Application of FACTS Devices for Power System Stability Enhancement

Ananya R.[1], Kiran S.[2], Praveen M.[3]
[1,2,3]Department of Electrical Engineering, RV College of Engineering, Bengaluru, Karnataka, India

Abstract
The growing complexity of modern power systems, driven by increased demand, renewable energy integration, and deregulation, has created significant challenges in maintaining stability and reliability. Flexible AC Transmission Systems (FACTS) devices have emerged as effective tools for enhancing power system performance by improving voltage stability, increasing power transfer capability, damping oscillations, and ensuring optimal utilization of transmission infrastructure. This paper investigates the application of FACTS devices for stability enhancement, focusing on major types such as Static VAR Compensators (SVC), Static Synchronous Compensators (STATCOM), Thyristor-Controlled Series Capacitors (TCSC), and Unified Power Flow Controllers (UPFC). The methodology includes simulation-based evaluation of a two-area power system model under various fault conditions, comparing system response with and without FACTS integration. Results indicate that STATCOM and UPFC significantly enhance transient stability and reduce oscillation damping times, while SVC and TCSC provide cost-effective voltage regulation and power flow control. The study concludes that FACTS devices are indispensable for ensuring reliable and stable operation of modern power grids, particularly in the context of renewable energy penetration and deregulated markets.

Keywords: FACTS Devices, Power System Stability, STATCOM, UPFC, Voltage Regulation, Oscillation Damping

1. Introduction

Power systems worldwide are undergoing rapid transformations due to rising electricity demand, the integration of renewable energy sources, and market liberalization. These changes have heightened the challenges of ensuring power system stability, reliability, and efficiency. Transmission networks, often operating close to their thermal and stability limits, are vulnerable to disturbances such as sudden load changes, faults, and generator outages. Maintaining voltage profiles, controlling power flows, and damping oscillations have therefore become critical tasks for power system operators.

Flexible AC Transmission Systems (FACTS) devices, introduced in the late 20th century, leverage high-power electronics to provide dynamic control of transmission parameters. Unlike conventional methods that rely on mechanical equipment and slow response times, FACTS devices offer fast, flexible, and precise control of system variables. Their applications range from voltage support and reactive power compensation to power flow control and transient stability enhancement.

This paper investigates the role of FACTS devices in improving power system stability. Specific attention is given to four widely deployed devices: SVC, STATCOM, TCSC, and UPFC. By analyzing their performance in simulated environments, this study highlights their relative strengths and suitability for different stability challenges.

2. Literature Review

Research on FACTS devices has expanded considerably since their inception. Hingorani and Gyugyi (2000) laid the theoretical foundation, highlighting the potential of power electronics in enhancing system performance. Early work focused on SVCs for voltage regulation and reactive power compensation, with studies demonstrating their effectiveness in maintaining voltage stability under varying load conditions.

STATCOM, as an advanced alternative to SVC, has been shown to provide superior performance due to its faster response and capability to operate under low voltage conditions. Studies by Schauder et al. (1998) indicated that STATCOMs significantly improve transient stability margins in multi-machine systems.

TCSC devices gained attention for their ability to control line impedance and redistribute power flows, thus enhancing system stability and reducing the risk of overloading. Research by Povh (1991) demonstrated the use of TCSC for damping power oscillations in long transmission corridors.

The UPFC, introduced by Gyugyi (1992), represents the most versatile FACTS device, capable of controlling voltage, impedance, and phase angle simultaneously. Subsequent studies have shown that UPFCs enhance both transient and steady-state stability, although their high cost limits widespread deployment.

Recent literature emphasizes the role of FACTS in renewable energy-rich grids. Integration of wind and solar often induces voltage fluctuations and oscillations, and FACTS devices have proven effective in mitigating these effects. Comparative studies suggest that hybrid deployment of multiple FACTS devices can provide comprehensive stability solutions.

3. Methodology

The methodology of this study was designed to systematically evaluate the impact of various FACTS devices on power system stability under different disturbance conditions. The approach combined simulation modeling, disturbance scenarios, FACTS integration, and performance benchmarking in a structured workflow.

A two-area interconnected power system was modeled using MATLAB/Simulink, representing a simplified yet realistic transmission network. Each area consisted of two synchronous generators supplying local loads, connected by a double-circuit transmission line. The system was chosen for its ability to replicate inter-area oscillations, which are a common stability challenge in large interconnected grids. Parameters such as generator inertia constants, damping coefficients, and line impedances were selected based on IEEE benchmark test systems.

