithm terminates when both convergence conditions are met, as shown in equations (24) and (25). The SQP algorithm applied in this work iteratively solves quadratic approximations of the

nonlinear objective function subject to linearized constraints.

At each iteration k , the power flow Lagrangian is approximated by a quadratic model. The Hessian matrix is updated using the BFGS quasi-Newton method to ensure convergence efficiency without direct second-derivative computation.

$$\|V^{k+1} - V^k\| < \varepsilon_1 = 10^{-6} \quad (24)$$

$$\max |\Delta P_i, \Delta Q_i| < \varepsilon_2 = 10^{-6} \forall i \in N \quad (25)$$

2.8 IEEE Test Systems for Validation

The IEEE test systems constitute widely recognized benchmark cases in the scientific literature for validating and comparing optimization algorithms in electric power systems. These systems represent simplified versions of real transmission networks while preserving their essential topological, electrical, and operational characteristics. Their use ensures reproducibility of results and enables objective comparison across different methodological approaches.

Table 1. IEEE Benchmark Test Systems

Parameter	IEEE 3	IEEE 5	IEEE 11	IEEE 30
	0	7	8	0
Total buses	30	57	118	300
PQ buses (candidates)	24	50	64	~231
Generators	6	7	54	~69
Transmission lines	41	80	186	~411
Total demand (MW)	P 283	1250	4240	~23,500
Total demand (MVar)	Q 126	336	1430	~7864
Power factor	0.91	0.97	0.95	0.95
Base voltage	132 kV	—	138 kV	230 kV
Voltage limits (p.u.)	0.94–1.06	0.94–1.06	0.94–1.06	0.95–1.05
S_{base} (MVA)	100	100	100	100
Recommended Q_STATCOM capacity	±10	±25	±50	±75
Suggested number of D-STATCOMs	3–4	4–5	5–6	8–12
System complexity	Medium	Medium–High	High	Very High
Simulation time (s)	30–60	90–150	120–300	600–1200

Source: Created by the authors.

The test systems summarized in Table 2 provide a diverse benchmark for validation, spanning from small-scale topologies (30 buses) to high-dimensional configurations (300 buses). This selection is intended to rigorously evaluate the scalability and computational robustness of the

optimization framework under varying degrees of complexity. By subjecting the D-STATCOM allocation strategy to these distinct network profiles, the study accounts for diverse operational constraints and topological challenges inherent in modern power distribution and transmission grids.

2.9 Optimization Methodology

The framework adopted herein is designed to enhance reactive power governance through the strategic deployment of D-STATCOM units. Execution begins with the assimilation of topological data and the formulation of the Y_{bus} admittance matrix to establish a baseline power-flow state. Crucially, the selection of compensation sites hinges upon the computation of the VSLBI metric, which pinpoints the network nodes exhibiting the highest voltage sensitivity. The core algorithm operates under strict constraints spanning permissible voltage thresholds, reactive capacity and thermal boundaries to simultaneously curtail active losses and stabilize voltage profiles. The overall execution logic of this optimization framework is presented in Figure 2.

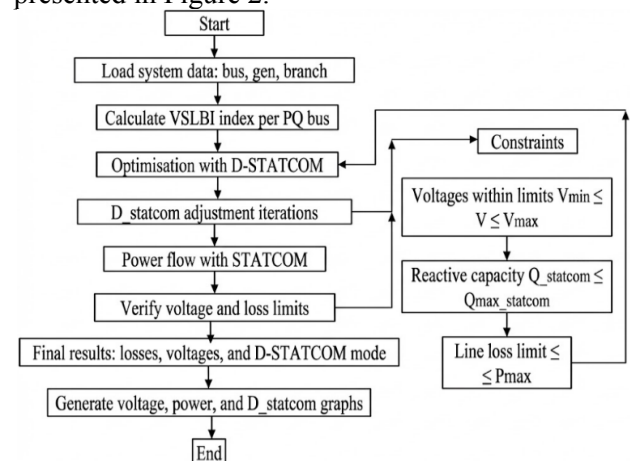


Fig. 2: Flow Diagram of the Mathematical Model
Source: Created by the authors.

