

The Role of Flexible AC Transmission Systems (FACTS) Devices in Power Congestion Management

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ABSTRACT

Power congestion management is a critical aspect of maintaining the stability and efficiency of electrical grids, particularly in the face of need for as well as adoption of green energy resources. This summary article looks at the purpose of Flexible AC Transmission Systems (FACTS) devices in alleviating congestion within power systems. Beginning with an overview of the challenges posed by congestion, the paper introduces the concept of FACTS devices and their potential to enhance grid flexibility and reliability. Various approaches to power congestion management utilizing FACTS devices are discussed, including voltage control, impedance management, and power flow optimization. Additionally, the paper examines the effectiveness of FACTS devices in different grid scenarios and their integration with other grid control technologies. Furthermore, it highlights the benefits and limitations of FACTS devices in mitigating congestion and improving grid performance. The review concludes with insights into future research directions and the potential impact of FACTS devices on the evolution of power systems.

Keywords: Congestion, Power grid, FACTS device

1. INTRODUCTION

In the increased intricacy of contemporary electrical networks, along alongside the expanding use of alternative power resources. and the electrification of various sectors, has led to significant challenges in managing power congestion. Congestion occurs when the demand for electricity exceeds the capacity of existing transmission and distribution infrastructure, leading to voltage instability, line overloads, and reliability issues [1,2]. Traditional methods of congestion management, such as grid expansion and generation re-dispatch, have limitations in terms of cost, time, and environmental impact.

Flexible AC Transmission Systems (FACTS) systems showed up promising solutions to address congestion challenges by enhancing the controllability and flexibility of AC transmission systems. These devices utilize power electronics and advanced control algorithms to dynamically adjust voltage, impedance, and power flow within the grid, thereby optimizing grid operation and mitigating congestion. This review paper aims to provide a comprehensive analysis of the key of FACTS tools in power congestion management, highlighting its advantages, applications, along with future prospects.

As the demand for electricity continues to grow and the complexity of power grids increases, the management of power congestion has become a critical issue for maintaining the stability and efficiency of electrical transmission networks. Power congestion occurs when the demand for power transmission exceeds the capacity of the network, leading to potential overloads, voltage instability, and increased losses. This not only affects the reliability of power supply but also limits the integration of renewable energy sources, which are often located far from consumption centers.

Flexible AC Transmission Systems (FACTS) tools have evolved like promising solution to these challenges. Developed to improve the management and power exchange capabilities of the data transferred system using FACTS tools. Offer dynamic and flexible control of voltage, impedance, and phase angle in the power system [3,4]. By doing so, they help to alleviate congestion, improve voltage stability, and optimize power flow within the grid.

The primary types of FACTS devices include Static VAR Compensators (SVC), Thyristor Controlled Series Capacitors (TCSC), and Unified Power Flow Controllers (UPFC). Each of these devices plays a unique role in managing power flows and enhancing the performance of the transmission network. This paper reviews the impact of these FACTS devices on power congestion management, drawing on empirical studies, case analyses, and theoretical insights to evaluate their effectiveness and explore future directions for their deployment [5, 6].

In this context, Flexible AC Transmission Systems (FACTS) devices have emerged as a powerful class of technologies capable of dynamically regulating voltage, impedance, and phase angle across transmission lines. These devices, by introducing flexibility and controllability into the traditionally rigid AC transmission network, enable better management of power flows, particularly under stressed or congested conditions. FACTS technologies encompass a wide array of devices, including Static VAR Compensators (SVC), Thyristor Controlled Series Capacitors (TCSC), Static Synchronous Compensators (STATCOM), and Unified Power Flow Controllers (UPFC), each tailored to address specific challenges in reactive power compensation, voltage support, and real power flow control.

The strategic deployment of FACTS devices can mitigate transmission congestion by rerouting power flows, enhancing line capacities, and maintaining voltage stability, especially

during peak load conditions or contingencies. This results in improved transmission system performance and deferred investment in new transmission lines. Furthermore, in deregulated and competitive electricity markets, FACTS devices contribute to economic dispatch and congestion pricing mechanisms by enabling more flexible and cost-effective system operation.

