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Recent Trends in Optimization Objectives for Power System Operation Improvement Using FACTS

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Abstract: The increasing penetration of renewable energy sources, extensive deployment of power-electronic interfaces, and growing operational uncertainty have significantly intensified the challenges associated with secure and efficient power system operation. Flexible AC Transmission Systems (FACTS) have emerged as key enabling technologies for enhancing system controllability, power quality, and operational flexibility. This article provides a comprehensive and structured review of recent trends in optimization objectives for power system operation improvement using FACTS devices, with particular emphasis on the evolution of control and optimization paradigms in modern power grids. First, the study presents a systematic classification of FACTS devices, shunt, series, combined, and hybrid configurations, along with the associated optimization techniques employed for their control, placement, and coordination. Second, the paper examines the principal optimization objectives for power system performance improvement, encompassing voltage profile enhancement, loss minimization, congestion management, economic and emission optimization, frequency and transient stability, power quality, reliability, and renewable energy integration. Third, recent research trends are analyzed, highlighting the transition from single-objective, steady-state formulations toward multi-objective, security-constrained, uncertainty-aware, and data-driven optimization frameworks. The growing adoption of meta-heuristic algorithms, artificial intelligence, and distributed optimization strategies for FACTS-based operation is critically discussed in the context of renewable-dominated and smart grid environments. The article concludes by identifying key research gaps and future directions, emphasizing the need for coordinated, adaptive, and resilient FACTS optimization frameworks to support next-generation power system operation under increasing complexity and variability.

Keywords: Flexible AC Transmission Systems (FACTS), Multi-objective optimization, Smart grid operation, Power Quality.

1.Introduction

In 1988, Hingorani [1] introduced the seminal concept of Flexible AC Transmission Systems (FACTS) in his paper "Power electronics in electric utilities: Role of power electronics in future power systems," advocating the extensive application of power-electronic technologies for enhanced control of AC power systems. The core idea was to endow AC networks with a level of controllability comparable to that of high-voltage direct current (HVDC) systems, thereby enabling flexible and rapid regulation of power flow, voltage, and system stability [2]. This vision was founded on the use of thyristor-based and self-commutated semiconductor devices, capable of controlled turn-on and turn-off, such as gate turn-off (GTO) thyristors, insulated gate bipolar transistors (IGBTs), and integrated gate-commutated thyristors (IGCTs) [3]. Although wide-bandgap technologies such as silicon carbide (SiC) devices were not yet available at the time, Hingorani's work laid the technological and conceptual foundation for modern FACTS implementations and the subsequent evolution of advanced power-electronic control in AC power systems [4,5].

The increasing complexity of modern power systems, driven by the large-scale integration of renewable energy sources, extensive deployment of power-electronic converters, and growing demand for high reliability and power quality, has introduced significant operational challenges. Reduced system inertia, stochastic generation patterns, and tighter security margins have limited the effectiveness of conventional control and planning approaches [6,7]. In this context, Flexible AC Transmission Systems (FACTS) have emerged as essential technologies for enhancing system controllability, enabling rapid and continuous regulation of voltage, power flow, and dynamic stability across transmission and distribution networks.

FACTS devices, ranging from shunt and series controllers to combined and hybrid configurations, offer versatile capabilities for improving power system operation. However, their effectiveness is highly dependent on the formulation of appropriate optimization objectives and the selection of suitable control and tuning strategies. Traditional single-objective optimization approaches, primarily focused on loss minimization or voltage regulation, are increasingly inadequate for addressing the multidimensional and time-varying nature of contemporary power systems [8,9]. As a result, recent research has emphasized advanced optimization frameworks that integrate technical, economic, environmental, and security-related objectives within unified control architectures.

Against this backdrop, this article provides a comprehensive review of recent trends in optimization objectives for power system operation improvement using FACTS devices. The study examines the evolution of optimization goals from conventional steady-state formulations toward multi-objective, security-constrained, uncertainty-aware, and data-driven approaches [10,11]. By synthesizing current developments in optimization techniques and FACTS-based control strategies, the article aims to highlight emerging research directions and identify key challenges and opportunities for enhancing the operation of next-generation power systems.

