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A Survey on Voltage Profile Enhancement using Integrated Power Flow Controller in Modern Power Systems

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ABSTRACT

Voltage profile enhancement is a critical aspect of maintaining stability, reliability, and efficient operation in modern power systems, especially with the increasing penetration of renewable energy sources and dynamic load variations. Among various Flexible AC Transmission Systems (FACTS) devices, the Integrated Power Flow Controller (IPFC) has emerged as a powerful solution for simultaneous control of multiple transmission line parameters, including voltage, active power, and reactive power. This survey paper presents a comprehensive review of voltage profile enhancement techniques using IPFC in modern power systems. The paper discusses the operating principles, configurations, and control strategies of IPFC, highlighting its capability to regulate voltage levels and improve power flow distribution across interconnected transmission lines. Various control approaches, including conventional methods and advanced techniques such as fuzzy logic, artificial intelligence, and optimization algorithms, are analyzed in terms of their effectiveness in enhancing voltage stability. In addition, the role of IPFC in mitigating power quality issues, reducing transmission congestion, and supporting renewable energy integration is examined.

Furthermore, this survey identifies key challenges associated with IPFC implementation, including high installation cost, complex control requirements, and coordination with other FACTS devices. Recent advancements and future research directions, such as smart grid integration and intelligent control systems, are also explored. Overall, the study emphasizes the significance of IPFC as an effective FACTS device for voltage profile enhancement, contributing to improved performance and stability of modern power systems.

Keywords: - IPFC, FACTS, Voltage Profile, Voltage Stability, Power Flow Control

1. INTRODUCTION

The reliable operation of modern power systems largely depends on maintaining an acceptable voltage profile across transmission and distribution networks. With the rapid growth in electricity demand, increasing system complexity, and the integration of renewable energy sources such as wind and solar, maintaining voltage stability has become a major challenge. Voltage profile deviations, including voltage drops and fluctuations, can lead to poor power quality, reduced system efficiency, and in severe cases, voltage collapse. Therefore, enhancing and controlling the voltage profile is a critical requirement for ensuring the secure and efficient operation of contemporary power systems [1].

Conventional methods for voltage control, such as tap-changing transformers, capacitor banks, and reactor compensation, are often insufficient to handle the fast and dynamic variations present in modern grids. To address these limitations, Flexible AC Transmission Systems (FACTS) technology has been widely adopted. FACTS devices provide dynamic and rapid control of power system parameters, including voltage, impedance, and phase angle, thereby improving system performance and stability. Among the various FACTS controllers, the Integrated Power Flow Controller (IPFC) has gained significant attention due to its unique capability to control multiple transmission lines simultaneously [2, 3].

The IPFC is an advanced FACTS device that utilizes multiple series-connected voltage source converters (VSCs) linked through a common DC bus. This configuration allows the IPFC to inject controllable voltage in different transmission lines, enabling coordinated control of active and reactive power flows. As a result, it can effectively regulate voltage profiles, balance load distribution among lines, and mitigate transmission congestion. The ability of IPFC to transfer real power between lines through a common DC link further enhances its flexibility and efficiency compared to other FACTS devices [4].

In recent years, the role of IPFC has become increasingly important with the integration of renewable energy sources into the grid. The intermittent nature of renewable generation introduces additional voltage fluctuations and stability issues, which can be effectively managed using IPFC-based control strategies. Furthermore, the incorporation of advanced control techniques such as fuzzy logic, artificial intelligence, and optimization algorithms has significantly improved the performance of IPFC in dynamic operating conditions [5, 6].

This survey paper focuses on the application of the Integrated Power Flow Controller for voltage profile enhancement in modern power systems. It aims to review various control techniques, operational strategies, and recent advancements associated with IPFC, while also identifying key challenges and future research directions. The study highlights the potential of IPFC as a powerful tool for improving voltage stability, enhancing power quality, and ensuring efficient operation of modern interconnected power networks [7].

2. LITERATURE REVIEW

In recent years, extensive research has been carried out on voltage profile enhancement and stability improvement in power systems using FACTS devices and advanced control techniques. In [1], I. Y. Fawzy et al. (2024) investigated the deployment of a STATCOM integrated with fuzzy logic control to enhance system performance under fault conditions. Their study demonstrated that fuzzy-based controllers significantly improve voltage regulation and dynamic response compared to conventional methods, especially during disturbances, thereby contributing to better voltage profile maintenance. Similarly, in [2], R. K. Singh and N. K. Singh (2022) analyzed transient stability improvement using various FACTS controllers. Their work highlighted that devices like STATCOM, SVC, and UPFC can effectively stabilize system voltage and improve overall dynamic performance when subjected to sudden load or generation changes.