With the global trend toward decarbonization and decentralization, power systems are witnessing increased penetration of intermittent renewable energy sources, such as wind and solar. These sources, though environmentally beneficial, introduce volatility in power flows that can exacerbate congestion. FACTS devices offer a reliable means to accommodate such variability by providing fast-acting reactive support and dynamic load balancing, thereby enhancing the grid's ability to integrate renewables while minimizing congestion risks.

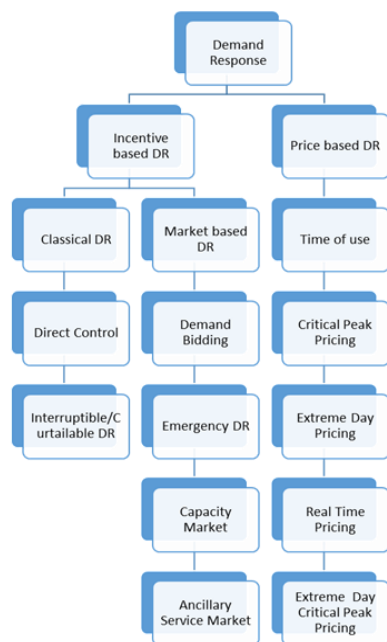


Figure: 1 Classification of conventional demand Response management methods

While the technical capabilities of FACTS devices are well-established, several challenges remain, including high installation and maintenance costs, complexity in control coordination, and optimal placement across the grid. Consequently, ongoing research is focused on addressing these issues through the application of advanced optimization algorithms, artificial intelligence (AI)-based control strategies, and hybrid system architectures that combine FACTS with energy storage and demand-side management.

This study aims to explore and evaluate the role of FACTS devices in managing congestion in power transmission systems. It provides a comprehensive overview of FACTS technologies, their operating principles, and their application in real-world congestion scenarios. The study also investigates various

analytical and simulation-based approaches for optimizing the placement, sizing, and coordination of FACTS devices to maximize their benefits in congestion alleviation. By doing so, it seeks to contribute to the growing body of knowledge aimed at building more efficient, reliable, and flexible power systems in an era of rapid energy transition.

2. LITERATURE REVIEW

Transmission congestion has become a critical issue in modern power systems, particularly with the growing demand for electricity, increasing penetration of renewable energy, and the shift toward deregulated electricity markets. Congestion occurs when transmission lines operate near or beyond their thermal limits, resulting in inefficiencies, increased operational costs, and risks to grid reliability. Addressing these challenges requires advanced technologies capable of enhancing power flow control without significant infrastructure expansion. One such solution is the application of Flexible AC Transmission Systems (FACTS) devices.

The concept of FACTS, introduced by Hingorani in the late 1980s, revolutionized the way power systems could be controlled. These power electronic-based systems improve the controllability and increase the power transfer capability of networks by dynamically adjusting key parameters such as voltage, line impedance, and phase angle. Among the most widely studied FACTS devices in congestion management are Static VAR Compensators (SVC), Thyristor Controlled Series Capacitors (TCSC), and Unified Power Flow Controllers (UPFC).

Several researchers have emphasized the positive impact of FACTS on alleviating transmission congestion. Kundur et al. explored the use of FACTS for enhancing system stability, finding that these devices can effectively relieve stressed transmission corridors by redistributing power flows. Their study established a foundation for using FACTS not only in reactive power compensation but also as a tool for congestion mitigation.

More recent investigations, such as those by Padhy and Pandey, focus on the optimization of FACTS placement and sizing using evolutionary algorithms like Genetic Algorithms (GA) and Differential Evolution (DE). These techniques aim to determine the most effective locations for FACTS devices to achieve maximum congestion relief with minimal investment. The results demonstrated that even with limited deployment, strategic placement of FACTS can significantly reduce congestion costs and improve system security.