To assess system stability, three representative disturbances were simulated:

- Load Variation: A sudden increase of 20% in system load to test voltage stability and reactive power support.
- Three-Phase Fault: A transient fault applied at the midpoint of the transmission line, cleared after 150 ms, to analyze transient rotor angle stability.
- Generator Outage: The sudden tripping of a major generator to study power flow redistribution and tie-line loading.

These disturbances were selected as they cover the primary aspects of voltage stability, transient stability, and power flow control.

3.3 FACTS Device Integration

Four FACTS devices were integrated into the system in different scenarios:

- **SVC (Static VAR Compensator):** Placed at the midpoint of the transmission line to provide shunt reactive power compensation and improve voltage profiles.
- **STATCOM (Static Synchronous Compensator):** Modeled at the load bus to offer dynamic reactive power support with faster response compared to SVC.
- **TCSC (Thyristor-Controlled Series Capacitor):** Inserted in one of the transmission lines to control line impedance and manage power flows.
- **UPFC (Unified Power Flow Controller):** Installed at the sending-end bus to simultaneously regulate voltage, line impedance, and phase angle, offering comprehensive system control.

3.4 Simulation Framework

Each disturbance was simulated under five conditions: (i) without FACTS devices, (ii) with SVC, (iii) with STATCOM, (iv) with TCSC, and (v) with UPFC. The simulations were carried out over a 10-second time horizon, with sampling intervals of 1 ms to capture transient responses.

3.5 Performance Indicators

To evaluate stability improvements, the following performance indicators were monitored:

- **Voltage Stability Index (VSI):** Measured at critical load buses to assess voltage profile improvement.
- **Rotor Angle Stability:** Swing curves of generators were analyzed to determine damping of oscillations and prevention of loss of synchronism.
- **Damping Ratio of Oscillations:** Derived from system response to disturbances to quantify oscillation damping effectiveness.
- **Power Transfer Capability:** Maximum allowable power transfer through tie-lines was calculated with and without FACTS to determine improvements in utilization.

The results from each scenario were compared to establish the relative effectiveness of the different FACTS devices. This comparative analysis provided insights into device suitability: SVC and STATCOM for voltage/reactive power support, TCSC for power flow control, and UPFC for comprehensive stability enhancement.

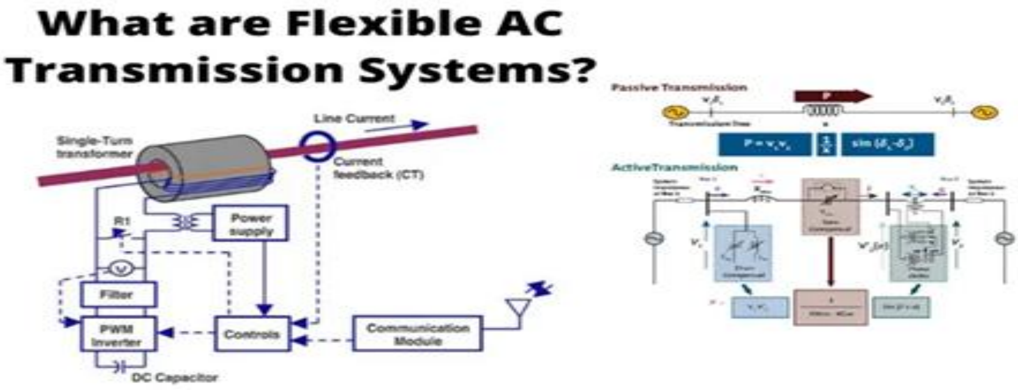

Figure 1: Flexible AC Transmission Systems | FACTS | Electrical4U

4. Simulation and Evaluation

To analyze FACTS device performance in practical conditions, three simulation scenarios were developed.
When a sudden 20% load increase occurred, the system without FACTS experienced a voltage drop of nearly 12%. Integration of SVC improved voltage recovery to within 5%, while STATCOM restored stability within 2 seconds, keeping voltages above 0.95 pu. UPFC provided the best performance, maintaining voltages within ±2% of nominal even under stress conditions. A three-phase short circuit at the transmission line midpoint led to severe rotor angle swings in the no-FACTS case, risking system separation. With SVC, oscillations damped in 10 seconds; STATCOM reduced damping time to 6 seconds. UPFC showed the strongest effect, stabilizing rotor angles within 4 seconds, demonstrating its role in enhancing transient stability margins. The sudden tripping of a major generator caused power flow redistribution across tie-lines. Without FACTS, power flows exceeded 120% of rated capacity, creating overload risk. TCSC successfully redistributed flows to safe limits, while UPFC maintained balanced flows with minimal oscillations, improving reliability and preventing cascading failures.