Further, in [3], H. Daealhaq and A. Tukkee (2021) focused on optimal placement of FACTS devices for minimizing power losses and enhancing voltage profiles. Using optimization techniques, they concluded that proper placement of controllers plays a crucial role in achieving maximum efficiency and voltage stability. In [4], M. Hassan et al. (2020) proposed a fuzzy logic-based SVC controller for transient stability enhancement. Their results indicated that intelligent control approaches outperform traditional controllers in handling nonlinearities and system uncertainties, thereby improving voltage stability during transient conditions.

Moreover, in [5], N. E. Akpeke et al. (2019) examined the contribution of FACTS devices in wind-integrated power systems. Their findings revealed that FACTS controllers significantly enhance voltage stability and reduce fluctuations caused by intermittent renewable generation. Similarly, in [6], A. Movahedi et al. (2019) designed optimized STATCOM controllers using advanced optimization techniques. The study emphasized that optimization-based controller design leads to improved transient response and better voltage regulation in complex power systems.

In [7], P. Lalitha Devamani and K. Radha Rani (2018) explored DSTATCOM-based load compensation using fuzzy logic. Their work demonstrated effective mitigation of voltage sag and improved load balancing, contributing to enhanced power quality. Additionally, in [8], Pranabesh Bala and Sovan Dalai (2017) introduced a Random Forest-based fault analysis method for the IEEE 14-bus system. Although primarily focused on fault detection, their approach indirectly supports voltage stability by enabling rapid identification and mitigation of system disturbances.

Furthermore, in [9], Mehmet Yesilbudak et al. (2017) investigated the effects of FACTS devices on voltage stability, concluding that these devices play a vital role in maintaining voltage profiles under varying load conditions. Finally, in [10], Zhou Qiu-kuan et al. (2017) proposed a novel method for measuring capacitive current in distribution networks, which is essential for accurate voltage control and system monitoring.

Overall, the reviewed literature clearly indicates that FACTS devices, particularly when combined with intelligent control and optimization techniques, significantly improve voltage profile, transient stability, and overall system performance. However, most studies focus on individual devices such as STATCOM and SVC, highlighting the need for further research on advanced controllers like the Integrated Power Flow Controller (IPFC) for more effective multi-line voltage regulation in modern power systems.

3. FACTS CONTROLLER

Flexible AC Transmission System (FACTS): Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability. The various basic applications of FACTS-devices are:

- Power flow control
- Increase of transmission capability
- Voltage control
- Reactive power compensation, stability improvement
- Power quality improvement
- Power conditioning.

The fig 1 is for classification of FACTS Controllers Based on power electronic devices. In this fig, left hand side column of FACTS-devices employs the use of thyristor valves or converters. This valves or converters are well known since several years. They have low switching frequency and low losses. The devices of the right hand side column of the fig has more advanced technology of voltage source converters based mainly on Insulated Gate Bipolar Transistors (IGBT) or Insulated Gate Commutated Thyristors (IGCT). Pulse width modulation technique is used to control the magnitude and phase of the voltage.

By the means of flexible and rapid control over the AC transmission parameters and network topology, FACTS technology can facilitate the power control, enhance the power transfer capacity, decrease the line losses and generation costs, and improve the stability and security of the power system. FACTS technology opens up new opportunities for controlling and enhancing the useable capacity of present, as well as new upgraded lines. FACTS are an evolving technology and can boost power transfer capability by 20–30% by increasing the flexibility of the systems. By providing added flexibility, FACTS device offers continuous control of power flow or voltage, against daily load changes or change in network topologies.