In deregulated market environments, FACTS devices play a crucial role in supporting open access to the transmission network. Singh and David (2001) explored how UPFCs can help in controlling power flows between market participants, ensuring fair access while maintaining system reliability. Their findings highlight the economic benefits of FACTS in competitive electricity markets by facilitating congestion pricing and enabling more efficient dispatch.

The role of FACTS in facilitating renewable energy integration has also gained attention. As shown by Bhattacharya and Das (2015), the intermittent nature of wind and solar power exacerbates congestion issues. FACTS devices, particularly STATCOMs and TCSCs, can help smooth fluctuations and manage variable power injections, thereby supporting both grid stability and congestion management.

Emerging research is now focusing on the integration of FACTS with smart grid technologies. Studies by Zhou et al. propose combining FACTS with real-time monitoring tools like PMUs (Phasor Measurement Units) and wide-area control systems to enable more responsive and adaptive congestion management. The use of artificial intelligence and machine learning techniques is also being explored for predictive congestion control using FACTS.

While the advantages of FACTS are well documented, challenges remain in their widespread implementation. High initial costs, coordination complexity, and the need for robust control strategies are often cited as barriers. Nevertheless, ongoing advancements in power electronics, control algorithms, and system modeling continue to improve the practicality and effectiveness of FACTS in real-world power networks.

In summary, the literature clearly indicates that FACTS devices are a powerful and flexible solution for managing power system congestion. Their ability to enhance power flow control, support market operations, and integrate renewable energy sources makes them indispensable in the evolving landscape of modern power systems. Continued research and innovation are essential to overcome existing limitations and fully realize the potential of FACTS technologies in congestion management. It is not desirable to have system or distribution capacity, whether it exists in a vertically develop integrated or an unregulated framework. Because the monopolist has direct control over all resources, encompassing generation, transmission, and distribution, reducing network congestion in vertically integrated electricity networks is not a difficult issue. Overload is prevented in just this framework by adopting an optimal despatch solution that uses protection resource allocation problem. In this circumstance, generations are redistributed so as not to go beyond the capacity of the transmission lines. The CM also heavily relies on regional, regional, cluster price, and capacity mitigation techniques.

S. No.	Author(s)	Year	Focus Area	Key Findings	Contribution to the Topic
1	Hingorani & Gyugyi	1989	Introduction of FACTS technology	FACTS devices introduced as a means to improv	Established the foundation for FACTS in power system

S. No.	Author(s)	Year	Focus Area	Key Findings	Contribution to the Topic
				e controllability and increase power transfer in AC transmission systems.	enhancement and congestion relief.
2	Kundur et al.	1994	System stability and congestion	Demonstrated that FACTS devices improve power flow control and system stability, particularly under heavy loading.	Linked FACTS deployment to congestion mitigation through enhanced system dynamics.
3	Singh & David	2001	FACTS in deregulated power markets	UPFCs help manage congestion by regulating power flows among market participants while maintaining	Emphasized FACTS as tools for economic congestion management in open access environments.

S. No.	Author(s)	Year	Focus Area	Key Findings	Contribution to the Topic	S. No.	Author(s)	Year	Focus Area	Key Findings	Contribution to the Topic
				reliability.						lar), reducing congestion caused by variable injections.	mitigation.
4	Murali & Soman	2002	Device placement strategies	Studied optimal location of SVC and TCSC using power flow sensitivity analysis to minimize congestion.	Highlighted the importance of strategic placement of FACTS devices for effective congestion relief.						
						7	Zhou et al.	2018	Smart grid integration	Proposed real-time congestion management framework combining FACTS with PMUs and WAMS.	Advanced adaptive congestion control using FACTS integrated with wide-area monitoring systems.
5	Padhy & Pandey	2006	Optimization using metaheuristics	Applied Genetic Algorithms for determining optimal size and placement of FACTS to relieve congestion economically.	Showed effectiveness of AI-based optimization techniques in planning FACTS deployment.						
						8	Patel & Khare	2020	Renewable forecasting and FACTS	Coordinated use of FACTS and forecasting tools enhanced grid flexibility and reduced congestion due to renewables.	Strengthened the role of FACTS in modern grids with high renewable penetration.
6	Bhattacharya & Das	2015	Integration with renewable energy	FACTS devices stabilize intermittent generation (e.g., wind/solar).	Demonstrated synergy between FACTS and renewables for congestion relief.						