Numerous studies have investigated optimization objectives aimed at enhancing power system operation through the effective utilization of FACTS devices. In [12], the authors discussed a broad range of analytical and meta-heuristic optimization techniques for identifying the most effective locations for deploying FACTS controllers. The study addresses key challenges in intelligent power systems, particularly stability enhancement, power quality improvement, and congestion management, while also surveying representative applications of FACTS technologies. Moreover, it emphasizes that modern power systems increasingly rely on smart grid infrastructures and advanced metering capabilities to deliver continuous, high-quality electric power to end users.

The authors [13] provided a comprehensive review that traces the generational evolution of FACTS technologies and synthesizes the key objectives underlying their optimal placement and operational coordination. The study further introduces the concept of cyber–physical power systems (CPPS) and discusses how distribution-FACTS (D-FACTS) devices can be leveraged to enhance network security and operational resilience. In addition, a bibliometric analysis is conducted to map the research landscape and identify prevailing trends in FACTS utilization. The findings outline prospective research directions for both utilities and academics, particularly in power system optimization and the deployment of FACTS within smart grid architectures.

The study [14] proposed an advanced honeybee colony–based optimization algorithm that enhances both local exploitation and global exploration capabilities to effectively address the coupled planning problem involving FACTS devices and energy storage systems (ESS). Four operating scenarios are systematically evaluated: (i) a base case without ESS or FACTS devices; (ii) deployment of FACTS devices only; (iii) deployment of ESS only; and (iv) coordinated integration of both FACTS and ESS. Based on a comprehensive benefits assessment and economic evaluation, the results demonstrate that the joint deployment of FACTS and ESS can markedly improve power system operational performance and deliver superior techno-economic value compared with isolated implementations.

The authors [15] investigated the Fata Morgana Algorithm (FATA), a meta-heuristic optimization method inspired by the physical phenomenon of mirage formation, to determine the optimal placement and sizing of FACTS devices in an IEEE 30-bus system with wind turbine integration. The performance of FATA is benchmarked against several recently proposed and enhanced optimizers, including the Improved RIME (IRIME) algorithm (based on the rime–ice formation phenomenon), Newton–Raphson-Based Optimization (NRBO), Resistance Capacitance Algorithm (RCA), Krill Optimization Algorithm (KOA), and the Grey Wolf Optimizer (GWO). The comparative assessment is conducted under multiple objective formulations, namely generation cost minimization, real power loss minimization, and a combined gross cost function integrating generation cost and power loss, demonstrating the capability of the proposed approach to address multi-criteria FACTS planning in renewable-integrated networks.

This article contributes a comprehensive and structured synthesis of recent trends in optimization objectives for improving power system operation using FACTS devices under high renewable penetration, widespread power-electronic interfacing, and elevated operational uncertainty. It systematically classifies FACTS technologies into shunt, series, combined, and hybrid configurations and links each class to the optimization techniques used for controller tuning, optimal placement, sizing, and coordinated operation. The study consolidates the principal optimization objectives addressed in the literature, covering voltage profile enhancement, loss minimization, frequency and transient stability, power quality, reliability, and critically analyzes the ongoing shift from single-objective, steady-state formulations toward multi-objective, security-constrained, uncertainty-aware, and data-driven optimization frameworks. In addition, it evaluates the growing adoption of meta-heuristic algorithms, artificial intelligence, and distributed optimization strategies for FACTS-enabled operation in smart grid environments and concludes by identifying key research gaps and future directions, emphasizing the necessity of coordinated, adaptive, and resilient FACTS optimization frameworks to support next-generation power system operation.

2. Classification of FACTS Devices and Associated Optimization Techniques

The rapid evolution of modern power systems, driven by high penetration of renewable energy sources (RESs), increasing power-electronic interfacing, and stringent power quality (PQ) and reliability requirements, has significantly intensified the operational complexity of transmission and distribution networks. In this context, Flexible AC Transmission Systems (FACTS) have emerged as a pivotal technological solution for enhancing system controllability, operational flexibility, and dynamic performance [16,17]. By enabling fast and continuous regulation of key electrical parameters such as voltage magnitude, phase angle, and line impedance, FACTS devices provide effective means to mitigate voltage instability, manage power flow congestion, damp electromechanical oscillations, and improve overall PQ. Figure 1 presents different kinds of FACTS devices based on their connection type to the power system.