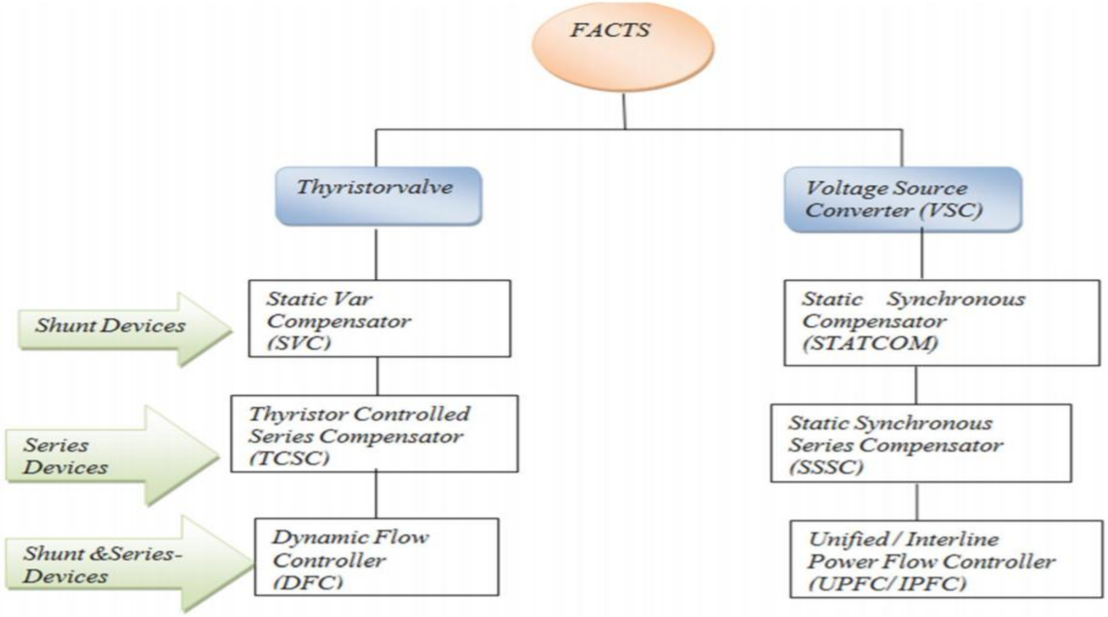

Figure 1: Overview Of major FACTS devices in terms of on power electronic devices

Classification of FACTS Controllers

In general, FACTS controllers can be divided into four categories [1-4]:

- Series Controllers
- Shunt Controllers
- Combined series-series Controllers
- Combined series-shunt Controllers

Depending on the power electronic devices used in the control, the FACTS controllers can be classified as [1, 3]:

- Variable impedance type
- Voltage Source Converter (VSC) type

The variable impedance type controllers include:

1. Static VAR Compensator (SVC), (shunt connected)
   Compensator (TCSC) (arrangement associated)
2. Thyristor Controlled Phase Shifting Transformer (TCPST) or Static PST (joined shunt and arrangement)
3. The VSC based FACTS controllers include:
4. Static Synchronous Compensator (STATCOM) (shunt associated)
5. Static Synchronous Series Compensator (SSSC) (arrangement associated)
6. Interline Power Flow Controller (IPFC) (joined arrangement)
7. Unified Power Flow Controller (UPFC) (joined shunt-arrangement)

4. IPFC

The Integrated Power Flow Controller (IPFC) is an advanced device in Flexible AC Transmission Systems (FACTS) technology that is used to control power flow and enhance voltage stability in modern power systems. Unlike conventional FACTS devices that operate on a single transmission line, the IPFC is capable of simultaneously controlling multiple transmission lines, making it highly effective for large-scale and complex power networks. It consists of two or more series-connected Voltage Source Converters (VSCs), each installed in different transmission lines and interconnected through a common DC link. This configuration allows the transfer of active power between lines, enabling efficient load sharing and improved utilization of transmission capacity.

The working principle of the IPFC is based on injecting a controllable voltage in series with each transmission line. By adjusting the magnitude and phase angle of this injected voltage, the IPFC can regulate both active and reactive power flow, thereby maintaining the desired voltage profile and improving system stability. The presence of a common DC link plays a crucial role, as it enables real power exchange between converters, allowing one transmission line to support another during overload or disturbance conditions.

The IPFC offers several advantages, including enhanced voltage regulation, improved power quality, reduced transmission congestion, and better dynamic performance of the system. It is particularly beneficial in modern grids with high penetration of renewable energy sources, where fluctuations in generation can cause instability. By providing coordinated control of multiple lines, the IPFC helps in maintaining a balanced and stable power system. Overall, it is considered a powerful and flexible solution for voltage profile enhancement and efficient power flow management in advanced power networks.

5. CONCLUSION

This survey highlights the critical importance of voltage profile enhancement in modern power systems, particularly in the presence of increasing load demand and large-scale integration of renewable energy sources. The reviewed literature demonstrates that Flexible AC Transmission Systems (FACTS) devices play a vital role in improving voltage stability, power quality, and overall system performance.