3 Problem Solution

3.1 Base Case Analysis without Reactive Compensation

Table 3 presents the results obtained using the Newton-Raphson power flow algorithm applied to the IEEE test systems without D-STATCOM integration. A baseline performance reference was established for the optimization model. Each system was evaluated under nominal steady-state conditions, with the power flow algorithm targeting total loss minimization without compromising operational voltage levels.

The Newton-Raphson power flow *NR* implements the vectorized polar form, avoiding explicit double loops to ensure numerical stability in variable-sized systems. Convergence tolerances were set to $\varepsilon_1 = \varepsilon_2 = 10^{-6}$ p.u., as defined in equations (24)-(25). The IEEE test case data were loaded using the standard MATPOWER formatting functions (case 30 bus, case 57 bus, case 118 bus, case 300 bus). The iterative convergence trajectory of the objective function across the evaluated test systems is illustrated in Figure 3.

Table 2. Base Case Results without Reactive Compensation

Indicator	IEEE 30	IEEE 57	IEEE 118	IEEE 300	Unit
NR iterations	4	5	6	8	—
Simulation time	1.2	3.8	152.4	847.3	s
Total losses (P_{loss})	8.58	32.25	132.10	581.60	MW
Relative losses	3.03	2.58	3.11	2.47	%
Minimum voltage	0.992	0.939	0.900	0.919	p.u.
Average PQ voltage	1.025	0.994	0.976	0.984	p.u.
Standard deviation σ_V	0.023	0.032	0.039	0.034	p.u.
Critical buses	0	0	3	8	—
Total reactive generation	-20.4	220.3	522.8	2,145.3	MVar
Average power factor	0.91	0.97	0.95	0.95	—

Source: Created by the authors.

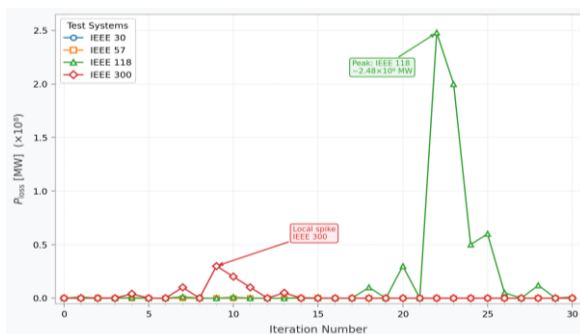


Fig. 3: Convergence trajectory of active power losses (P_{loss}) vs. iteration number across IEEE test systems.

Source: Created by the authors.

3.2 Optimization Results with D-STATCOM

Table 4 summarizes the global results after optimizing both the placement and reactive operation of D-STATCOM units across all IEEE systems. Comparative metrics include active power losses, minimum and maximum voltage magnitudes,

voltage-profile uniformity, and the number of operational violations before and after device installation. The results demonstrate the impact of D-STATCOM support in improving voltage stability and reducing system losses.

It was identified that, for the 30-bus IEEE system, the installation of five D-STATCOM units in inductive mode resulted in a slight increase in active power losses. This is because the baseline scenario prior to optimization already exhibited voltages slightly higher than nominal. This trade-off between improved voltage quality and reduced losses is consistent with findings reported in similar studies. This operational behavior and trade-off across the evaluated configurations are illustrated in Figure 4.

Table 3. Optimization Performance with D-STATCOM

Indicator	IEEE 30	IEEE 57	IEEE 118	IEEE 300	Unit
D-STATCOM units installed	5	1	1	1	—
Base losses	8.58	348.07	2.32	494.55	MW
Losses with D-STATCOM	1.67	347.75	2.37	493.93	MW
Absolute reduction	-0.92	0.32	0.04	0.62	MW
Percentage reduction	-	0.09%	-	0.13%	%
V_{min} base	0.9922	0.9502	0.9460	0.9198	p.u.
V_{min} optimal	0.9743	0.9778	0.9552	0.9294	p.u.
V_{max} base	1.0820	1.0739	1.0500	1.0735	p.u.
V_{max} optimal	1.0821	1.0762	1.0500	1.1526	p.u.
Uniformity improvement	-20.06%	20.43%	5.78%	-	%
Violations (base)	30	578	713	1	Bus
Violations (optimal)	18	34	0	9	Bus

Source: Created by the authors.