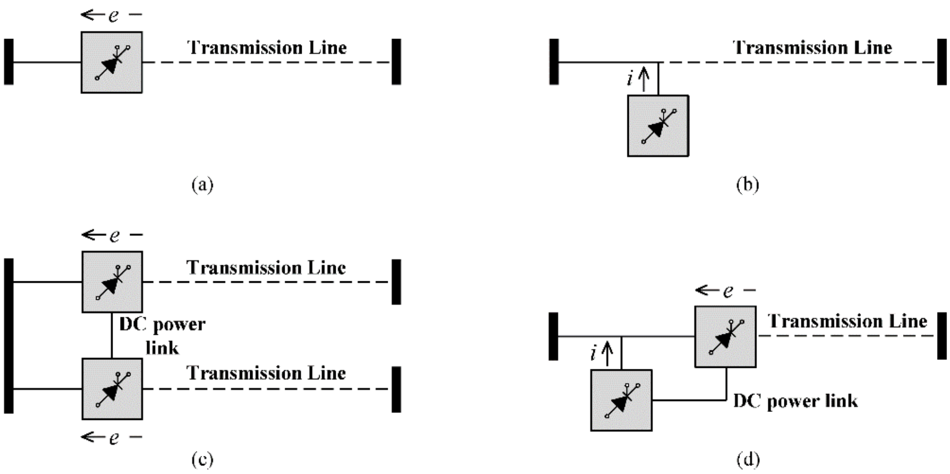

Figure 1. Different kinds of FACTS devices based on their connection type to the power system. (a) series; (b) shunt; (c) series-series; and (d) series-shunt [18].

FACTS devices are conventionally classified according to their connection topology and functional role into shunt, series, combined, and hybrid configurations. Each category offers distinct control capabilities and dynamic characteristics, making their suitability strongly dependent on system topology, operating conditions, and performance objectives [19,20]. However, the inherent nonlinearity, multivariable nature, and time-varying behavior of power systems equipped with FACTS devices render classical tuning and control approaches increasingly inadequate, particularly under high RES variability and network uncertainty [21,22]. To address these challenges, a wide range of optimization techniques, spanning conventional methods, meta-heuristic algorithms, and artificial intelligence (AI)–based approaches, have been extensively employed for FACTS controller tuning, optimal placement, and coordinated operation. Optimization frameworks play a critical role in enhancing FACTS effectiveness by minimizing power losses, improving voltage profiles, ensuring stability margins, and enabling adaptive real-time control.

Recently, hybrid and distributed optimization paradigms, including reinforcement learning and distributed artificial intelligence (DAI), have gained increasing attention due to their scalability, robustness, and suitability for decentralized smart grid environments. Within this framework, the classification of FACTS devices and the corresponding optimization techniques used for their control and deployment constitute a foundational component for understanding current research trends and identifying future development pathways [23,24]. Table 1 highlights classification of FACTS Devices and Associated Optimization Techniques.

Table 1. Classification of FACTS Devices and Associated Optimization Techniques [25-36].

FACTS Category	Device Type	Operating Principle	Primary Control Objectives	Typical Optimization Techniques
Shunt FACTS	SVC (Static VAR Compensator)	Thyristor-controlled reactors and capacitors regulate reactive power injection	Voltage regulation; reactive power compensation; stability enhancement	GA; PSO; DE; ANN; Fuzzy Logic
	STATCOM (Static Synchronous Compensator)	VSC-based fast reactive power control independent of grid voltage	Dynamic voltage support; harmonic reduction; transient stability	PSO; GWO; WOA; MPC; DAI-based control
Series FACTS	TCSC (Thyristor-Controlled Series Capacitor)	Variable series reactance control via thyristors	Power flow control; damping of power oscillations	GA; PSO; ABC; SSA
	SSSC (Static Synchronous Series Compensator)	VSC injects controllable series voltage	Power flow regulation; oscillation damping	PSO; DE; Hybrid AI methods
Combined FACTS	UPFC (Unified Power Flow Controller)	Combination of series and shunt VSCs	Simultaneous control of voltage; impedance; and phase angle	GA-PSO hybrids; NSGA-II; RL
	IPFC (Interline Power Flow Controller)	Multiple series VSCs sharing a common DC link	Coordinated power flow control across lines	Multi-objective GA; PSO
Hybrid FACTS	DPFC (Distributed Power Flow Controller)	Decoupled series units replacing a common DC link	Power flow and voltage control with enhanced reliability	PSO; GWO; Distributed Optimization
FACTS with AI-Based Control	FACTS-AI Integration	Intelligent adaptive control using real-time data	Fast dynamic response; robustness under uncertainty	ANN; CNN; LSTM; Reinforcement Learning; DAI
FACTS with Meta-Heuristic Optimization	FACTS-Optimized Systems	Parameter tuning and placement optimization	Loss minimization; voltage profile enhancement	GA; PSO; GWO; WOA; SSA; Hybrid Methods