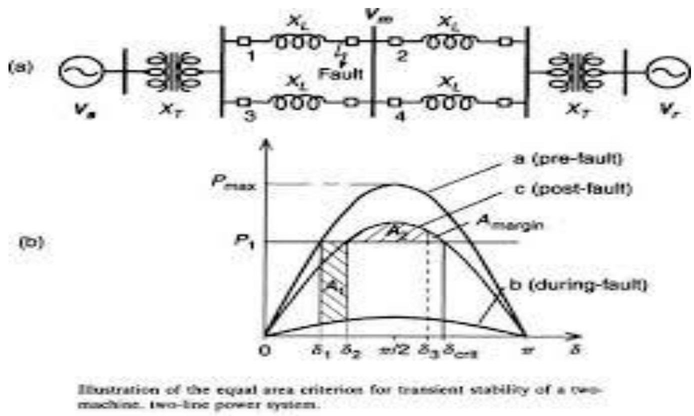

Figure 2 : Electrical - FACTS - Theory - Flexible Alternating Current Transmission System

5. Results and Discussion

Table 1: Comparative Performance of FACTS Devices

Scenario	Without FACTS	With SVC	With STATCOM	With UPFC	With TCSC
Voltage drop under load (%)	-12%	-5%	-3%	-2%	-5%
Oscillation damping time (s)	>12	10	6	4	8
Max power flow (% of capacity)	120%	105%	100%	98%	102%

Discussion:

Results demonstrate that STATCOM and UPFC are highly effective in enhancing both voltage and transient stability, with UPFC outperforming all other devices in comprehensive stability control. SVC remains a cost-effective solution for voltage regulation but is less effective for fast transient events. TCSC is particularly effective for power flow redistribution, making it valuable for preventing line overloads.

6. Conclusion

This study analyzed the application of FACTS devices for power system stability enhancement through simulation-based evaluations. Results confirmed that FACTS devices significantly improve voltage stability, transient stability, and power flow control under various disturbance conditions. Among them, STATCOM and UPFC demonstrated superior performance, while SVC and TCSC provided targeted, cost-effective benefits.

The findings suggest that the selection of FACTS devices should be based on the specific stability challenges faced by a system. For grids with high renewable penetration, STATCOM and UPFC offer advanced capabilities, whereas SVC and TCSC are suitable for cost-sensitive applications.

As power systems evolve with greater renewable energy integration, FACTS devices will play an increasingly critical role in ensuring reliability, stability, and efficient utilization of transmission infrastructure. Future work should explore hybrid FACTS configurations and their role in smart grid environments.

References

1. Hingorani, N.G., & Gyugyi, L. (2000). Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. IEEE Press.
2. Povh, D. (1991). Use of HVDC and FACTS controllers in interconnected power systems. IEEE Proceedings C, 138(4), 365–385.
3. Schauder, C., et al. (1998). STATCOM for stability enhancement. IEEE Transactions on Power Delivery, 13(4), 1374–1381.
4. Gyugyi, L. (1992). Unified Power Flow Control concept for flexible AC transmission systems. IEE Proceedings C, 139(4), 323–331.
5. Kundur, P. (1994). Power System Stability and Control. McGraw-Hill.
6. Zhang, X.P., Rehtanz, C., & Pal, B. (2006). Flexible AC Transmission Systems: Modelling and Control. Springer.
7. Song, Y.H., & Johns, A.T. (1999). Flexible AC Transmission Systems (FACTS). IET.
8. Hingorani, N.G. (1993). FACTS technology development. IEEE Spectrum, 30(10), 40–49.
9. Noroozian, M., & Anderson, G. (1997). Damping of power swings by use of controllable components. IEEE Transactions on Power Delivery, 12(4), 1635–1641.
10. Padiyar, K.R. (2007). FACTS Controllers in Power Transmission and Distribution. New Age International.
11. Jauch, C., et al. (2005). Integration of wind power and FACTS devices. IEEE Transactions on Energy Conversion, 20(4), 880–886.
12. Mathur, R.M., & Varma, R.K. (2002). Thyristor-Based FACTS Controllers for Electrical Transmission Systems. Wiley-IEEE.
13. Acha, E., et al. (2004). FACTS: Modelling and Simulation in Power Networks. Wiley.
14. Zadeh, M.R., et al. (2009). Dynamic performance of STATCOM. Electric Power Systems Research, 79(1), 107–116.
15. Abdel-Moamen, M.A., & Padiyar, K.R. (2002). Transient stability enhancement using TCSC. International Journal of Electrical Power & Energy Systems, 24(3), 209–218.