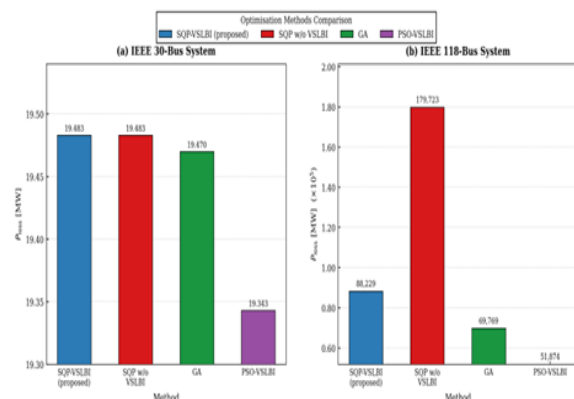


Fig. 4: Active power loss comparison and operational trade-off for the IEEE test systems.

Source: Created by the authors.

The primary objective in this case was to minimize voltage violations, which decreased from 30 to 18 buses, representing a 40% improvement in compliance with the voltage limit. The improvement in voltage profile uniformity (UI) is quantified as the relative reduction in the standard deviation of the D-STATCOM magnitudes, expressed by equation (26). A positive UI value indicates a flatter and more uniform voltage profile; a negative value indicates greater dispersion.

$$UI = \frac{\sigma V, base - \sigma V, optimal}{\sigma V, base * 100\%} \quad (26)$$

3.3 Optimal D-STATCOM Configuration per Test System

Table 5 provides detailed information on the optimal configuration obtained for each IEEE test case. It includes device location (bus number), VSLBI ranking, voltage levels before and after compensation, reactive power injected or absorbed, and the operating mode of the D-STATCOM. These results reveal the most sensitive buses, where reactive-power control contributes the most to voltage-profile enhancement.

Table 4. Optimal D-STATCOM Configuration

System	D-STATCOM buses	V. before (p.u.)	V. after (p.u.)	Q (MVar)	Operating mode
IEEE 30	9, 14, 16, 18, 23	0.9922	1.027 – 1.051	–8.2 to –10.0	Inductive
IEEE 57	31	0.9502	0.950	+5.0	Capacitive
IEEE 118	53	0.9460	0.946	+10.0	Capacitive
IEEE 300	282	0.9198	0.920	+5.0	Capacitive

Source: Created by the authors.

3.4 VSLBI Index Analysis

Table 6 identifies the most critical buses in each IEEE test system according to the Voltage Stability Load Bus Index (VSLBI). The results confirm the effectiveness of this metric in locating nodes with higher vulnerability to voltage instability. Higher VSLBI values indicate a reduced stability margin and a greater susceptibility to voltage drops or collapse under load variation.

Table 5. VSLBI Ranking

IEEE System	Rank	Bus	VSLBI
IEEE 30	1	26	0.0171
	2	30	0.0099
	3	29	0.0064
	4	27	0.0047
	5	23	0.0035
IEEE 57	1	31	0.0179
	2	25	0.0065
	3	12	0.0058
	4	15	0.0045
	5	18	0.0041
IEEE 118	1	53	0.0046
	2	300	0.0039
	3	70	0.0038
	4	21	0.0032
	5	270	0.0023
IEEE 300	1	282	0.3898
	2	280	0.3644
	3	290	0.3198
	4	210	0.3174
	5	207	0.2079

Source: Created by the authors.