Table 1 presents a structured classification of FACTS devices alongside their operating principles, primary control objectives, commonly adopted optimization techniques, and representative applications. The table highlights the strong interdependence between FACTS topology and the choice of optimization strategy, reflecting both device-level dynamics and system-level performance requirements. Shunt FACTS devices, such as Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs), are primarily employed for voltage regulation and reactive power compensation. Due to their fast-dynamic response and strong nonlinear characteristics, meta-heuristic optimization techniques, particularly Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), are widely used for parameter tuning and controller design. More recently, AI-based methods, including artificial neural networks and fuzzy logic controllers, have demonstrated superior adaptability under fluctuating load and RES conditions.

Series FACTS devices, including Thyristor-Controlled Series Capacitors (TCSCs) and Static Synchronous Series Compensators (SSSCs), focus mainly on power flow control and oscillation damping. Optimization techniques in this category are typically oriented toward congestion management and stability enhancement, with swarm-based and evolutionary algorithms offering effective solutions for multi-objective tuning problems. The growing adoption of hybrid optimization approaches reflects the need to balance convergence speed with global optimality. Combined FACTS devices, notably the Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC), provide simultaneous control over multiple power system variables. As shown in Table 1, their high dimensionality and coupled control structure necessitate advanced multi-objective optimization frameworks, such as hybrid GA–PSO algorithms and non-dominated sorting genetic algorithms (NSGA-II). These methods enable coordinated optimization of voltage regulation, power flow control, and loss minimization within a unified control architecture.

Hybrid and distributed FACTS configurations, such as the Distributed Power Flow Controller (DPFC), represent an emerging research direction aimed at enhancing system reliability and scalability. The absence of a common DC link and the distributed nature of control significantly increase system complexity, thereby motivating the use of distributed and cooperative optimization techniques. Algorithms such as Grey Wolf Optimization (GWO) and distributed PSO have shown promising results in managing such decentralized control structures. Finally, the article demonstrates the growing integration of AI-driven optimization techniques with FACTS devices. Machine learning models, including deep neural networks and reinforcement learning, are increasingly employed to enable adaptive, self-learning control mechanisms capable of responding to real-time system disturbances.

3. Optimization Objectives for Power System Performance Improvement

The increasing complexity of modern power systems, driven by high renewable energy penetration, extensive power-electronic interfacing, distributed generation, and evolving load characteristics, has necessitated a paradigm shift from traditional deterministic operation toward optimization-driven planning and control. Power system performance is no longer evaluated solely on the basis of supply–demand balance, but rather through a multidimensional lens encompassing voltage stability, power quality, economic efficiency, environmental sustainability, reliability, and dynamic security [37-42]. In this context, optimization objectives constitute the cornerstone of advanced power system analysis, enabling systematic and quantitative improvement of system performance under diverse operating conditions and constraints. In addition, optimization objectives in power systems are inherently multi-criteria and often conflicting. For instance, minimizing active power losses may conflict with voltage profile enhancement, while cost minimization objectives may compete with emission reduction or renewable energy utilization targets. Consequently, modern optimization frameworks increasingly rely on multi-objective formulations capable of capturing trade-offs among technical, economic, and environmental goals. These formulations are typically embedded within optimal power flow (OPF), security-constrained OPF (SCOPF), or dynamic optimization structures, incorporating both continuous and discrete decision variables [43-46].