Conventional FACTS controllers such as STATCOM, SVC, and DSTATCOM, especially when combined with advanced control techniques like fuzzy logic, optimization algorithms, and machine learning, have shown significant improvements in transient stability and voltage regulation under dynamic operating conditions.

However, most existing studies primarily focus on individual FACTS devices and their localized impact on system performance. In contrast, the Integrated Power Flow Controller (IPFC) offers a more advanced and flexible solution by enabling simultaneous control of multiple transmission lines, thereby providing superior capability for voltage profile enhancement and power flow management. Despite its advantages, research on IPFC is comparatively limited, particularly in the context of modern smart grids and renewable-integrated power systems.

In conclusion, the integration of advanced FACTS devices like IPFC, along with intelligent control strategies, presents a promising approach for addressing voltage stability challenges in contemporary power networks. Future research should focus on optimized IPFC placement, cost-effective implementation, and the incorporation of AI-based control techniques to further enhance system efficiency, reliability, and scalability. This will contribute significantly to the development of robust, stable, and sustainable power systems.

REFERENCES

1. Y. Fawzy et al., “Deployment of STATCOM with fuzzy logic control for improving power system performance under fault conditions,” Journal of Robotics and Control, vol. 5, no. 3, pp. 636–646, 2024.
2. R. K. Singh and N. K. Singh, “Transient stability improvement using FACTS controllers,” Sustainable Energy Technologies and Assessments, vol. 53, 2022.
3. H. Daealhaq and A. Tukkee, “Power loss reduction and voltage profile improvement using optimal FACTS placement,” IOP Conf. Series, 2021.
4. M. Hassan, X. Sun, and A. Ate, “Fuzzy logic controller based SVC for transient stability enhancement,” TELKOMNIKA, vol. 18, no. 5, pp. 2665–2673, 2020.
5. N. E. Akpeke, C. M. Muriithi, and C. Mwaniki, “Contribution of FACTS devices to transient stability improvement in wind-integrated systems,” Engineering, Technology & Applied Science Research, vol. 9, no. 6, pp. 4893–4900, 2019.
6. Movahedi, A. H. Niasar, and G. B. Gharehpetian, “Designing STATCOM controllers using optimization techniques for transient stability improvement,” Int. Journal of Electrical Power & Energy Systems, vol. 106, pp. 455–466, 2019.
7. P. Lalitha Devamani and K. Radha Rani, “DSTATCOM based load compensation using fuzzy logic,” Int. Journal of Innovative Research, 2018.
8. Pranabesh Bala and Sovan Dalai, “Random Forest based Fault Analysis Method in IEEE 14 Bus System”, 3rd International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), IEEE 2017.

9. Mehmet Yesilbudak, Salih Ermis and Ramazan Bayindir, “Investigation of the effects of FACTS devices on the voltage stability of power systems”, 6th International Conference on Renewable Energy Research and Applications (ICRERA), IEEE 2017.
10. Zhou Qiu-kuan YAO Jun LIU Yan et al. "A new method for measuring capacitive current in distribution network based on three-frequency method" Electrical Measurement & Instrumentation vol. 54 no. 10 pp. 44-49 2017.
11. Teng Hao "Accurate measurement method of capacitive current in resonant grounding system with damping resistance" Journal of Electric Power Science and Technology vol. 31 no. 1 pp. 97-102 2017.
12. Cui Ying-yu HE Fang Zhang Yong-hu et al. "Experiment of overcurrent of capacitive current in distribution network" Power System Protection and Control vol. 21 no. 21 pp. 147-151 2017.
13. M. Venkateswara Reddy, Sishnu Prasad Muni and A. V. R. S. Sharma, “Enhancement of Voltage Profile for IEEE 14 Bus System with Inter line Power Flow Controller”, Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTS E), IEEE 2016.
14. Edrisian, A. Goudarzi, M. Ebadian et al., "Assessing the effective parameters on operation improvement of SCIG based wind farms connected to network", International Journal of Renewable Energy Research, vol. 6, no. 2, pp. 585-592, May 2016.
15. Sanjib Ganguly and Dipanjan Samajpati, “Distributed Generation Allocation on Radial Distribution Networks Under Uncertainties of Load and Generation Using Genetic Algorithm”, IEEE Transactions on Sustainable Energy, Vol. 06, Issue 03, March 2015.