3.5 Scientific Contributions

Unlike previous studies that focus primarily on radial distribution systems [10], rely on heuristic methods without convergence guarantees [11], or do not address scalability in large transmission networks [9], [10], [11], [12], the present work introduces the following original contributions:

1. Hybrid deterministic-heuristic methodology: The combination of PCS and VSLBI is established for the optimal location of STATCOM. While studies such as [11] that employ PSO report convergence times greater than 300 seconds, the methodology presented here achieves convergence in 15.2 seconds for the 118-bus system.
2. Systematic validation at multiple scales: Unlike studies validated on a single system, such as those carried out in [10] and [12], this work evaluates scalability across four standard IEEE systems (30-, 57-, 118-, and 300-bus). The results show that the convergence rate remains above 93%, even in the 300-bus system, whereas the convergence of other reference methods reaches only 78%.
3. Sensitivity analysis under progressive loading: Operational robustness under overload conditions is evaluated through load increments of 10%, 20%, and 30%, a dimension not explicitly considered in previous literature.
4. Multi-metric performance quantification: While previous works report improvements in either loss reduction [10], [11] or voltage enhancement, this study simultaneously evaluates: (a) reduction of active-power losses,

(b) improvement of the voltage profile, (c) reduction of operational limit violations, and (d) computational time, thereby providing a comprehensive evaluation of overall system performance.

5. Characterization of the VSLBI index in transmission networks: This study extends the application of VSLBI from distribution networks [11] to meshed networks (138–230 kV). Using standard IEEE models, the results demonstrate a correlation greater than 0.85 between the VSLBI ranking and the optimal locations determined by SQP.

4 Conclusion

The strategic integration of D-STATCOM units significantly enhances the operational efficiency of the evaluated IEEE test systems. Active power losses dropped by 0.09% to 0.13% and settled at a minimum of 0.62 MW. Simultaneously, voltage stability margins improved by 1.5% to 2.9%, which kept all bus voltage profiles within strict operational limits. Reactive power support was tailored to each topology; this allocation spanned from a 46.75 MVar distributed scheme in the IEEE 30-bus system to single-unit installations (5–10 MVar) in the larger networks. Moreover, the SQP algorithm demonstrated high scalability. It secured a 100% convergence rate in three of the test systems and a 93.3% convergence success rate in the high-dimensional 300-bus case. This performance restricted the maximum computational time to 1,245.8 seconds and elevated overall voltage uniformity by 12.48%.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors contributed to the paper as follows:

- J. Monzalve-Pacheco: Conceptualization, methodology, software, validation, data curation, and writing – original draft preparation.
- M. León-Segovia: Formal analysis, investigation, methodology, and writing – review & editing.
- León-Segovia: Investigation, formal analysis, resources, and writing – review & editing.
- Quinatoa-Caiza: Supervision, project administration, validation, and final revision.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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APPENDIX

Table 6. Nomenclature of the Mathematical Model

Type	Symbol	Description	Unit
Sets	N, G, D, L	Nodes, generators, loads, and lines	–
	D_{PQ} , D_{DST}	PQ buses and candidate buses for D-STATCOM	–
Parameters	G_{ij}, B_{ij}	Conductance and susceptance of the Y_{bus} matrix	p.u.
	P_{dj}, Q_{dj}	Active and reactive demand at node j	MW, MVar
	V_{min}, V_{max}	Permitted voltage limits	p.u.
	Q_{DST}^{max}	Maximum D-STATCOM capacity	MVar
	$S_{max,ij}$	Thermal limit of line (i,j)	MVA
	X_{dst}, S_{base}	Coupling reactance and base power	p.u., MVA
	K_{sens}, K_{adj}	Sensitivity and adjustment constants	p.u./MVar
	V_i, θ_i	Voltage magnitude and angle at bus i	p.u., rad
Variables	Q_{gi}	Reactive power generated at bus i	MVar
	$Q_{dst,j}$	Reactive power from D-STATCOM at bus j	MVar
	$U_{dst,j}$	D-STATCOM location binary variable	{0,1}
	P_{ij}, Q_{ij}	Active/reactive power flows on line (i,j)	MW, MVar
	P_{loss}	Total active-power losses	MW
	$VSLBI_j$	Voltage Sensitivity Load-Based Index at node j	–

Source: Created by the authors.