Furthermore, the integration of Flexible AC Transmission Systems (FACTS), energy storage systems, and intelligent control devices has expanded the decision space of optimization problems, enabling more granular and dynamic system control. However, this expansion also increases nonlinearity, dimensionality, and uncertainty, rendering classical gradient-based methods insufficient in many practical scenarios. As a result, meta-heuristic and artificial intelligence–based optimization techniques have become central to achieving robust and adaptive performance improvement, particularly in renewable-dominated and smart grid environments [47-50]. Within this framework, clearly defined optimization objectives serve as the foundation for algorithm selection, controller design, and performance evaluation. A structured classification of these objectives is therefore essential for understanding current research trends and guiding future developments in power system optimization. Table 2 presents optimization objectives for power system performance improvement.

Table 2. Optimization Objectives for Power System Performance Improvement [51-60].

Objective Domain	Optimization Objective	Performance Metrics	Decision Variables	Key Constraints	Common Optimization Techniques
Voltage Profile Improvement	Minimize voltage deviation	Voltage deviation, L-index	Generator voltages, tap changers	Voltage limits, device ratings	AC-OPF, PSO, GA, DE, GWO
Active Power Loss Reduction	Minimize real power losses	Total system losses (MW)	Reactive power dispatch, taps, capacitors	Thermal and voltage limits	OPF, PSO, GA, MILP
Reactive Power Optimization	Improve VAR support	Reactive reserve margin	Shunt devices, STATCOM/SVC output	Q-limits, voltage limits	PSO, GA, NSGA-II
Congestion Management	Reduce line overloads	Line loading index	Series FACTS, UPFC parameters	Thermal limits, N-1 security	SCOPF, PSO, NSGA-II
Economic Dispatch	Minimize generation cost	Fuel and operational cost	Generator outputs, unit commitment	Power balance, ramp limits	MILP, GA, PSO
Emission Reduction	Minimize environmental emissions	CO_2, NOx emission indices	Generation scheduling	Demand balance, emission limits	MOPSO, NSGA-II
Frequency Stability	Reduce frequency deviation	RoCoF, frequency nadir	AGC gains, storage dispatch	Response time, power limits	MPC, RL, PSO
Power Quality Improvement	Reduce harmonics and sags	THD, sag depth	Active filter and DVR settings	IEEE PQ standards	GA, PSO, ML-based tuning
Reliability Enhancement	Improve system reliability	SAIDI, ENS	Network reconfiguration, DG placement	Radiality, protection constraints	MILP, stochastic optimization
Renewable Integration	Maximize RES utilization	Curtailment, hosting capacity	DG and storage sizing	Voltage rise, thermal limits	Stochastic OPF, PSO, GA

Table 2 provides a comprehensive classification of the principal objective domains addressed in contemporary power system optimization studies. It systematically links each objective domain to its corresponding performance metrics, decision variables, constraints, and commonly employed optimization techniques. Voltage profile improvement and active power loss reduction emerge as fundamental objectives, reflecting the enduring importance of voltage stability and energy efficiency in both transmission and distribution networks. These objectives are typically addressed through reactive power optimization, transformer tap control, and FACTS device tuning, with optimization techniques such as AC-OPF and population-based meta-heuristics offering effective solutions under nonlinear operating conditions. Reactive power optimization and congestion management objectives are particularly relevant in heavily loaded networks and corridors with high renewable integration. The table highlights how series and combined FACTS devices, when optimally controlled, play a critical role in alleviating line overloads and maintaining secure power flows. The adoption of security-constrained and multi-objective optimization techniques underscores the increasing emphasis on system resilience and operational security.

Economic dispatch and emission minimization objectives reflect the growing convergence of economic and environmental considerations in power system operation. The table illustrates how multi-objective evolutionary algorithms are widely used to balance cost efficiency with emission reduction targets, enabling decision-makers to explore Pareto-optimal solutions rather than relying on single-objective formulations. Dynamic performance objectives, including frequency stability, transient stability, and power quality improvement, are gaining prominence due to reduced system inertia and increased power-electronic penetration. The table demonstrates that advanced control-oriented optimization techniques, such as model predictive control and reinforcement learning, are particularly well suited for these objectives, owing to their ability to handle fast dynamics and real-time uncertainties.