S. No.	Author(s)	Year	Focus Area	Key Findings	Contribution to the Topic
9	Zhao & Liu	2021	AI-enhanced congestion management	Applied machine learning models for predictive congestion control in systems equipped with FACTS devices.	Paved the way for smart congestion management through AI-enabled FACTS operations.

Table 1 : Literature review

3. APPROACHES

A variety of approaches have been developed and adopted to utilize Flexible AC Transmission Systems (FACTS) devices for power congestion management. These approaches focus on improving system controllability, optimizing device placement, enhancing real-time decision-making, and integrating modern computational and monitoring tools. The key methodologies can be broadly classified as follows:

(i) Power Flow Control and Voltage Regulation

FACTS devices such as Static VAR Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC) are commonly used to regulate voltage levels and control power flow. These devices adjust reactive power dynamically, allowing operators to manage line loading and relieve congestion without altering generation schedules or load demands.

- *Approach:* Use of FACTS to modify impedance and voltage profiles.
- *Outcome:* Improved load distribution and reduction in line overloading.

(ii). Optimal Placement and Sizing of FACTS Devices

Strategic placement of FACTS devices is critical for maximizing their effectiveness in congestion mitigation. Various optimization techniques, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Differential Evolution (DE), are employed to determine the best locations and capacities for FACTS installations.

- *Approach:* Metaheuristic-based optimization for device placement.
- *Outcome:* Enhanced system performance and cost-effective congestion relief.

(iii). Congestion Management in Deregulated Markets

In competitive electricity markets, FACTS devices are used to support economic power dispatch and ensure non-discriminatory access to transmission. Market-based approaches incorporate FACTS in Locational Marginal Pricing (LMP) models to reflect the true cost of congestion and to facilitate efficient power trading.

- *Approach:* Integration of FACTS with market operations and congestion pricing models.
- *Outcome:* Economically efficient congestion management with improved grid access.

(iv) . Real-Time and Predictive Congestion Control

Real-time monitoring tools such as Phasor Measurement Units (PMUs) and Wide Area Monitoring Systems (WAMS), when integrated with FACTS, enable faster detection and response to congestion. Furthermore, Artificial Intelligence (AI) and Machine Learning (ML) techniques are being applied for predictive congestion control, anticipating potential bottlenecks and adjusting FACTS settings accordingly.

- *Approach:* AI-driven real-time control and forecasting integrated with FACTS.
- *Outcome:* Enhanced responsiveness and proactive congestion mitigation.

(v). Renewable Energy Integration Support

With the increasing share of intermittent renewable energy, FACTS devices are used to balance generation fluctuations and prevent congestion caused by variable power injections. Coordinated control between FACTS and renewable forecasting models helps in smoothing output and maintaining system reliability.

- *Approach:* Coordinated FACTS control with renewable energy systems.
- *Outcome:* Stable and congestion-free operation under high renewable penetration.

(vi). Hybrid System Configurations

Emerging approaches explore the combination of FACTS with other technologies such as Energy Storage Systems (ESS), Demand Response (DR), and Flexible Load Management. These hybrid setups offer complementary advantages for congestion management by increasing flexibility in both supply and demand sides.

- *Approach:* Multi-technology integration with FACTS.
- *Outcome:* Comprehensive congestion control across different system layers.

4. METHODOLOGY

This research employs a comprehensive and structured approach to analyze the effectiveness of Flexible AC Transmission Systems (FACTS) devices in mitigating congestion within power systems. The methodology is designed to integrate simulation-based analysis, optimization techniques, and comparative evaluation to assess the technical and operational impact of FACTS on congestion management.