Finally, reliability enhancement and renewable energy integration objectives highlight the strategic shift toward resilient, low-carbon power systems. Optimization of network reconfiguration, distributed generation placement, and energy storage scheduling plays a central role in minimizing outage impacts and maximizing renewable hosting capacity. The table clearly indicates a trend toward stochastic and robust optimization frameworks to address the inherent uncertainty associated with renewable generation and demand variability. Overall, the table provides a unified and structured perspective on optimization objectives for power system performance improvement, demonstrating how technical, economic, environmental, and resilience-oriented goals are jointly addressed through advanced optimization methodologies. This synthesis offers a valuable reference for researchers and practitioners seeking to design integrated optimization frameworks for next-generation power systems.

4. Recent Trends in Optimization Objectives for Power System

The transformation of conventional power systems into highly interconnected, renewable-rich, and power-electronics-dominated networks has fundamentally reshaped operational objectives and control paradigms. The widespread integration of intermittent renewable energy sources, coupled with reduced system inertia and increased uncertainty, has exposed the limitations of traditional FACTS control strategies that were primarily focused on single-objective, steady-state performance enhancement. In response, recent research has increasingly emphasized advanced optimization-based frameworks that exploit the full controllability of FACTS devices to achieve secure, economical, and resilient power system operation [61,62].

Modern FACTS devices, such as STATCOM, TCSC, SSSC, and UPFC, provide fast, continuous, and multidimensional control over voltage, power flow, and system dynamics. However, their effective deployment and coordination require well-defined optimization objectives capable of capturing the complex trade-offs between technical performance, economic efficiency, environmental sustainability, and operational security [63-65]. As a result, optimization objectives have evolved from classical loss minimization and voltage regulation toward multi-objective, security-constrained, and uncertainty-aware formulations. Recent trends further highlight the growing role of intelligent and data-driven optimization techniques in FACTS-based operation. Meta-heuristic algorithms, reinforcement learning, and distributed artificial intelligence are increasingly employed to address nonlinearity, high dimensionality, and real-time adaptability requirements [66-68]. Table 3 outlines recent trends in optimization objectives for power system operation improvement using FACTS Devices.

Table 3. Recent Trends in Optimization Objectives for Power System Operation Improvement Using FACTS Devices [69-80].

Recent Trend / Objective Theme	Primary Optimization Objectives	FACTS Devices	Key Performance Metrics	Application Context	Dominant Optimization Techniques
Multi-objective co-optimization	Simultaneous minimization of cost, losses, voltage deviation, and emissions	UPFC, IPFC, TCSC, STATCOM	Cost, P_{loss}, voltage deviation, CO_2	Day-ahead / security-constrained operation	NSGA-II, MOPSO, hybrid OPF-metaheuristics
Congestion management with high RES penetration	Minimize line overloads and redispatch cost	TCSC, SSSC, UPFC	Line loading index, congestion cost	Transmission corridors with wind/solar	SCOPF, PSO, DE, RL-assisted control
Voltage stability enhancement	Maximize voltage stability margin	STATCOM, SVC, UPFC	L-index, voltage deviation	Weak grids and renewable buses	AC-OPF, PSO, GWO
Dynamic stability and oscillation damping	Improve damping and suppress oscillations	UPFC, TCSC, STATCOM	Damping ratio, ITAE	Wide-area real-time control	Eigenvalue optimization, MPC, RL
Transient stability improvement	Increase critical clearing time	UPFC, STATCOM, TCSC	CCT, rotor angle deviation	Fault ride-through support	Simulation-based PSO, DE
Renewable hosting capacity maximization	Maximize RES penetration with security	STATCOM, UPFC	Hosting capacity, curtailment	Distribution and sub-transmission grids	Stochastic OPF, NSGA-II
Loss minimization with coordinated FACTS	Reduce system active power losses	STATCOM, SVC, TCSC, UPFC	Total P_{loss}	Voltage/VAR control areas	AC-OPF, PSO, GA
Optimal placement and sizing	Minimize total cost and maximize benefits	STATCOM, SVC, TCSC, UPFC	NPC, voltage profile, reliability indices	Planning and expansion studies	Stochastic optimization, MILP, metaheuristics
Power quality enhancement	Reduce harmonics and voltage sags	STATCOM, DVR, UPQC	THD, sag depth	Distribution networks, microgrids	Multi-objective optimization, ML-based tuning
Resilience and contingency-aware operation	Minimize load shedding under contingencies	UPFC, STATCOM, TCSC	EENS, recovery time	Extreme events and N-1 security	Robust SCOPF, heuristic restoration

The table 3 provides a comprehensive synthesis of contemporary research directions, linking emerging optimization objectives with corresponding FACTS technologies, performance metrics, application contexts, and dominant solution techniques. A prominent trend highlighted in the table 3 is the shift toward multi-objective co-optimization frameworks, in which economic, technical, and environmental objectives are addressed simultaneously. Combined FACTS devices, particularly UPFC and IPFC, are frequently employed due to their ability to control multiple system variables concurrently. The widespread use of evolutionary multi-objective algorithms reflects the growing preference for Pareto-based decision-making over single-objective optimization.

Congestion management under high renewable energy penetration represents another major research focus. The table shows that series and combined FACTS devices are increasingly optimized to mitigate line overloads, reduce redispatch costs, and accommodate renewable power fluctuations. Security-constrained optimization and reinforcement learning–assisted control approaches have gained traction in this domain, enabling adaptive and anticipatory congestion relief. In this direction, Voltage stability and dynamic performance enhancement remain critical objectives, particularly in weak grids and renewable-dominated areas. As illustrated in the table 3, shunt FACTS devices such as STATCOM and SVC are widely optimized to maximize voltage stability margins and improve damping of electromechanical oscillations. The adoption of model predictive control and eigenvalue-based optimization techniques underscores the need to address both steady-state and dynamic system behavior.

The article also highlights increasing attention to transient stability improvement and fault ride-through support, where FACTS devices are optimized to enhance critical clearing times and reduce post-fault deviations. Simulation-based and robust optimization techniques are commonly employed in this context due to the nonlinear and time-critical nature of transient phenomena. Another notable trend is the integration of FACTS devices into renewable hosting capacity maximization strategies. Optimization objectives increasingly target the reduction of renewable curtailment and the expansion of hosting capacity while maintaining system security. Stochastic and chance-constrained optimization frameworks are particularly relevant in these applications, reflecting the probabilistic nature of renewable generation.

5. Conclusion

This article has presented a comprehensive review of recent trends in optimization objectives for power system operation improvement using Flexible AC Transmission Systems (FACTS), emphasizing their evolving role in addressing the technical, economic, and operational challenges of modern power grids. Through a structured analysis, the study has demonstrated that FACTS devices have progressed from being auxiliary voltage and power flow control tools to becoming central components in advanced, optimization-driven power system operation. The classification of FACTS devices into shunt, series, combined, and hybrid categories has highlighted the diversity of controllability offered by contemporary power-electronic technologies. When coupled with appropriate optimization techniques, these devices enable precise regulation of voltage profiles, power flows, and system dynamics across multiple time scales. The article further revealed that traditional deterministic and single-objective optimization approaches are increasingly inadequate for capturing the nonlinear, multi-variable, and uncertain nature of renewable-rich power systems.

Moreover, an in-depth examination of optimization objectives for power system performance improvement showed a clear expansion from classical goals, such as loss minimization and voltage regulation, toward broader, multi-dimensional objectives that integrate economic efficiency, environmental sustainability, reliability, resilience, and power quality. In this context, FACTS-based optimization has emerged as a critical enabler for balancing competing objectives and enhancing overall system performance. In this context, the analysis of recent trends underscored a decisive shift toward multi-objective, security-constrained, and uncertainty-aware optimization frameworks, supported by meta-heuristic algorithms, artificial intelligence, and data-driven control strategies.

In particular, the growing use of reinforcement learning, model predictive control, and distributed artificial intelligence reflects the need for adaptive and scalable solutions capable of operating under real-time variability, contingencies, and evolving market conditions. These approaches position FACTS devices as integral components of future smart grids, rather than isolated control elements. Despite significant progress, several challenges remain. These include the coordination of multiple FACTS devices across wide-area networks, integration with market mechanisms and cyber-physical infrastructures, scalability of optimization algorithms for large-scale systems, and the need for standardized benchmarking and real-time validation. Addressing these challenges can be essential to fully exploit the potential of FACTS technologies in next-generation power systems. In conclusion, FACTS-based optimization represents a powerful and indispensable pathway for achieving secure, efficient, and resilient power system operation in the era of high renewable penetration. Continued research focusing on coordinated, intelligent, and robust optimization frameworks will be pivotal in enabling the sustainable transformation of future power grids.

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