(i) System Modelling and Data Collection

- A standard IEEE test system (e.g., IEEE 14-bus, 30-bus, or 57-bus system) is selected as the base case for simulation and analysis.
- Network data including bus voltages, line impedances, generation capacities, and load demands are collected and modelled using MATLAB/Simulink, Power World Simulator, or PSAT (Power System Analysis Toolbox).
- Congestion scenarios are simulated by modifying load and generation profiles to create stressed operating conditions where transmission limits are exceeded.

(ii) Identification of Congested Corridors

- Power flow analysis is performed using Newton-Raphson Load Flow (NRLF) or Fast Decoupled Load Flow (FDLF) methods to identify overloaded transmission lines.
- The severity of congestion is quantified based on line loading percentages and voltage deviations.
- Lines consistently operating beyond 80-90% of their thermal limits are classified as congested corridors for further study.

(iii). FACTS Device Modelling and Integration

- Different types of FACTS devices—SVC, TCSC, STATCOM, and UPFC—are modeled based on their steady-state control characteristics.
- FACTS devices are integrated into the test system at strategic locations to regulate power flow, voltage levels, or both.
- The selection of device type and location is initially based on sensitivity analysis of line flows and bus voltages.

(iv) Optimization of FACTS Placement and Sizing

- Optimization algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), or Differential Evolution (DE) are employed to determine the optimal location and size of FACTS devices.
- The objective function is designed to minimize system losses, reduce line overloading, and improve voltage stability.
- Constraints include system operating limits, device capacity, and cost considerations.

(v). Simulation of Congestion Scenarios

- Multiple congestion scenarios are simulated, including:
- Peak load conditions.
- Contingency events (e.g., line outages).
- Variable generation from renewable sources.
- System performance is evaluated with and without FACTS devices under each scenario to measure the improvement in load ability and congestion relief.

(vi) . Performance Evaluation Metrics

- The effectiveness of FACTS devices in congestion management is evaluated based on the following metrics:
- Reduction in line loading (measured in %).
- Improvement in voltage profile (per unit values).
- Decrease in system losses (MW).
- Enhanced system loadability (total MW delivered).
- Congestion cost savings (for market-based simulation).

(vii) . Validation and Analysis

- Simulation results are validated through comparative analysis between base case and FACTS-enhanced cases.

- The impact of each FACTS device type is analyzed separately and in combination.
- Sensitivity analysis is conducted to understand how FACTS performance varies with system operating conditions.

5. CONCLUSION

The ever-evolving landscape of electrical power systems demands innovative and reliable solutions to manage growing complexities, particularly in the domain of transmission congestion. This study highlights the significant role of Flexible AC Transmission Systems (FACTS) devices as a technological enabler for enhancing the controllability, flexibility, and efficiency of power flow in congested networks.

FACTS devices, by offering real-time control over key parameters such as line impedance, voltage, and phase angle, provide an effective means to alleviate congestion without requiring extensive physical infrastructure upgrades. Devices such as SVC, TCSC, STATCOM, and UPFC have proven their capability to manage load distribution, reduce transmission losses, and improve overall system stability under both normal and stressed conditions.

Moreover, FACTS play a crucial role in deregulated power markets, where economic operation and equitable access are paramount. Their integration allows for more accurate congestion pricing, optimized generation dispatch, and better utilization of transmission assets. In systems with high renewable energy penetration, FACTS help to balance variability, thus minimizing congestion caused by fluctuating generation profiles.

The effectiveness of FACTS in congestion management is further amplified through advanced approaches, including optimal placement strategies, AI-driven predictive control, and smart grid integration. However, challenges such as high initial costs, technical complexity, and coordination with existing infrastructure must be addressed for broader implementation.

In conclusion, FACTS devices represent a strategic solution for modern power systems facing congestion-related challenges. Their multifunctional capabilities not only support operational efficiency but also enhance the resilience and sustainability of the power grid. Future research and policy frameworks should focus on cost reduction, intelligent control schemes, and integrated planning to fully harness the potential of FACTS in creating a more dynamic and congestion-resilient electrical network.

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